General Physics

Principles and Applications

Lectures in General Physics
for Sciences and Engineering Faculties

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Preface

In general, study the physics concepts provide the student with a clear and logical presentation of the basic concepts and principles of physics and to strengthen an understanding of the concepts and principles through a broad range of interesting applications to the real world.

General physics gives the concepts and applications of the physics concepts in sciences and engineering. I hope it to be a good course for our students in Engineering faculties. It is essential that the students understand the basic concepts and principles before attempting to solve assigned problems. You can best accomplish this goal by carefully reading the textbook before you attend your lecture on the covered material. When reading the text, you should jot down those points that are not clear to you.

This Lecture notes based on Physics for Scientists and Engineers by Serway and its Power point slides from Cengage Learning Company, and then they edited by including concepts, examples, and solved problems.

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Chapter 1 – Measurements

Physics

Fundamental Science

- Concerned with the fundamental principles of the Universe
- Foundation of other physical sciences
- Has simplicity of fundamental concepts

Divided into six major areas:

- Classical Mechanics
- Relativity
- Thermodynamics
- Electromagnetism
- Optics
- Quantum Mechanics

Objectives of Physics

To find the limited number of fundamental laws that govern natural phenomena

To use these laws to develop theories that can predict the results of future experiments

Express the laws in the language of mathematics

- Mathematics provides the bridge between theory and experiment.

Theory and Experiments

Should complement each other

When a discrepancy occurs, theory may be modified or new theories formulated.

- A theory may apply to limited conditions.
  - Example: Newtonian Mechanics is confined to objects traveling slowly with respect to the speed of light.
- Try to develop a more general theory

Measurements

Used to describe natural phenomena

Each measurement is associated with a physical quantity

Need defined standards

Characteristics of standards for measurements

- Readily accessible
- Possess some property that can be measured reliably
- Must yield the same results when used by anyone anywhere
- Cannot change with time

Standards of Fundamental Quantities

Standardized systems

- Agreed upon by some authority, usually a governmental body

SI – Systéme International (Main system used in this text)

- Agreed to in 1960 by an international committee

Fundamental Quantities and Their Units

Quantity	SI Unit
Length	meter
Mass	kilogram
Time	second
Temperature	Kelvin
Electric Current	Ampere
Luminous Intensity	Candela
Amount of Substance	mole

- In mechanics, three fundamental quantities are used: Length, Mass, Time
- All other quantities in mechanics can be expressed in terms of the three fundamental quantities.

Derived quantities can be expressed as a mathematical combination of fundamental quantities.

Examples:

- Area
  - A product of two lengths
- Speed
  - A ratio of a length to a time interval
- Density
  - A ratio of mass to volume

Prefixes

Prefixes correspond to powers of 10.

Each prefix has a specific name and has a specific abbreviation.

The prefixes can be used with any basic units.

They are multipliers of the basic unit.

Examples: 1 mm = 10^{-3} m 1 mg = 10^{-3} g

TABLE 1.4 *Prefixes for Powers of Ten*

Power	Prefix	Abbreviation	Power	Prefix	Abbreviation
10^{-24}	yocto	y	10^{3}	kilo	k
10^{-21}	zepto	z	10^{6}	mega	M
10^{-18}	atto	a	10^{9}	giga	G
10^{-15}	femto	f	10^{12}	tera	T
10^{-12}	pico	p	10^{15}	peta	P
10^{-9}	nano	n	10^{18}	exa	E
10^{-6}	micro	μ	10^{21}	zetta	Z
10^{-3}	milli	m	10^{24}	yotta	Y
10^{-2}	centi	c			
10^{-1}	deci	d			

Models of Matter

Some Greeks thought matter is made of atoms. No additional structure

JJ Thomson (1897) found electrons and showed atoms had structure.

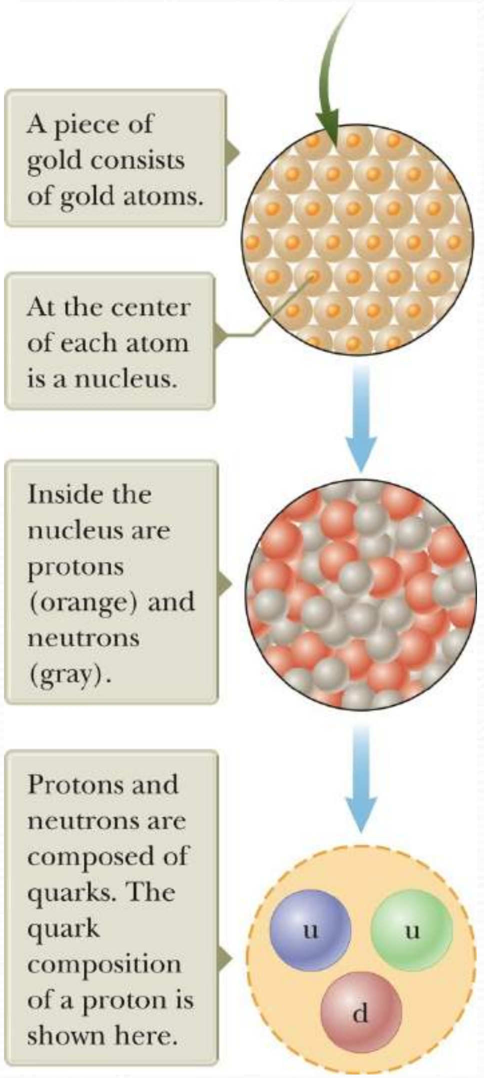
Rutherford (1911) determined a central nucleus surrounded by electrons.

Nucleus has structure, containing protons and neutrons

- Number of protons gives atomic number
- Number of protons and neutrons gives mass number

Protons and neutrons are made up of quarks.
Six Quarks: Up, down, strange, charmed, bottom, top

- Fractional electric charges
  - +⅔ of Up, charmed, top
  - ⅓ of Down, strange, bottom



Basic Quantities and Their Dimension

Dimension has a specific meaning – it denotes the physical nature of a quantity.

Dimensions are often denoted with square brackets.

- Length [L]
- Mass [M]
- Time [T]

Dimensions and Units

Each dimension can have many actual units.

Table 1.5 for the dimensions and units of some derived quantities

TABLE 1.5 *Dimensions and Units of Four Derived Quantities*

Quantity	Area (A)	Volume (V)	Speed (v)	Acceleration (a)
Dimensions	L^2	L^3	L/T	L/T^2
SI units	m^2	m^3	m/s	m/s^2
U.S. customary units	ft^2	ft^3	ft/s	ft/s^2

Dimensions and Units

Quantity	SI Unit		Dimension
velocity	m/s	ms^{-1}	LT^{-1}
acceleration	m/s^2	ms^{-2}	LT^{-2}
force	N $kg\ m/s^2$	$kg\ ms^{-2}$	$M\ LT^{-2}$
energy (or work)	Joule J N m, $kg\ m^2/s^2$	$kg\ m^2s^{-2}$	ML^2T^{-2}
power	Watt W N m/s $kg\ m^2/s^3$	Nms^{-1} $kg\ m^2s^{-3}$	ML^2T^{-3}
pressure (or stress)	Pascal P, N/m^2, $kg/m/s^2$	Nm^{-2} $kg\ m^{-1}s^{-2}$	$ML^{-1}T^{-2}$
density	kg/m^3	$kg\ m^{-3}$	ML^{-3}

Dimensional Analysis

Technique to check the correctness of an equation or to assist in deriving an equation

Dimensions (length, mass, time, combinations) can be treated as algebraic quantities.

- Add, subtract, multiply, divide

Both sides of equation must have the same dimensions.

Any relationship can be correct only if the dimensions on both sides of the equation are the same.

Cannot give numerical factors: this is its limitation

Example: Given the equation: $x = ½\, at^2$ Check dimensions on each side:

$$L = \frac{L}{\cancel{T^2}} \cdot \cancel{T^2} = L$$

The T^2's cancel, leaving L for the dimensions of each side.

- The equation is dimensionally correct.
- There are no dimensions for the constant.

Dimensional Analysis to Determine a Power Law

Determine powers in a proportionality

- Example: find the exponents in the expression

$$x \propto a^m t^n$$

  - You must have lengths on both sides.
  - Acceleration has dimensions of L/T^2
  - Time has dimensions of T.
  - Analysis gives $x \propto at^2$

Example

Suppose that the acceleration of a particle moving in circle of radius *r* with uniform velocity *v* is proportional to the r^n and v^m. Use the dimensional analysis to determine the power n and m.

Solution

Let us assume *a* is represented in this expression $a = k\, r^n v^m$

Where *k* is the proportionality constant of dimensionless unit.

The right hand side $[a] = \quad = \dfrac{L}{T^2}$

The left hand side

$$[k\, r^{n}\, v^{m}] = L^{n}\left(\frac{L}{T}\right)^{m} = \frac{L^{n+m}}{T^{m}}$$

Therefore

$$\frac{L}{T^{2}} = \frac{L^{n+m}}{T^{m}}$$

hence

n+m=1 and m=2

Therefore. n =-1 and the acceleration a is $a = k\, r^{-1}\, v^{2}$

k=1 $a = \dfrac{v^{2}}{r}$

Conversion of Units

When units are not consistent, you may need to convert to appropriate ones.

See Appendix A for an extensive list of conversion factors.

Units can be treated like algebraic quantities that can cancel each other out.

Always include units for every quantity, you can carry the units through the entire calculation.

Multiply original value by a ratio equal to one.

Example:

$$15.0\,in = ?\,cm$$

$$15.0\,\cancel{in}\left(\frac{2.54\,cm}{1\,\cancel{in}}\right) = 38.1\,cm$$

- Note the value inside the parentheses is equal to 1, since 1 inch is defined as 2.54 cm.

conversions

Length

$1 \text{ in.} = 2.54 \text{ cm (exact)}$

$1 \text{ m} = 39.37 \text{ in.} = 3.281 \text{ ft}$

$1 \text{ ft} = 0.304\,8 \text{ m}$

$12 \text{ in.} = 1 \text{ ft}$

$3 \text{ ft} = 1 \text{ yd}$

$1 \text{ yd} = 0.914\,4 \text{ m}$

$1 \text{ km} = 0.621 \text{ mi}$

$1 \text{ mi} = 1.609 \text{ km}$

$1 \text{ mi} = 5\,280 \text{ ft}$

$1\ \mu\text{m} = 10^{-6} \text{ m} = 10^{3} \text{ nm}$

$1 \text{ lightyear} = 9.461 \times 10^{15} \text{ m}$

Area

$1 \text{ m}^2 = 10^4 \text{ cm}^2 = 10.76 \text{ ft}^2$

$1 \text{ ft}^2 = 0.092\,9 \text{ m}^2 = 144 \text{ in.}^2$

$1 \text{ in.}^2 = 6.452 \text{ cm}^2$

Volume

$1 \text{ m}^3 = 10^6 \text{ cm}^3 = 6.102 \times 10^4 \text{ in.}^3$

$1 \text{ ft}^3 = 1\,728 \text{ in.}^3 = 2.83 \times 10^{-2} \text{ m}^3$

$1 \text{ L} = 1\,000 \text{ cm}^3 = 1.057\,6 \text{ qt} = 0.035\,3 \text{ ft}^3$

$1 \text{ ft}^3 = 7.481 \text{ gal} = 28.32 \text{ L} = 2.832 \times 10^{-2} \text{ m}^3$

$1 \text{ gal} = 3.786 \text{ L} = 231 \text{ in.}^3$

Mass

$1\,000 \text{ kg} = 1 \text{ t (metric ton)}$

$1 \text{ slug} = 14.59 \text{ kg}$

$1 \text{ u} = 1.66 \times 10^{-27} \text{ kg} = 931.5 \text{ MeV}/c^2$

conversions

Force

$1\ \text{N} = 0.224\,8\ \text{lb}$

$1\ \text{lb} = 4.448\ \text{N}$

Velocity

$1\ \text{mi/h} = 1.47\ \text{ft/s} = 0.447\ \text{m/s} = 1.61\ \text{km/h}$

$1\ \text{m/s} = 100\ \text{cm/s} = 3.281\ \text{ft/s}$

$1\ \text{mi/min} = 60\ \text{mi/h} = 88\ \text{ft/s}$

Acceleration

$1\ \text{m/s}^2 = 3.28\ \text{ft/s}^2 = 100\ \text{cm/s}^2$

$1\ \text{ft/s}^2 = 0.304\,8\ \text{m/s}^2 = 30.48\ \text{cm/s}^2$

Pressure

$1\ \text{bar} = 10^5\ \text{N/m}^2 = 14.50\ \text{lb/in.}^2$

$1\ \text{atm} = 760\ \text{mm Hg} = 76.0\ \text{cm Hg}$

$1\ \text{atm} = 14.7\ \text{lb/in.}^2 = 1.013 \times 10^5\ \text{N/m}^2$

$1\ \text{Pa} = 1\ \text{N/m}^2 = 1.45 \times 10^{-4}\ \text{lb/in.}^2$

Time

$1\ \text{yr} = 365\ \text{days} = 3.16 \times 10^7\ \text{s}$

$1\ \text{day} = 24\ \text{h} = 1.44 \times 10^3\ \text{min} = 8.64 \times 10^4\ \text{s}$

Energy

$1\ \text{J} = 0.738\ \text{ft} \cdot \text{lb}$

$1\ \text{cal} = 4.186\ \text{J}$

$1\ \text{Btu} = 252\ \text{cal} = 1.054 \times 10^3\ \text{J}$

$1\ \text{eV} = 1.602 \times 10^{-19}\ \text{J}$

$1\ \text{kWh} = 3.60 \times 10^6\ \text{J}$

Power

$1\ \text{hp} = 550\ \text{ft} \cdot \text{lb/s} = 0.746\ \text{kW}$

$1\ \text{W} = 1\ \text{J/s} = 0.738\ \text{ft} \cdot \text{lb/s}$

$1\ \text{Btu/h} = 0.293\ \text{W}$

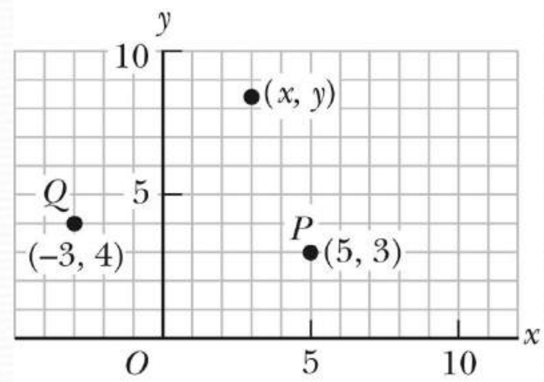
Coordinate Systems

Used to describe the position of a point in space

Common coordinate systems are:

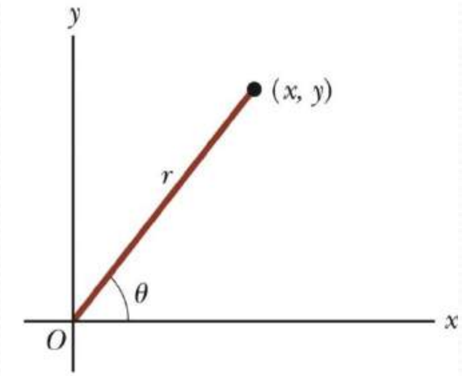
Cartesian Coordinate System

In Cartesian (Also called rectangular) coordinate system: x- and y- axes intersect at the origin Points are labeled (x,y)



Polar Coordinate System

Origin and reference line are noted

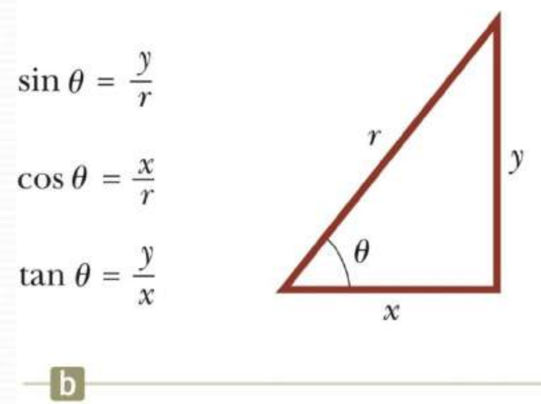


Point is distance r from the origin in the direction of angle θ, from reference line. The reference line is often the x-axis. Points are labeled (r,θ). Based on forming a right triangle from r and θ

$x = r\cos\theta$ *and* $y = r\sin\theta$

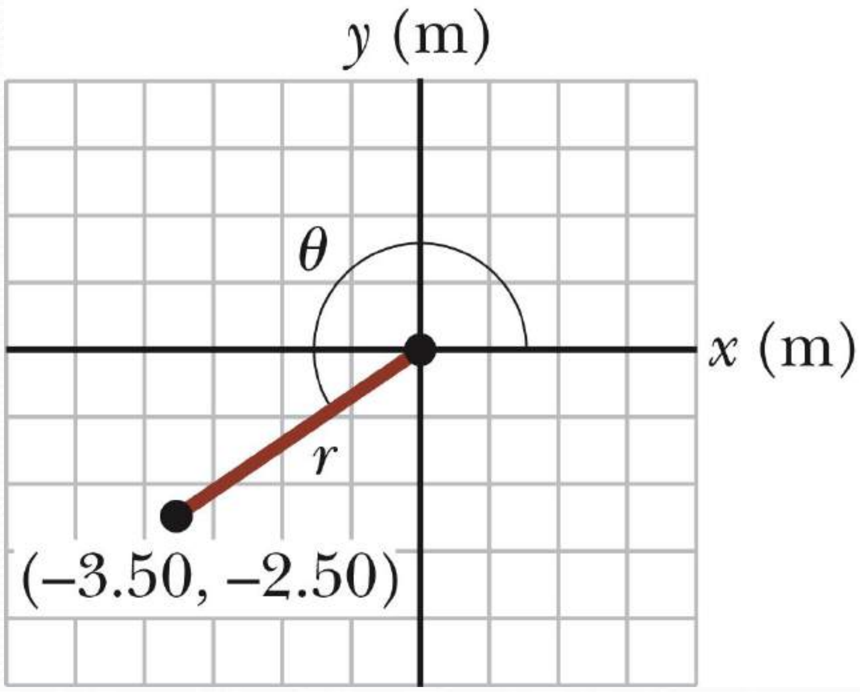
If the Cartesian coordinates are known: $\tan\theta = \dfrac{y}{x}$

$$r = \sqrt{x^2 + y^2}$$



Example

The Cartesian coordinates of a point in the *xy* plane are $(x,y) = (-3.50, -2.50)$ m, as shown in the figure. Find the polar coordinates of this point.



Solution: From Equation 3.4,

$$r = \sqrt{x^2 + y^2}$$

$$= \sqrt{(-3.50\text{ m})^2 + (-2.50\text{ m})^2}$$

$$= 4.30\text{ m}$$

and from Equation 3.3,

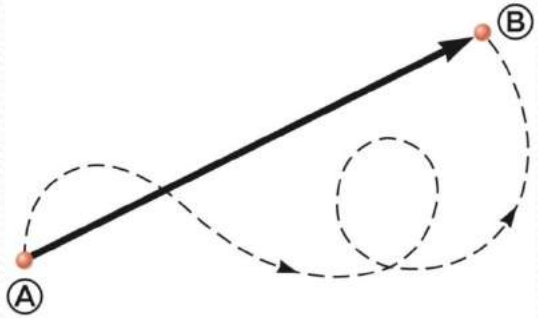
$$\tan\theta = \frac{y}{x} = \frac{-2.50\text{ m}}{-3.50\text{ m}} = 0.714$$

$$\theta = 216^\circ \quad \text{(signs give quadrant)}$$

Vectors and Scalars

A ***scalar quantity*** is completely specified by a single value with an appropriate unit and has no direction. It may be positive or negative.

A ***vector quantity*** is completely described by a number and appropriate units plus a direction.



Example: A particle travels from A to B along

the path shown by the broken line.

- This is the ***distance*** traveled and is a scalar.

The ***displacement*** is the solid line from A to B

- The ***displacement*** is the solid line from A to B and it is a vector
- The displacement is independent of the path taken between the two points.

Vector Notation

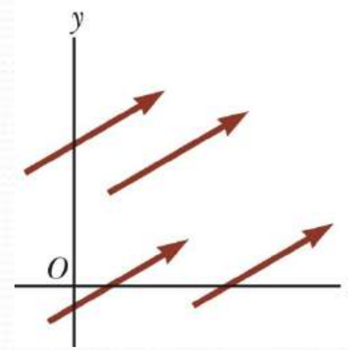
Text uses bold with arrow to denote a vector: $\vec{A}$ or for printing is simple bold print: **A**. When dealing with just the magnitude of a vector in print, an italic letter will be used: *A* or $|\vec{A}|$

- The magnitude of the vector has physical units.
- The magnitude of a vector is always a positive number.

Equality of Two Vectors

Two vectors are ***equal*** if they have the same magnitude and the same direction.

$\vec{A} = \vec{B}$ if $A = B$ and they point along parallel lines



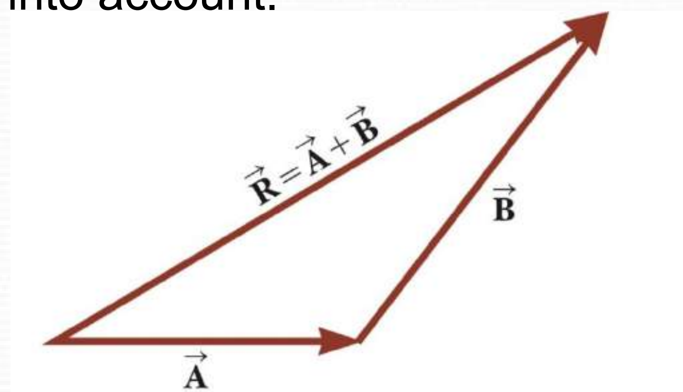
Adding Vectors

Vector addition is very different from adding scalar quantities.

When adding vectors, their directions must be taken into account.

The resultant is drawn from the origin of the first vector to the end of the last vector.

Measure the length of the resultant and its angle.



The negative of the vector will have the same magnitude, but point in the opposite direction.

- Represented as $-\vec{A}$
-

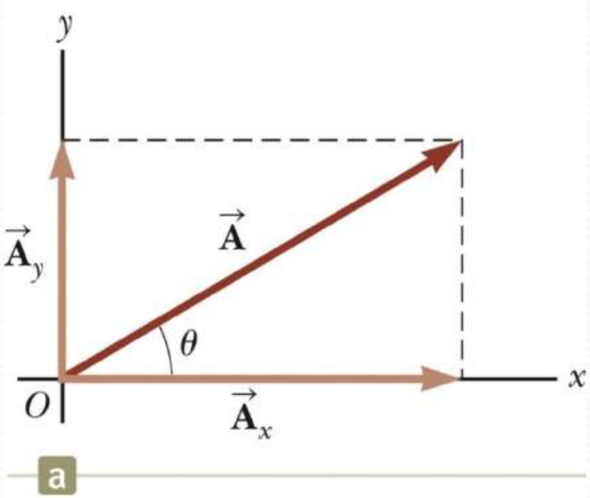
To subtract two vectors use $\vec{A}-\vec{B}$ as $\vec{A}+(-\vec{B})$

Components of a Vector

A **component** is a projection of a vector along an axis. Any vector can be completely described by its components.

It is useful to use **rectangular components.**

- A_x and A_y are the projections of the vector along the x- and y-axes.



The **x-component** of a vector is the projection along the x-axis. $A_x = A \cos \vartheta$
The **y-component** of a vector is the projection along the y-axis. $A_y = A \sin \vartheta$
This assumes the angle θ is measured with respect to the x-axis.
If not, do not use these equations, use the sides of the triangle directly.

The components are the legs of the right triangle whose hypotenuse is the length of *A.*

- $A = \sqrt{A_x^2 + A_y^2}$ and $\theta = \tan^{-1}\frac{A_y}{A_x}$
- May still have to find *θ* with respect to the positive *x*-axis

In a problem, a vector may be specified by its components or its magnitude and direction.

Unit Vectors

A ***unit vector*** is a dimensionless vector with a magnitude of exactly 1.

Unit vectors are used to specify a direction and have no other physical significance.

The symbols $\hat{i}, \hat{j},$ and $\hat{k}$ represent unit vectors

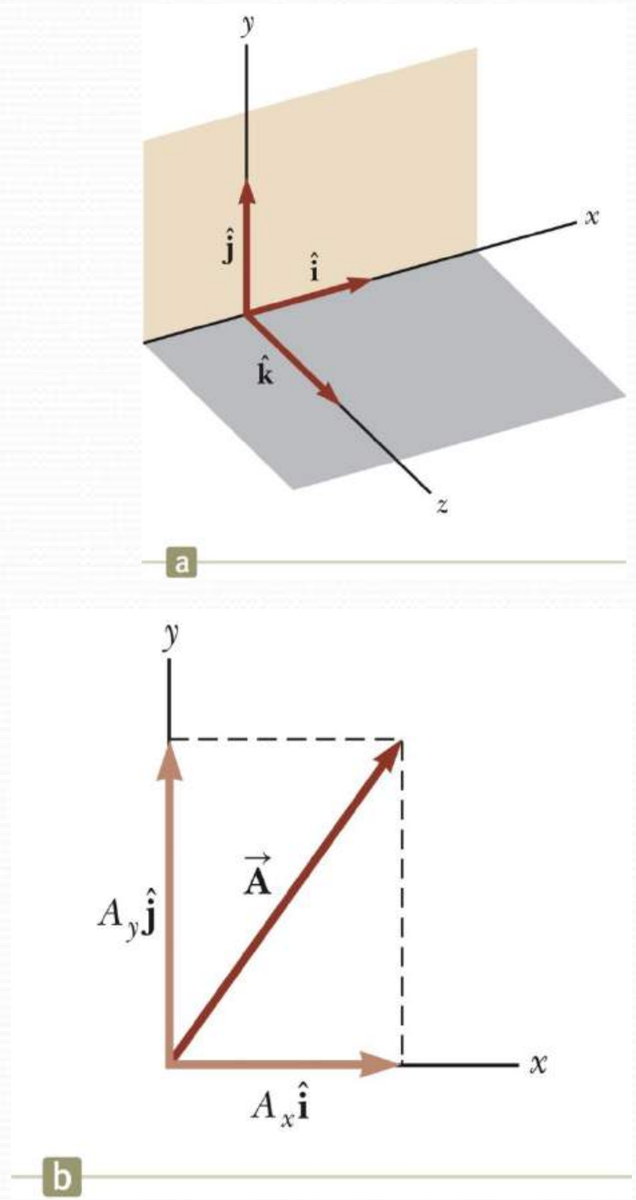
They form a set of mutually perpendicular vectors in a right-handed coordinate system

The magnitude of each unit vector is 1

$$\left|\hat{\mathbf{i}}\right| = \left|\hat{\mathbf{j}}\right| = \left|\hat{\mathbf{k}}\right| = 1$$

$\mathbf{A_x}$ is the same as $A_x\,\hat{\mathbf{i}}$ and $\mathbf{A_y}$ is the same as $A_y\,\hat{\mathbf{j}}$ etc.
The complete vector can be expressed as:

$$\vec{\mathbf{A}} = A_x\hat{\mathbf{i}} + A_y\hat{\mathbf{j}}$$



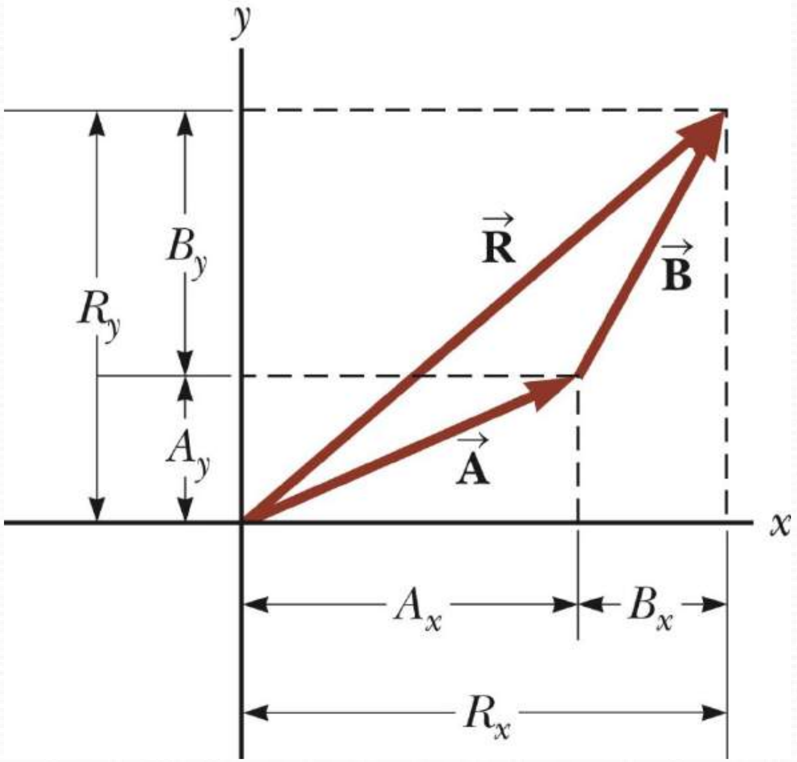
Adding Vectors Using Unit Vectors

Using $\vec{\mathbf{R}} = \vec{\mathbf{A}} + \vec{\mathbf{B}}$

Then $\vec{\mathbf{R}} = \left(A_x\hat{\mathbf{i}} + A_y\hat{\mathbf{j}}\right) + \left(B_x\hat{\mathbf{i}} + B_y\hat{\mathbf{j}}\right)$

$\vec{\mathbf{R}} = \left(A_x + B_x\right)\hat{\mathbf{i}} + \left(A_y + B_y\right)\hat{\mathbf{j}}$

$\vec{\mathbf{R}} = R_x\hat{\mathbf{i}} + R_y\hat{\mathbf{j}}$



So $R_x = A_x + B_x$ and $R_y = A_y + B_y$

$$R = \sqrt{R_x^2 + R_y^2} \qquad \theta = \tan^{-1}\frac{R_y}{R_x}$$

Three-Dimensional Extension

$\vec{\mathbf{R}} = \left(A_x\hat{\mathbf{i}} + A_y\hat{\mathbf{j}} + A_z\hat{\mathbf{k}}\right) + \left(B_x\hat{\mathbf{i}} + B_y\hat{\mathbf{j}} + B_z\hat{\mathbf{k}}\right)$

$\vec{\mathbf{R}} = \left(A_x + B_x\right)\hat{\mathbf{i}} + \left(A_y + B_y\right)\hat{\mathbf{j}} + \left(A_z + B_z\right)\hat{\mathbf{k}}$

$\vec{\mathbf{R}} = R_x\hat{\mathbf{i}} + R_y\hat{\mathbf{j}} + R_z\hat{\mathbf{k}}$

$$R = \sqrt{R_x^2 + R_y^2 + R_z^2} \qquad \theta_x = \cos^{-1}\frac{R_x}{R}$$

The result of the multiplication or division of a vector by a scalar is a vector.

The magnitude of the vector is multiplied or divided by the scalar

Example

Two vectors are given by $A = 3i - 2j$ and $B = -i - 4j$. Calculate (a) $\vec{A} + \vec{B}$, (b) $\vec{A}$ - $\vec{B}$, (c) $|\vec{A} + \vec{B}|$, (d) $|\vec{A} - \vec{B}|$, and (e) the direction of $\vec{A} + \vec{B}$ and $|\vec{A} - \vec{B}|$.

(a) $\vec{A} + \vec{B} = (3i - 2j) + (-i - 4j) = 2i - 6j$

(b) $\vec{A} - \vec{B} = (3i - 2j) - (-i - 4j) = 4i + 2j$

(c) $|\vec{A} + \vec{B}| = \sqrt{2^2 + (-6)^2} = 6.32$

(d) $|\vec{A} - \vec{B}| = \sqrt{4^2 + 2^2} = 4.47$

(e) For $\vec{A} + \vec{B}$, $\theta = \tan^{-1}(-6/2) = -71.6^\circ = 288^\circ$

For $\vec{A} - \vec{B}$, $\theta = \tan^{-1}(2/4) = 26.6^\circ$

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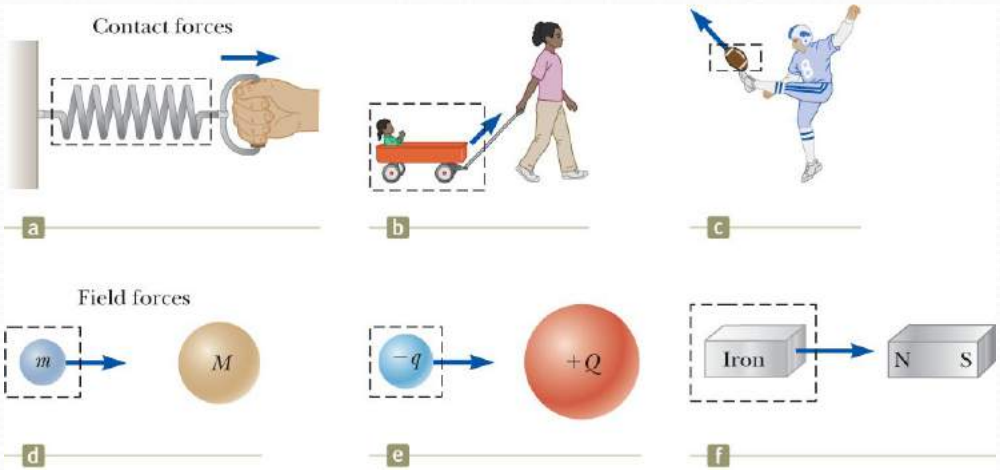
Chapter 2 - Force and Laws of Motion

Forces

- A force is that which causes an acceleration. Formulated by Sir Isaac Newton (1642 – 1727)



Classes of Forces

Contact forces involve physical contact between two objects. Examples a, b, c

Field forces act through empty space. Examples d, e, f

Fundamental Forces

Gravitational force: Between objects

Electromagnetic forces: Between electric charges

Nuclear force: Between subatomic particles

Weak forces: Arise in certain radioactive decay processes

Note: These are all field forces.

Newton's First Law

states that an object at rest will remain at rest and an object in motion will remain in motion with a constant velocity unless acted on by a net external force.

- Can conclude that any isolated object is either at rest or moving at a constant velocity

The First Law also allows the definition of ***force*** as ***that which causes a change in the motion of an object.***

The tendency of an object to resist any attempt to change its velocity is called ***inertia.***

Mass is that property of an object that specifies how much resistance an object exhibits to changes in its velocity.

Mass is a scalar quantity. The SI unit of mass is kg.

Mass and **weight** are two different quantities.

Weight is equal to the magnitude of the gravitational force exerted on the object.

- Weight will vary with location.
- m_{earth} = 3 kg; m_{moon} = 3 kg
- w_{earth} = 30 N; w_{moon} ~ 6 N

Newton’s Second Law

states that the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass. Force is the cause of *changes* in motion, as measured by the acceleration.

- Remember, an object can have motion in the absence of forces.

$$\vec{a} \propto \frac{\sum \vec{F}}{m}, \quad \sum \vec{F} = m\vec{a}$$

$\sum \vec{F}$ is the net force. May also be called the total force, resultant force

- This is the vector sum of all the forces acting on the object.

Newton’s Second Law can be expressed in terms of components:

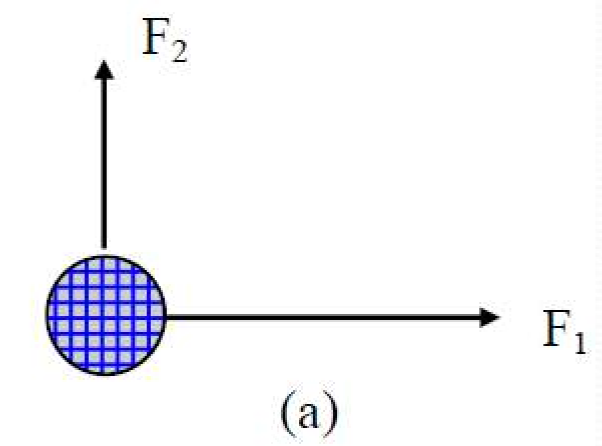
- $\Sigma F_x = m\, a_x$
- $\Sigma F_y = m\, a_y$
- $\Sigma F_z = m\, a_z$

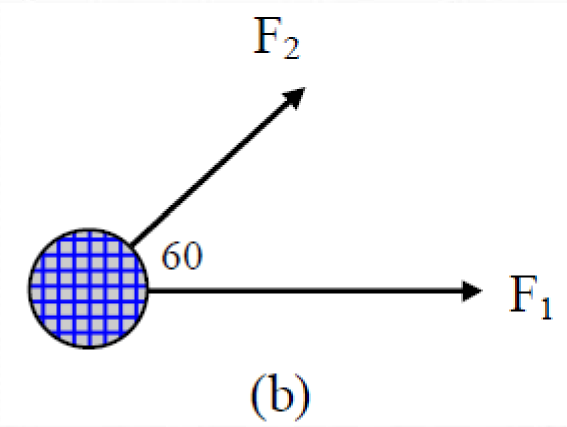
The SI unit of force is the **newton** (N).

- $1\ \text{N} = 1\ \text{kg}\cdot\text{m} / \text{s}^2$

Example

Two forces, F_1 and F_2, act on a 5-kg mass. If F_1 =20 N and F_2 =15 N,
find the acceleration in (a) and (b) of the Figure





Solution

(a) $\sum F = F_1 + F_2 = (20i + 15j)$ N

$\sum F = ma \therefore 20i + 15j = 5\ a$

$a = (4i + 3j)$ m/s2 or $a = 5$m/s2

(b) $F_{2x} = 15 \cos 60 = 7.5$ N

$F_{2y} = 15 \sin 60 = 13$ N

$F_2 = (7.5i + 13j)$ N

$\sum F = F_1 + F_2 = (27.5i + 13j) = ma = 5\ a$

$a = (5.5i + 2.6j)$ m/s2 or $a = 6.08$m/s2

Gravitational Force

The gravitational force, $\vec{F}_g$, is the force that the earth exerts on an object.

This force is directed toward the center of the earth.

From Newton's Second Law:

- $\vec{F}_g = m\vec{g}$

Its magnitude is called the weight of the object.

- Weight = $F_g = mg$
- g, and therefore the weight, is less at higher altitudes.
- This can be extended to other planets, but the value of g varies from planet to planet, so the object's weight will vary from planet to planet.
- The weight is a property of a *system* of items: the object and the Earth.

Note about units:

- Kilogram is **not** a unit of weight.
- 1 kg = 2.2 lb is an equivalence valid only on the Earth's surface.

Newton’s Third Law

If two objects interact, the force $\vec{F}_{12}$ exerted by object 1 on object 2 is equal in magnitude and opposite in direction to the force $\vec{F}_{21}$ exerted by object 2 on object 1.

- $\vec{F}_{12} = -\vec{F}_{21}$
- Note on notation: $\vec{F}_{AB}$ is the force exerted *by* A *on* B.

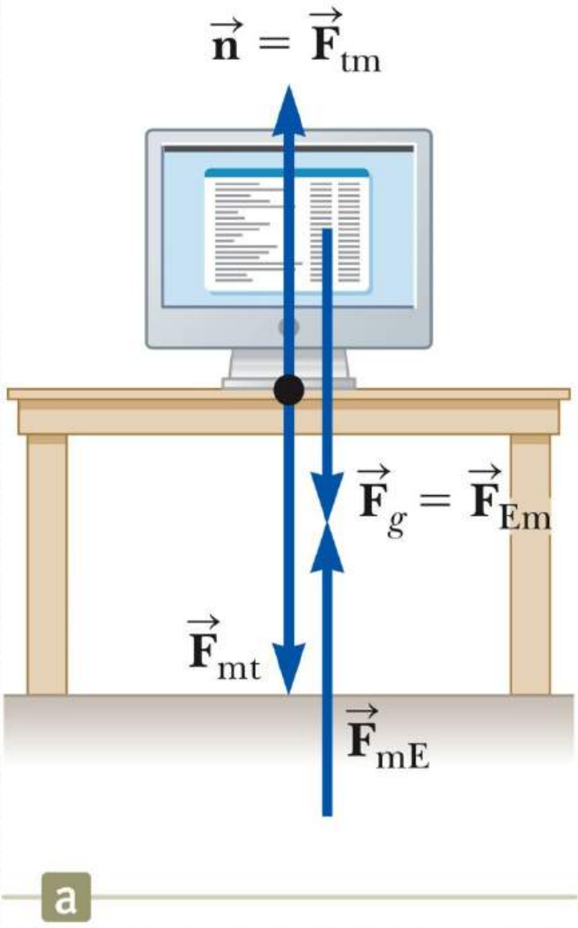
The action force is equal in magnitude to the reaction force and opposite in direction.

- One of the forces is the action force, the other is the reaction force.

The normal force (table on monitor) is the reaction of the force the monitor exerts on the table. (Figure a)

- Normal means perpendicular, in this case

The action (Earth on monitor) force is equal in magnitude and opposite in direction to the reaction force, the force the monitor exerts on the Earth.



Free Body Diagram

In a free body diagram, you want the forces acting on a particular object. (Figure b)

- Model the object as a particle

The normal force and the force of gravity are the forces that act on the monitor.

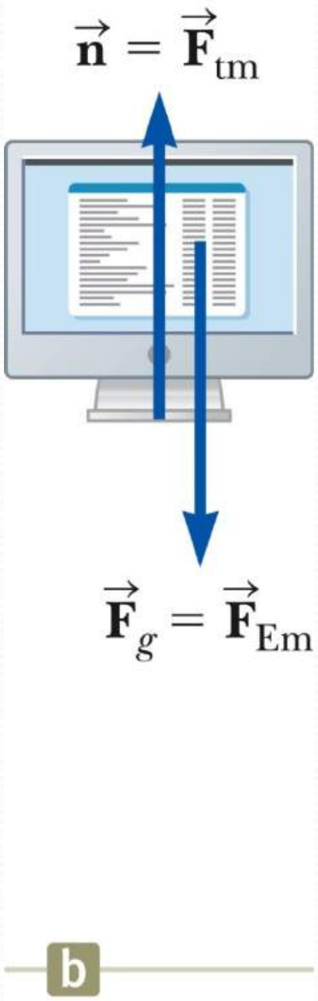
The most important step in solving problems involving Newton's Laws is to draw the free body diagram.

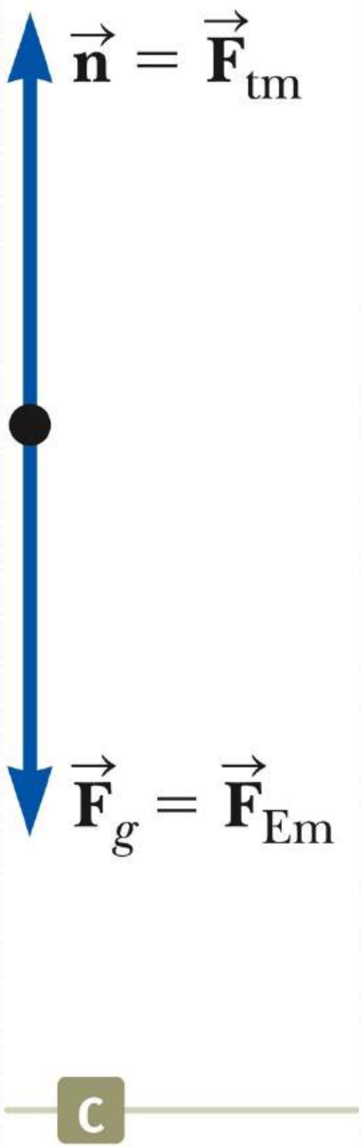
Be sure to include only the forces acting on the object of interest.

Include any field forces acting on the object.

Do not assume the normal force equals the weight.

The forces that act on the object are shown as being applied to the dot. The free body helps isolate only those forces acting on the object and eliminate the other forces from the analysis.





The object in Equilibrium

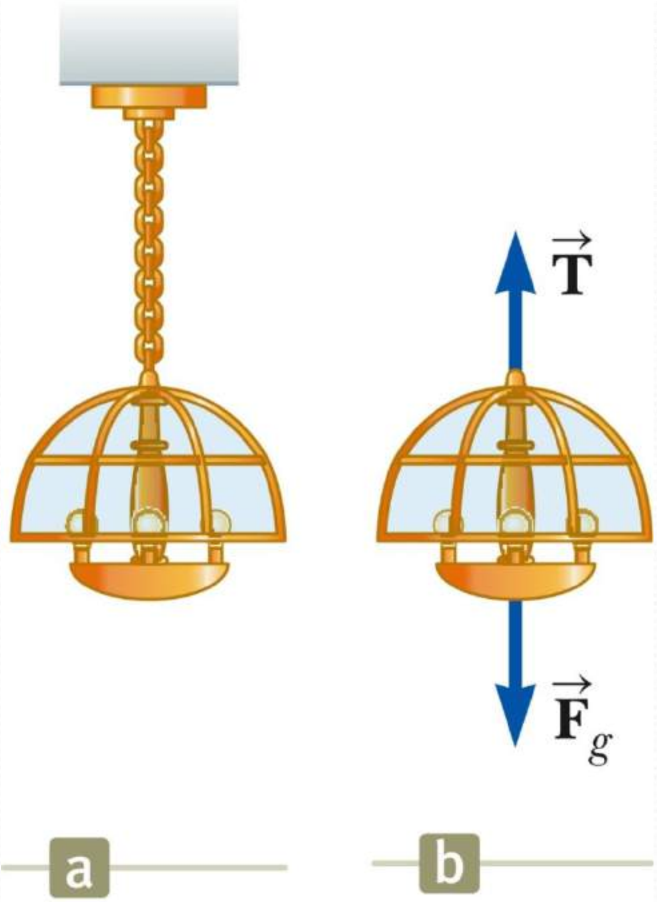
If the acceleration of an object is zero, the object is said to be in **equilibrium.**

- The model is the *particle in equilibrium.*

Mathematically, the net force acting on the object is zero.

$\Sigma F = 0$

Equilibrium, Example



A lamp is suspended from a chain of negligible mass.

The forces acting on the lamp are:

- the downward force of gravity
- the upward tension in the chain

Applying equilibrium gives

$$\sum F_y = 0 \rightarrow T - F_g = 0 \rightarrow T = F_g$$

The Object Under a Net Force, example

Forces acting on the crate:

- A tension, acting through the rope, is the magnitude of force $\vec{T}$
- The gravitational force, $\vec{F}_g$
- The normal force, $\vec{n}$, exerted by the floor

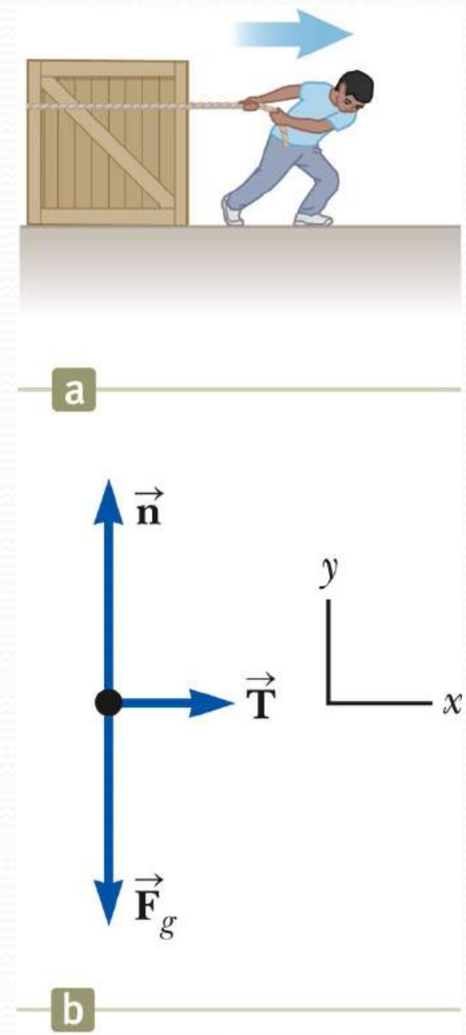
Apply Newton's Second Law in component form:

$$\sum F_x = T = ma_x$$

$$\sum F_y = n - F_g = 0 \rightarrow n = F_g$$

Solve for the unknown(s)

If the tension is constant, then *a* is constant and the kinematic equations can be used to more fully describe the motion of the crate.



Equilibrium, Example

Conceptualize the traffic light

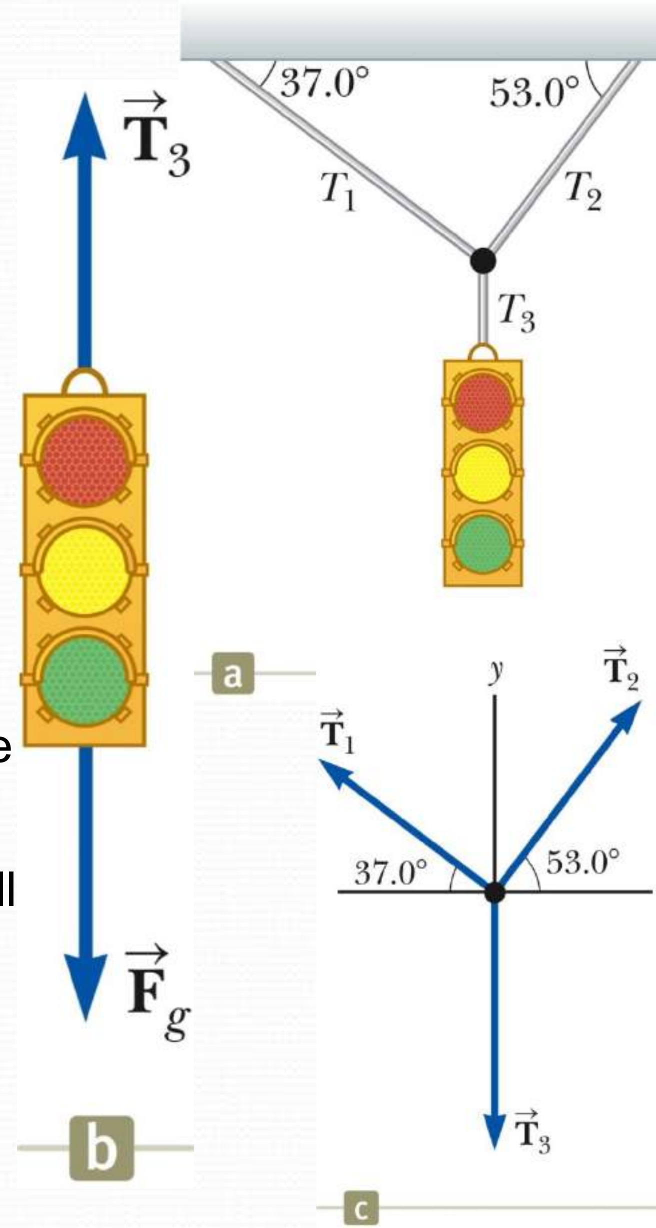
- Assume cables don't break
- Nothing is moving

Categorize as an equilibrium problem

- No movement, so acceleration is zero

Analyze

- Construct a diagram for the forces acting on the light
- Construct a free body diagram for the knot where the three cables are joined
- The knot is a convenient point to choose since all the forces of interest act along lines passing through the knot.
- Apply equilibrium equations to the knot
- Find T_1, T_2 and T_3 from applying equilibrium in the x- and y-directions to the knot



Equilibrium, Example, final

Finalize

- Think about different situations and see if the results are reasonable.
- Knowing that the knot is in equilibrium (a = 0) allows us to write

Force	***x* Component**	***y* Component**
$\mathbf{T}_1$	$-T_1 \cos 37.0°$	$T_1 \sin 37.0°$
$\mathbf{T}_2$	$T_2 \cos 53.0°$	$T_2 \sin 53.0°$
$\mathbf{T}_3$	0	-122 N

(1) $$\sum F_x = -T_1 \cos 37.0° + T_2 \cos 53.0° = 0$$

(2) $$\sum F_y = T_1 \sin 37.0° + T_2 \sin 53.0° + (-122\text{ N}) = 0$$

(3) $$T_2 = T_1\left(\frac{\cos 37.0°}{\cos 53.0°}\right) = 1.33T_1$$

$$T_1 \sin 37.0° + (1.33T_1)(\sin 53.0°) - 122\text{ N} = 0$$

$$T_1 = 73.4\text{ N}$$

$$T_2 = 1.33T_1 = 97.4\text{ N}$$

Frictional Force

Friction and energy loss due to friction appear every day in our life.

The maximum force of friction F is

F = μ N

Where **N** is a Normal force.

μ Is the coefficient between the two surfaces.

The value of μ depends upon the two materials in contact , and it is essentially independent of the surface area , as shown in Table 1.

TABLE 5.1 *Coefficients of Friction*

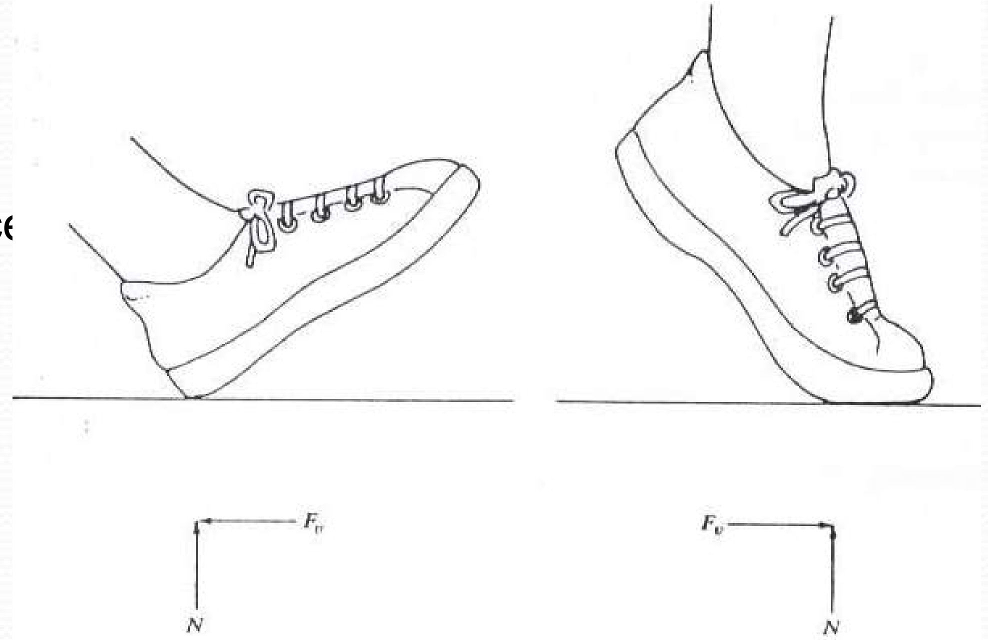
	μ_s	μ_k
Rubber on concrete	1.0	0.8
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Glass on glass	0.94	0.4
Copper on steel	0.53	0.36
Wood on wood	0.25–0.5	0.2
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow	—	0.04
Metal on metal (lubricated)	0.15	0.06
Teflon on Teflon	0.04	0.04
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003

Note: All values are approximate. In some cases, the coefficient of friction can exceed 1.0.

When a person is walking , as the heel of the foot touches the ground a force is transmitted from the foot to the ground. we can resolve this force into horizontal and vertical components. the vertical reaction force is applied by the surface and is labeled N (normal force).

we can resolve this force into horizontal and vertical components . the vertical reaction force is applied by the surface and is labeled N (normal force).

the horizontal reaction component must be applied by frictional forces, as shown in figure.



Measurements have been made of the horizontal force component of the heel as it strikes the ground when a person is walking , and it has been to be = 0.15 W, where W is the person’s weight.

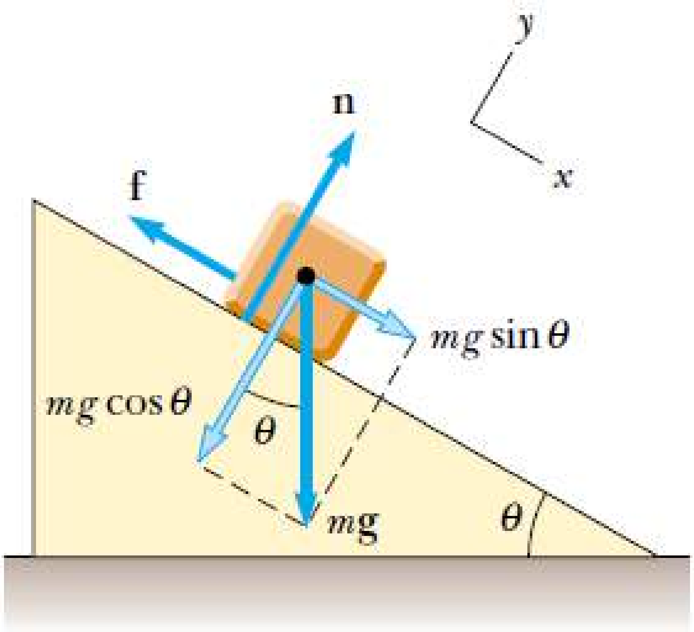
The frictional force is large enough both when the heel touches down and when the toe leaves the surface to prevent a person from slipping. this how large the frictional force must be in order to prevent the heel from slipping.

Friction Example, 1

A 3kg block starts from rest at the top of 30o incline and slides with *a* = 1.78 m/s2. Find

(a) the coefficient of kinetic friction between the block and the plane

(b) the friction force acting on the block



Solution

Given $m = 3\text{kg}$, $\theta = 30_o$

$mg\sin 30 - f = ma \Rightarrow f = m(g\sin 30 - a) \Rightarrow f = 9.37\text{N}$

$N - mg\cos 30 = 0 \Rightarrow N = mg\cos 30$

$f = 9.37\text{N}$

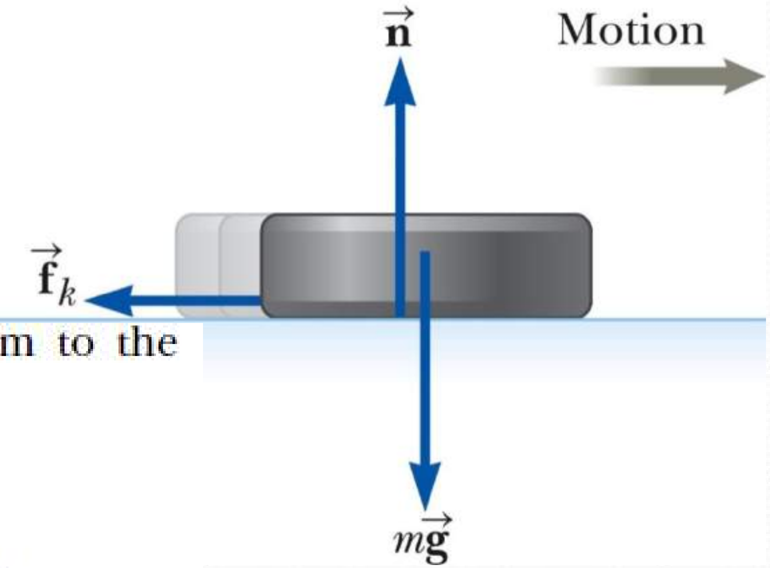
$\mu_k = N/f = 0.368$

Friction, Example 2

Draw the free-body diagram, including the force of kinetic friction.

Continue with the solution as with any Newton's Law problem.

This example gives information about the motion which can be used to find the acceleration to use in Newton's Laws.



we apply Newton's second law in component form to the puck and obtain

$$(1) \qquad \sum F_x = -f_k = ma_x$$

$$(2) \qquad \sum F_y = n - mg = 0 \qquad (a_y = 0)$$

But $f_k = \mu_k n$, and from (2) we see that $n = mg$. Therefore, (1) becomes

$$-\mu_k n = -\mu_k mg = ma_x$$

$$a_x = -\mu_k g$$

Dynamics force

According to second law of Newton, the force is equal

F = ma

momentum = **mv**

The change in momentum **Δ(mv)** over a short interval of time is

F = Δ(mv) / Δt

Example 1

A 60 Kg person walking at 1 m/sec bumps into a wall and stops in a distance of 2.5 cm in about 0.05 sec . what is the force developed on impact ?

Δ(mv) = (60 Kg) (1m/sec) – (60 Kg) (0 m/sec)

= 60 Kg m/sec

the force developed on impact is

F = Δ(mv)/Δt = 60Kg m/sec / 0.05 = 1200 Kg m/sec^2

F = 1200 Newton

Example 2

A. A person walking at 1 m/sec hits his head on a steel beam . Assume his head stops in 0.5 cm in about 0.01 sec . If the mass of his head is 4Kg, What is the force developed ?

$\Delta(mv) = (4Kg)(1m/sec) - (4Kg)(0m/sec) = 4\ Kg\ m/sec$

$F = \Delta(mv) / \Delta t = 4\ kg\ m/sec / 0.01$

$F = 400$ Newton

b. if the steel beam has 2 cm of padding and Δt is increased to 0.04 sec , what is the force developed ?

$F = \Delta(mv) / \Delta t$

$F = (4\ Kg\ m/sec) / 0.04\ sec$

$F = 100$ Newton

General Physics

for Science and Engineering Faculties

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Chapter 3 - Static Equilibrium and Elasticity

Static Equilibrium

Equilibrium implies that the object moves with both constant velocity and constant angular velocity relative to an observer in an inertial reference frame.

Will deal now with the special case in which both of these velocities are equal to zero

- This is called *static equilibrium.*

Static equilibrium is a common situation in engineering.

The principles involved are of particular interest to civil engineers, architects, and mechanical engineers.

Rigid Object in Equilibrium

In *the particle in equilibrium model* a particle moves with constant velocity because the net force acting on it is zero.

- The objects often cannot be modeled as particles.

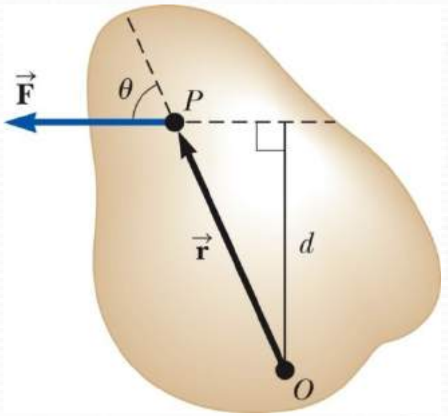
For an extended object to be in equilibrium, a second condition of equilibrium must be satisfied.

- This second condition involves the rotational motion of the extended object.

Torque

$\vec{\tau}$

- The tendency of the force to cause a rotation about O depends on F and the moment arm *d.* The net torque on a rigid object causes it to undergo an angular acceleration.



The net external force on the object must equal zero.

- $\sum \vec{F}_{ext} = 0$
- If the object is modeled as a particle, then this is the only condition that must be satisfied.

The net external torque on the object about any axis must be zero.

- $\sum \vec{\tau}_{ext} = 0$
- This is needed if the object cannot be modeled as a particle.

These conditions describe the **rigid object in equilibrium analysis model.**

We will restrict the applications to situations in which all the forces lie in the xy plane. There are three resulting equations:

- $\Sigma F_x = 0$, $\Sigma F_y = 0$
- $\Sigma \tau_z = 0$

Center of Mass

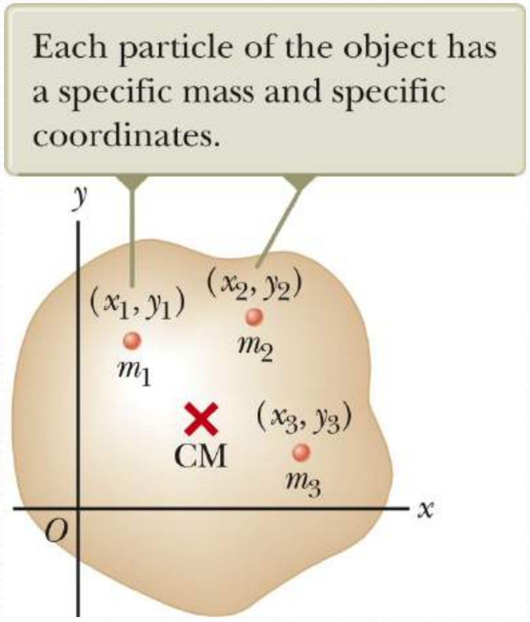
An object can be divided into many small particles.

- Each particle will have a specific mass and specific coordinates.

The x coordinate of the center of mass will be

$$x_{CM} = \frac{\sum_i m_i x_i}{\sum_i m_i}$$

Similar expressions can be found for the y and z coordinates.

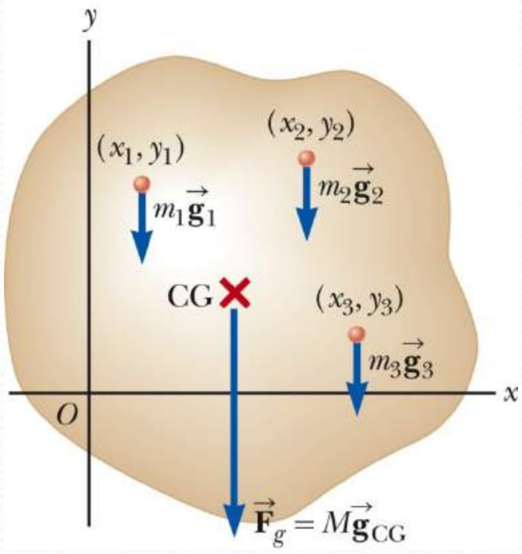


Center of Gravity

All the various gravitational forces acting on all the various mass elements are equivalent to a single gravitational force acting through a single point called the center of gravity (CG).

Each particle contributes a torque about an axis through the origin equal in magnitude to the particle's weight multiplied by its moment arm.

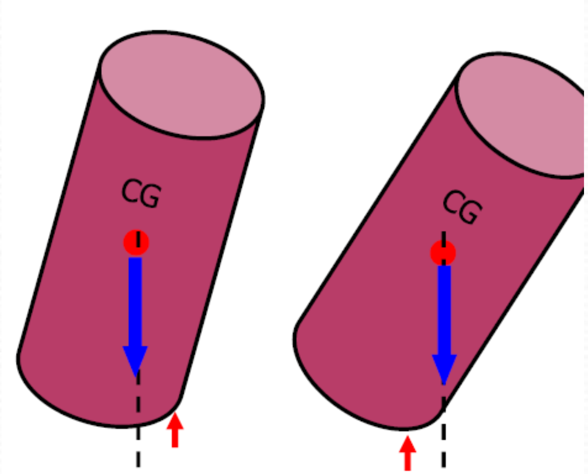
The center of gravity of the object coincides with its center of mass.



stability

Why things fall over

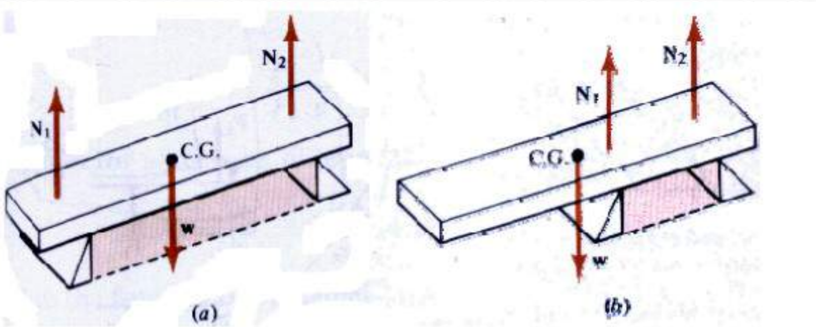
- if the center of gravity is **supported**, the object will not fall over.
- You generally want a running back with a low CG, then it’s harder to knock him down.
- The lower the CG the more **stable** an object is. Stable, not easy to knock over!



Condition for stability

If the CG is above the edge, the object will not fall.

If the vertical line extending down from the CG is inside the edge the object will return to its upright position, the torque due to gravity brings it back.



The beam is in equilibrium

The beam is not in equilibrium

Problem-Solving Strategy – Equilibrium Problems

Conceptualize

- Identify all the forces acting on the object.
- Image the effect of each force on the rotation of the object if it were the only force acting on the object.

Categorize

- Confirm the object is a rigid object in equilibrium.
- The object must have zero translational acceleration and zero angular acceleration.

Analyze

- Draw a diagram.
- Show and label all external forces acting on the object.
- Particle under a net force model: he object on which the forces act can be represented in a free body diagram as a dot because it does not matter where on the object the forces are applied.
- Rigid object in equilibrium model: Cannot use a dot to represent the object because the location where the forces act is important in the calculations.

Problem-Solving Strategy – Equilibrium Problems, 2

Analyze, cont

- Establish a convenient coordinate system.
- Find the components of the forces along the two axes.
- Apply the first condition for equilibrium ($\Sigma F=0$). Be careful of signs.
- Choose a convenient axis for calculating the net torque on the rigid object.
- Choose an axis that simplifies the calculations as much as possible.
- Apply the second condition for equilibrium.
- The two conditions of equilibrium will give a system of equations.
- Solve the equations simultaneously.

Finalize

- Make sure your results are consistent with your diagram.
- If the solution gives a negative for a force, it is in the opposite direction to what you drew in the diagram.
- Check your results to confirm $\Sigma F_x = 0$, $\Sigma F_y = 0$, $\Sigma \tau = 0$.

Center of Gravity of Humans

Another technique used to determine the center of gravity of humans is described in the figure below.

A board of length l is supported at its ends resting on scales adjusted to read zero with the board alone.

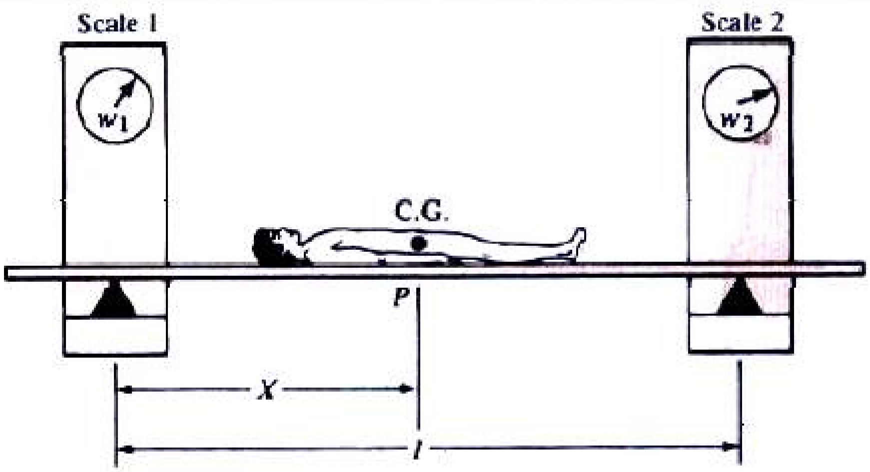
When a person lies on the board the scales read w1 and w2.

The condition for the torque Στ = 0 can be used to Find X.

- The torque about point P is

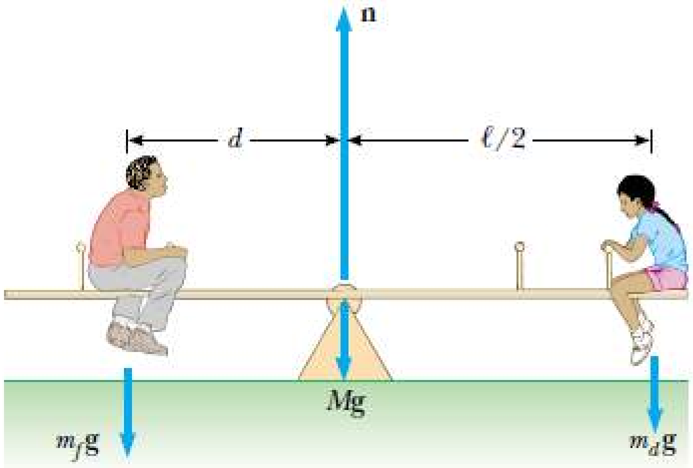
$$\boxed{Xw_1-(l-X)w_2=0}$$

$$\boxed{X=\frac{lw_2}{w_1+w_2}}$$



The Seesaw Revisited Example

A seesaw consisting of a uniform board of mass ***M*** and length **L** supports a father and daughter with masses m_f and m_d, respectively, as shown in Figure. The support (called the *fulcrum*) is under the center of gravity of the board, the father is a distance ***d*** from the center, and the daughter is a distance **L/2** from the center.



(A) Determine the magnitude of the upward force **n** exerted by the support on the board.

- $\Sigma F_y = 0$

$$n - m_f g - m_d g - Mg = 0$$

$$n = \boxed{m_f g + m_d g + Mg}$$

- $\Sigma F_x = 0$ The equation also applies, but we do not need to consider it because no forces act horizontally on the board.)

(B) Determine where the father should sit

to balance the system.

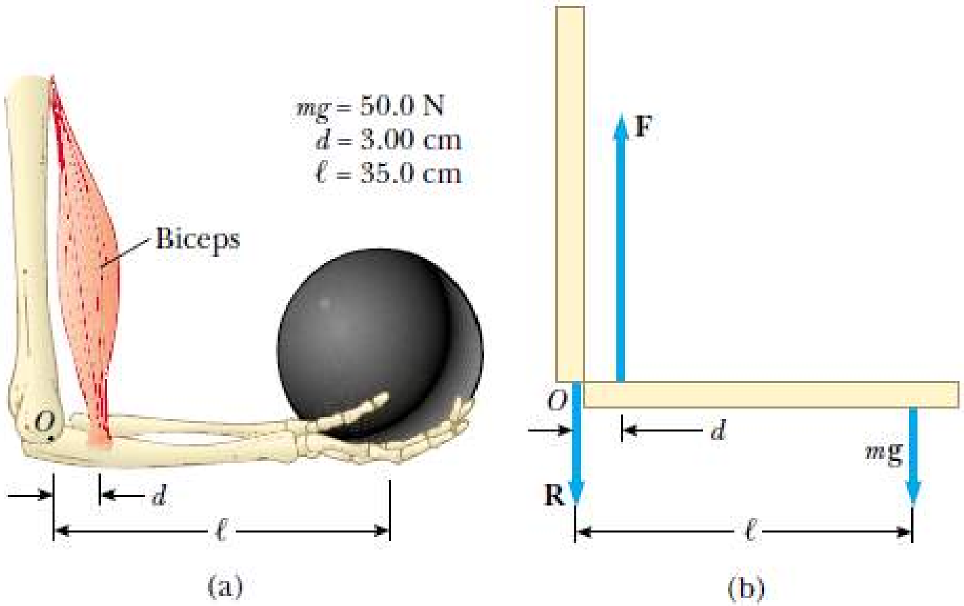
- $\Sigma F_x = 0$, $\Sigma F_y = 0$, $\Sigma \tau_z = 0$ that

$$(m_f g)(d) - (m_d g)\frac{\ell}{2} = 0$$

$$d = \boxed{\left(\frac{m_d}{m_f}\right)\frac{1}{2}\ell}$$

Example **A Weighted Hand**

F is the upward force exerted by the biceps and R is the downward forc exerted by the upper arm at the joint.



$$\sum F_y = F - R - 50.0\text{ N} = 0$$

$$\sum \tau = Fd - mg\ell = 0$$

$$F(3.00\text{ cm}) - (50.0\text{ N})(35.0\text{ cm}) = 0$$

$$F = \boxed{583\text{ N}}$$

This value for *F* can be substituted into to give *R* =533 N. As this example shows, the forces at joints and in muscles can be extremely large.

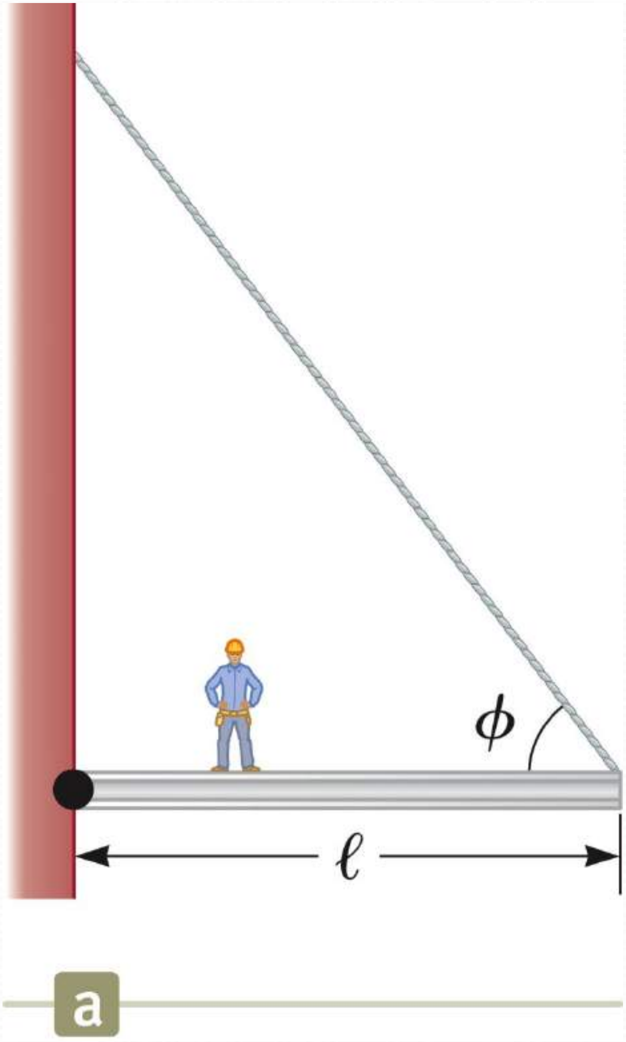
Horizontal Beam Example

Conceptualize

- The beam is uniform.
- So the center of gravity is at the geometric center of the beam.
- The person is standing on the beam.
- What are the tension in the cable and the force exerted by the wall on the beam?

Categorize

- The system is at rest, categorize as a rigid object in equilibrium.



Horizontal Beam Example, 2

Analyze

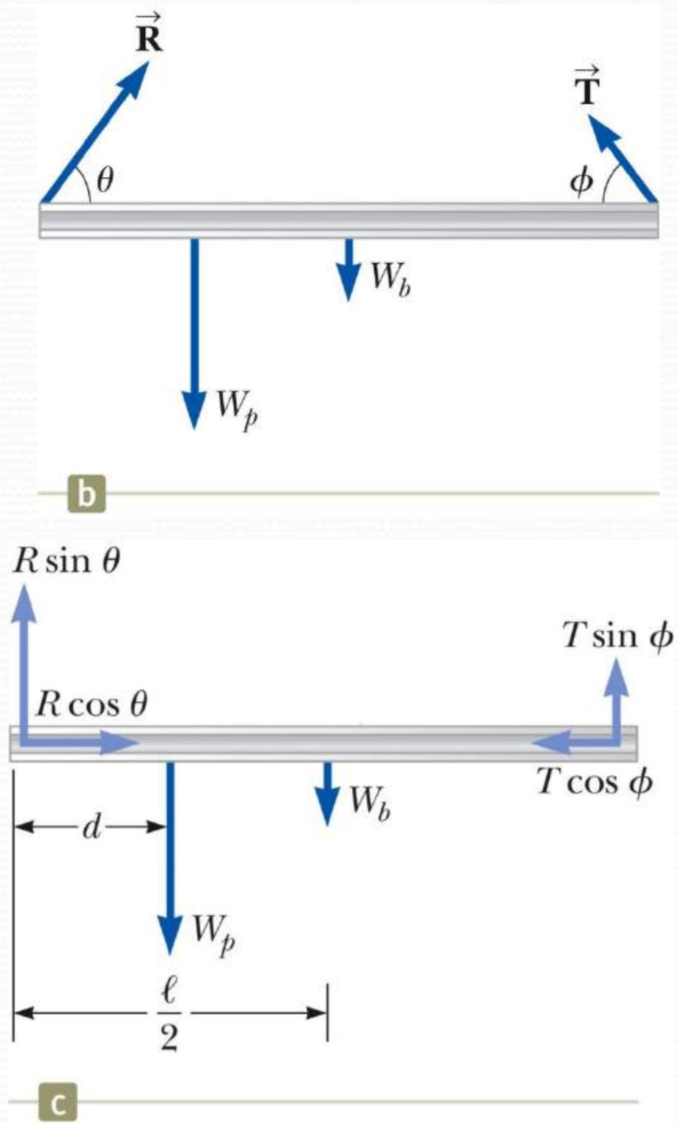
- Draw a force diagram.
- Use the pivot in the problem (at the wall) as the pivot.
  - This will generally be easiest.
- Note there are three unknowns (T, R, θ).

Analyze, cont.

- The forces can be resolved into components.
- Apply the two conditions of equilibrium to obtain three equations.
- Solve for the unknowns.

Finalize

- The positive value for θ indicates the direction of R was correct in the diagram.



Ladder Example

Conceptualize

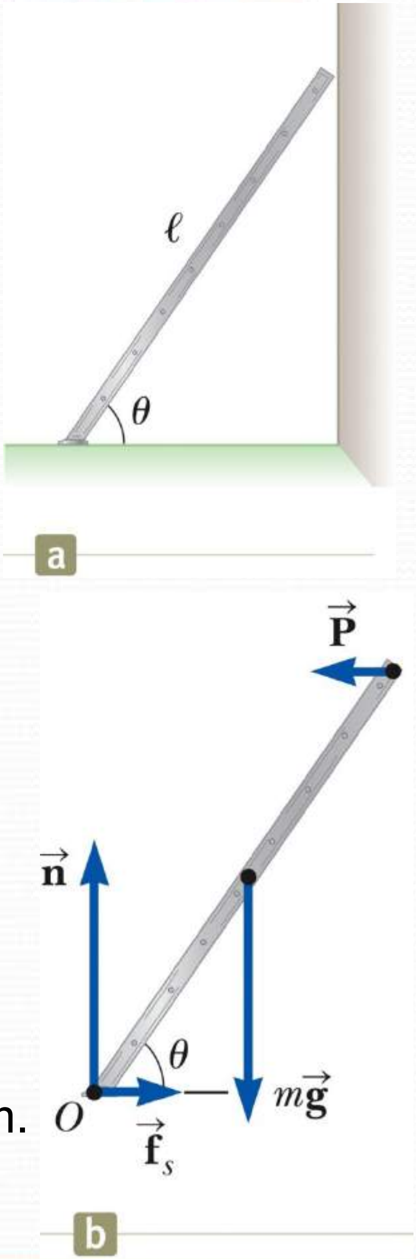
- The ladder is uniform.
- So the weight of the ladder acts through its geometric center (its center of gravity).
- There is static friction between the ladder and the ground.

Categorize

- Model the object as a rigid object in equilibrium.

Analyze

- Draw a diagram showing all the forces acting on the ladder.
- The frictional force is $f_s = \mu_s n$.
- Let O be the axis of rotation.
- Apply the equations for the two conditions of equilibrium.
- Solve the equations.



Elasticity

So far we have assumed that objects remain rigid when external forces act on them.

- Except springs

Actually, all objects are deformable to some extent.

- It is possible to change the size and/or shape of the object by applying external forces.

Internal forces resist the deformation.

Stress

- Is proportional to the force causing the deformation
- It is the external force acting on the object per unit cross-sectional area.

Strain

- Is the result of a stress
- Is a measure of the degree of deformation

Elastic Modulus

The elastic modulus is the constant of proportionality between the stress and the strain.

- For sufficiently small stresses, the stress is directly proportional to the stress.
- It depends on the material being deformed.
- It also depends on the nature of the deformation.

The elastic modulus, in general, relates what is done to a solid object to how that object responds.

$$\textit{elastic}\ \text{mod}\textit{ulus} \equiv \frac{\textit{stress}}{\textit{strain}}$$

Various types of deformation have unique elastic moduli.

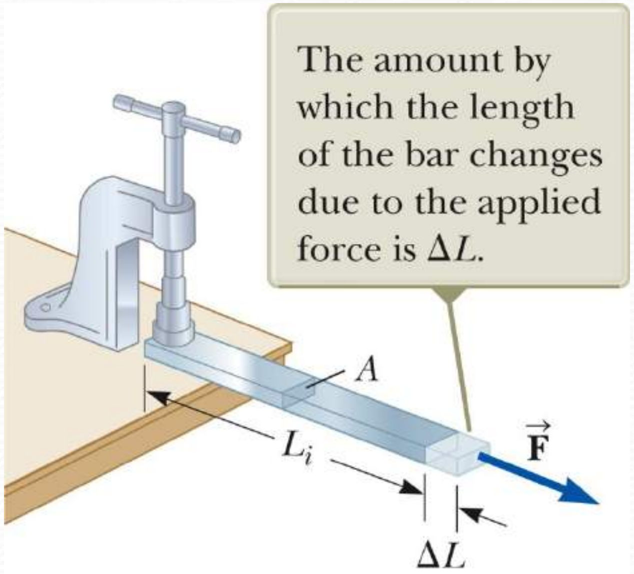
Young's Modulus: Measures the resistance of a solid to a change in its length

Shear Modulus: Measures the resistance of motion of the planes within a solid parallel to each other

Bulk Modulus: Measures the resistance of solids or liquids to changes in their volume

Young's Modulus

The bar is stretched by an amount ΔL under the action of the force F.



The **tensile stress** is the ratio of the magnitude of the external force to the cross-sectional area A.

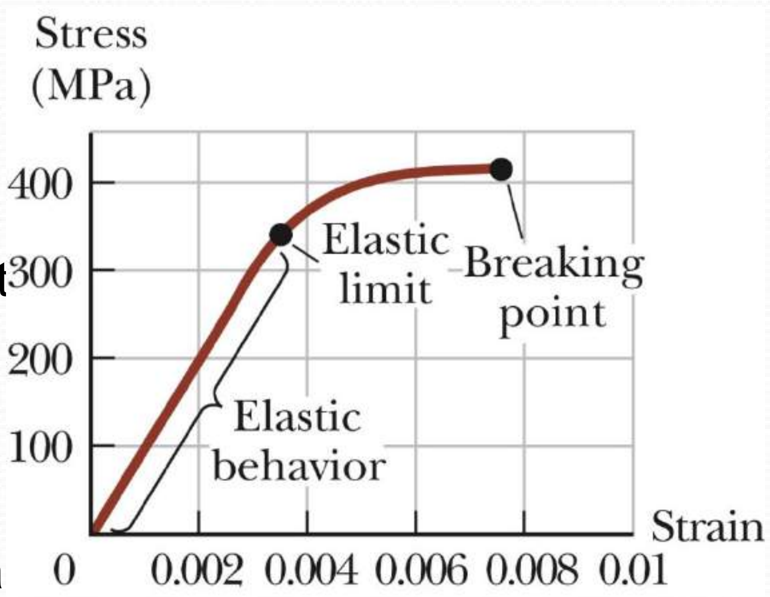
The **tension strain** is the ratio of the change in length to the original length.

Young's modulus, Y, is the ratio of those two ratios:

$$Y \equiv \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{F/A}{\Delta L / L_i}$$

Units are N / m^2

Experiments show that for certain stresses, the stress is directly proportional to the strain. This is t elastic behavior part of the curve.



When the stress exceeds **the elastic limit**, the substance will be permanently deformed.

With additional stress, the material ultimately brea

Shear Modulus

Another type of deformation occurs when a force acts parallel to one of its faces while the opposite face is held fixed by another force.

This is called a ***shear stress.***

For small deformations, no change in volume occurs with this deformation.

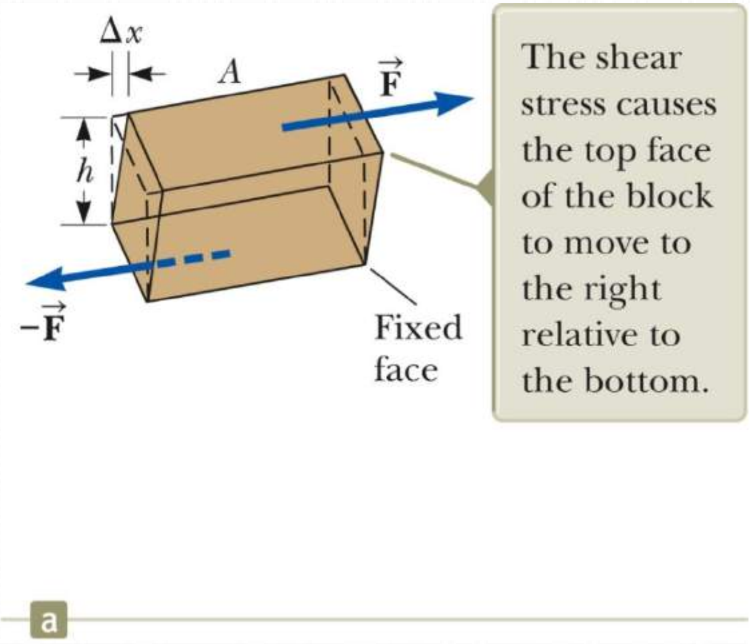
- A good first approximation

The shear strain is Δx / h.

- Δx is the horizontal distance the sheared face moves.
- h is the height of the object.

The shear stress is F / A.

- F is the tangential force.
- A is the area of the face being sheared.



The shear modulus is the ratio of the shear stress to the shear strain.

$$S = \frac{\text{shear stress}}{\text{shear strain}} = \frac{F/A}{\Delta x/h}$$

Units are N / m^2

Example

A 200-kg load is hung on a wire having a length of 4.00 m, cross-sectional area $0.200 \times 10^{-4} m^2$, and Young's modulus $8.00 \times 10^{10} N/m^2$. What is its increase in length?

Example

Assume that Young's modulus for bone is 1.5x10^10 N/m2 and that a bone will fracture if more than 1.5x10^8 N/m2 is exerted. (a) What is the maximum force that can be exerted on the femur bone in the leg if it has a minimum effective diameter of 2.50 cm? (b) If a force of this magnitude is applied compressively, by how much does the 25.0-cm-long bone shorten?

Example

A man leg can be thought of as a shaft of bone 1.2 m long. If the strain is 1.3×10^{-4} when the leg supports his weight, by how much is his leg shortened?

Example: Shear stress on the spine

Between each pair of vertebrae of the spine is a disc of cartilage of thickness 0.5 cm. Assume the disc has a radius of 0.04 m. The shear modulus of cartilage is 1 10^7 N=m^2. A shear force of 10 N is applied to one end of the disc while the other end is held fixed. (a) What is the resulting shear strain? (b) How far has one end of the disc moved with respect to the other end?

Solution: (a) The shear strain is caused by the shear force,

$$\begin{aligned} \text{strain} &= \frac{F}{AS} \\ \text{strain} &= \frac{10\ \text{N}}{\pi(0.04\ \text{m})^2(1 \times 10^7\ \text{N/m}^2)} \\ \text{strain} &= 1.99 \times 10^{-4}. \end{aligned}$$

(b) A shear strain is dened as the displacement over the height,

$$\begin{aligned} \text{strain} &= \frac{\Delta x}{h} \\ \Delta x &= h \times \text{strain} \\ \Delta x &= (0.5\ \text{cm})(1.99 \times 10^{-4}) \\ \Delta x &= 0.99\ \mu\text{m}. \end{aligned}$$

Bulk Modulus

Another type of deformation occurs when a force of uniform magnitude is applied perpendicularly over the entire surface of the object.

The object will undergo a change in volume, but not in shape.

The volume stress is defined as the ratio of the magnitude of the total force, F, exerted on the surface to the area, A, of the surface.

- This is also called the ***pressure.***

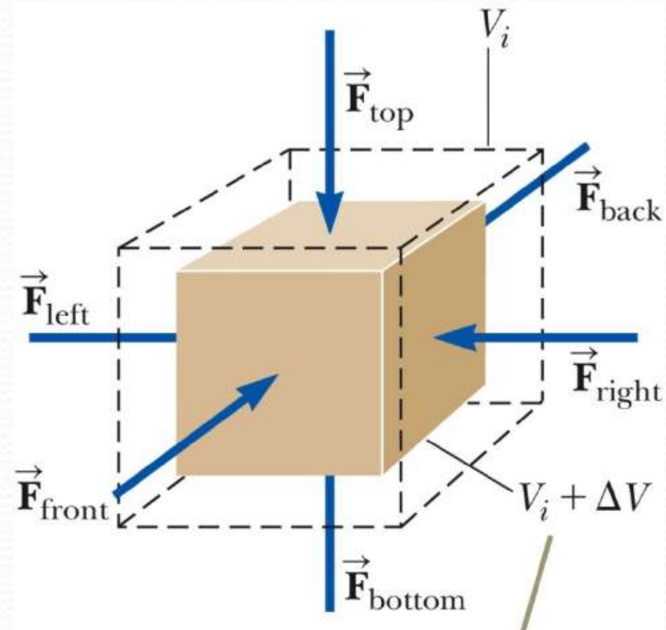
The volume strain is the ratio of the change in volume to the original volume.

The bulk modulus is the ratio of the volume stress to the volume strain.

$$B = \frac{\text{volume stress}}{\text{volume strain}} = -\frac{\Delta F / A}{\Delta V / V_i} = -\frac{\Delta P}{\Delta V / V_i}$$

The negative indicates that an increase in pressure will result in a decrease in volume.

The compressibility is the inverse of the bulk modulus.



The cube undergoes a change in volume but no change in shape.

Moduli and Types of Materials

Both solids and liquids have a bulk modulus.

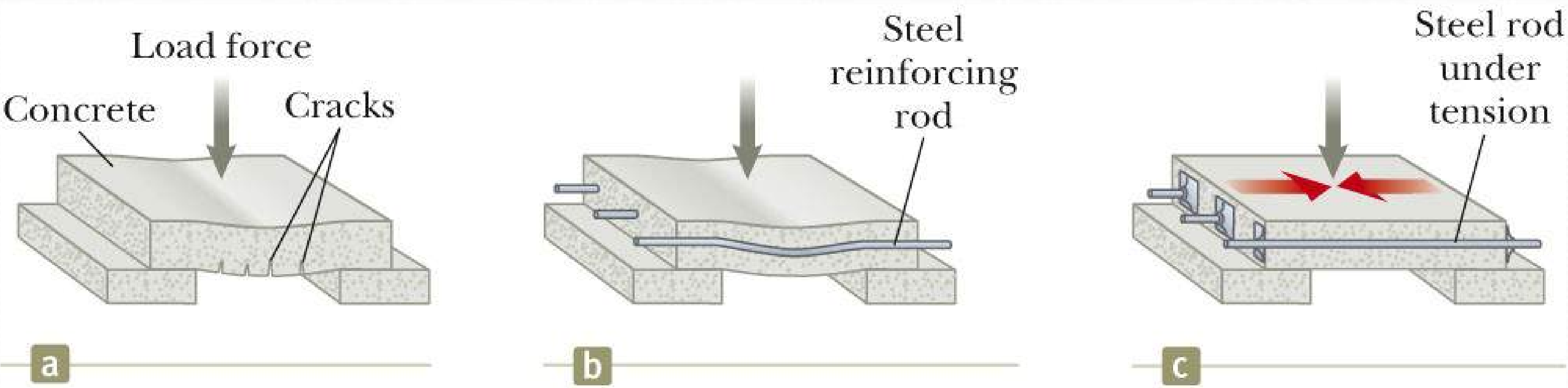
Liquids cannot sustain a shearing stress or a tensile stress.

- If a shearing force or a tensile force is applied to a liquid, the liquid will flow in response.

TABLE 12.1 *Typical Values for Elastic Moduli*

Substance	Young's Modulus (N/m^2)	Shear Modulus (N/m^2)	Bulk Modulus (N/m^2)
Tungsten	35×10^{10}	14×10^{10}	20×10^{10}
Steel	20×10^{10}	8.4×10^{10}	6×10^{10}
Copper	11×10^{10}	4.2×10^{10}	14×10^{10}
Brass	9.1×10^{10}	3.5×10^{10}	6.1×10^{10}
Aluminum	7.0×10^{10}	2.5×10^{10}	7.0×10^{10}
Glass	$6.5\text{–}7.8 \times 10^{10}$	$2.6\text{–}3.2 \times 10^{10}$	$5.0\text{–}5.5 \times 10^{10}$
Quartz	5.6×10^{10}	2.6×10^{10}	2.7×10^{10}
Water	—	—	0.21×10^{10}
Mercury	—	—	2.8×10^{10}

Prestressed Concrete



If the stress on a solid object exceeds a certain value, the object fractures.

Concrete is normally very brittle when it is cast in thin sections.

- The slab tends to sag and crack at unsupported areas.

The slab can be strengthened by the use of steel rods to reinforce the concrete.

The concrete is stronger under compression than under tension.

Pre-stressed Concrete, cont.

A significant increase in shear strength is achieved if the reinforced concrete is pre-stressed.

As the concrete is being poured, the steel rods are held under tension by external forces.

These external forces are released after the concrete cures.

This results in a permanent tension in the steel and hence a compressive stress on the concrete.

This permits the concrete to support a much heavier load.

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Chapter 4 - Energy, work, and power

Introduction to Energy

The concept of energy is one of the most important topics in science and engineering.

Every physical process that occurs in the Universe involves energy and energy transfers or transformations.

Energy is not easily defined.

Systems

A *system* is a small portion of the Universe.

A valid system:

- May be a single object or particle
- May be a collection of objects or particles
- May be a region of space
- May vary with time in size and shape

System Example

A force applied to an object in empty space

Work

The **work**, W, done on a system by an agent exerting a constant force on the system is the product of the magnitude F of the force, the magnitude Δr of the displacement of the point of application of the force, and $\cos\theta$, where θ is the angle between the force and the displacement vectors.

A force does no work on the object if the force does not move through a displacement.

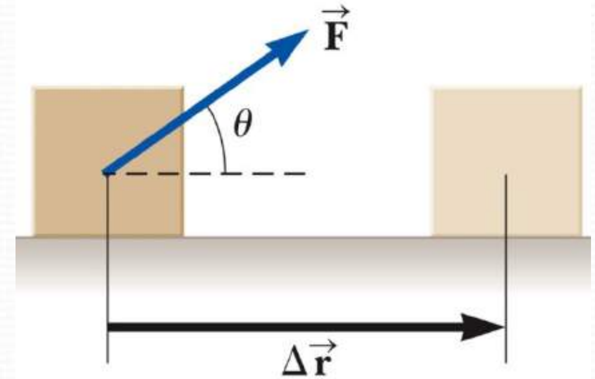
- The work done by a force on a moving object is zero when the force applied is perpendicular to the displacement of its point of application.
- Work can be given as $W = F\Delta r\cos\theta = \vec{F}\cdot\Delta\vec{r}$

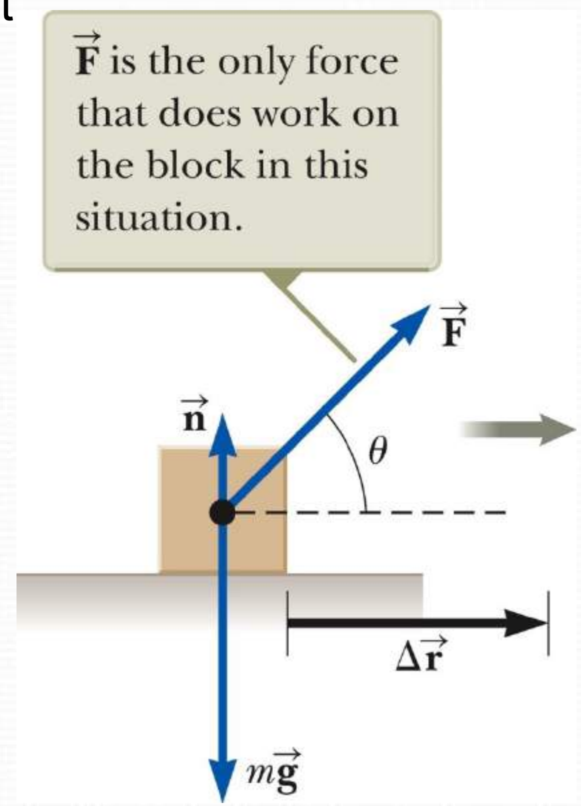
Work is a scalar quantity.

The unit of work is a joule (J = N · m)

- 1 joule = 1 newton · 1 meter = kg · m² / s²

Example: The normal force and the gravitational force do no work on the object. $\cos\theta = \cos 90^\circ = 0$





Kinetic Energy

One possible result of work acting as an influence on a system is that the system changes its speed. The system could possess *kinetic energy.*

Kinetic Energy is the energy of a particle due to its motion.

- $K = ½\ mv^2$
  - K is the kinetic energy
  - m is the mass of the particle
  - v is the speed of the particle

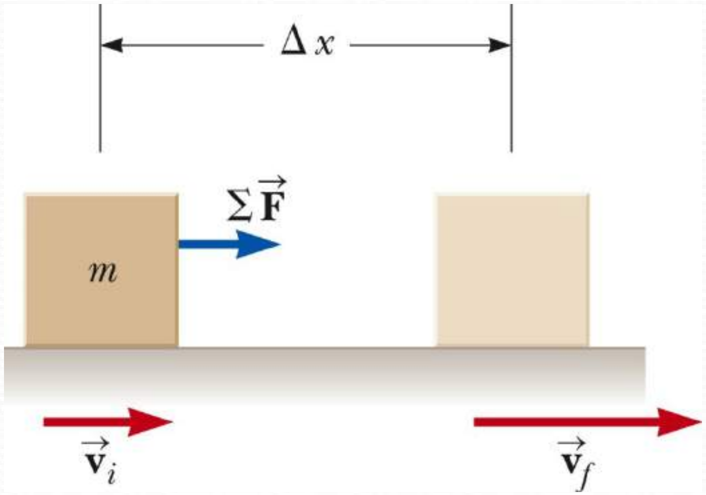
A change in kinetic energy is one possible result of doing work to transfer energy into a system. Calculating the work:

$$W_{ext} = \int_{x_i}^{x_f} \sum F\, dx = \int_{x_i}^{x_f} ma\, dx$$

$$W_{ext} = \int_{v_i}^{v_f} mv\, dv$$

$$W_{ext} = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

$$W_{ext} = K_f - K_i = \Delta K$$



This is the **Work-Kinetic Energy Theorem**.

Potential Energy

The system is the Earth and the book. Do work on the book by lifting it slowly through a vertical displacement. $\Delta\vec{r} = (y_f - y_i)\hat{\mathbf{j}}$

The work done on the system must appear as an increase in the energy of the system. The energy storage mechanism is called *potential energy.*

Gravitational potential energy is the energy associated with an object at a given location above the surface of the Earth.

$$W_{ext} = \left(\vec{F}_{app}\right) \cdot \Delta\vec{r}$$

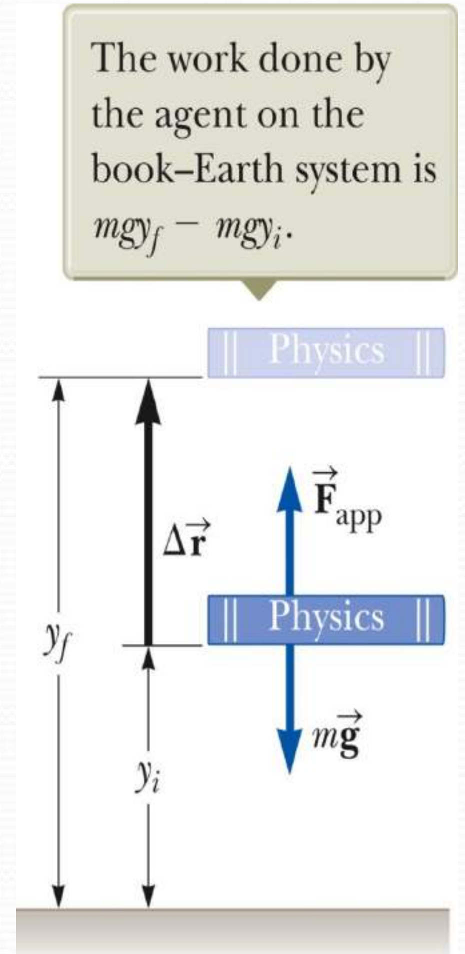
$$W_{ext} = (mg\hat{\mathbf{j}}) \cdot \left[\left(y_f - y_i\right)\hat{\mathbf{j}}\right]$$

$$W_{ext} = mgy_f - mgy_i$$

The quantity *mgy* is identified as the **gravitational potential energy**,

$U_g = mgy$, U_g is a scalar. Units are joules (J)

Work may change the gravitational potential energy of the system. $W_{ext} = \Delta u_g$



Energy Review

Kinetic Energy: Associated with movement of members of a system

Potential Energy: Determined by the configuration of the system such as Gravitational and Elastic Potential Energies

Internal Energy: Related to the temperature of the system

Types of Systems

Non-isolated systems: Energy can cross the system boundary in a variety of ways.

- Total energy of the system changes

Isolated systems: Energy does not cross the boundary of the system

- Total energy of the system is constant

Conservation of energy

- Can be used if no non-conservative forces act within the isolated system
- Applies to biological organisms, technological systems, engineering situations, etc

Ways to Transfer Energy Into or Out of A System

In non-isolated systems, energy crosses the boundary of the system during some time interval due to an interaction with the environment.

Work – transfers energy by applying a force and causing a displacement of the point of application of the force.

Mechanical Wave – transfers energy by allowing a disturbance to propagate through a medium.

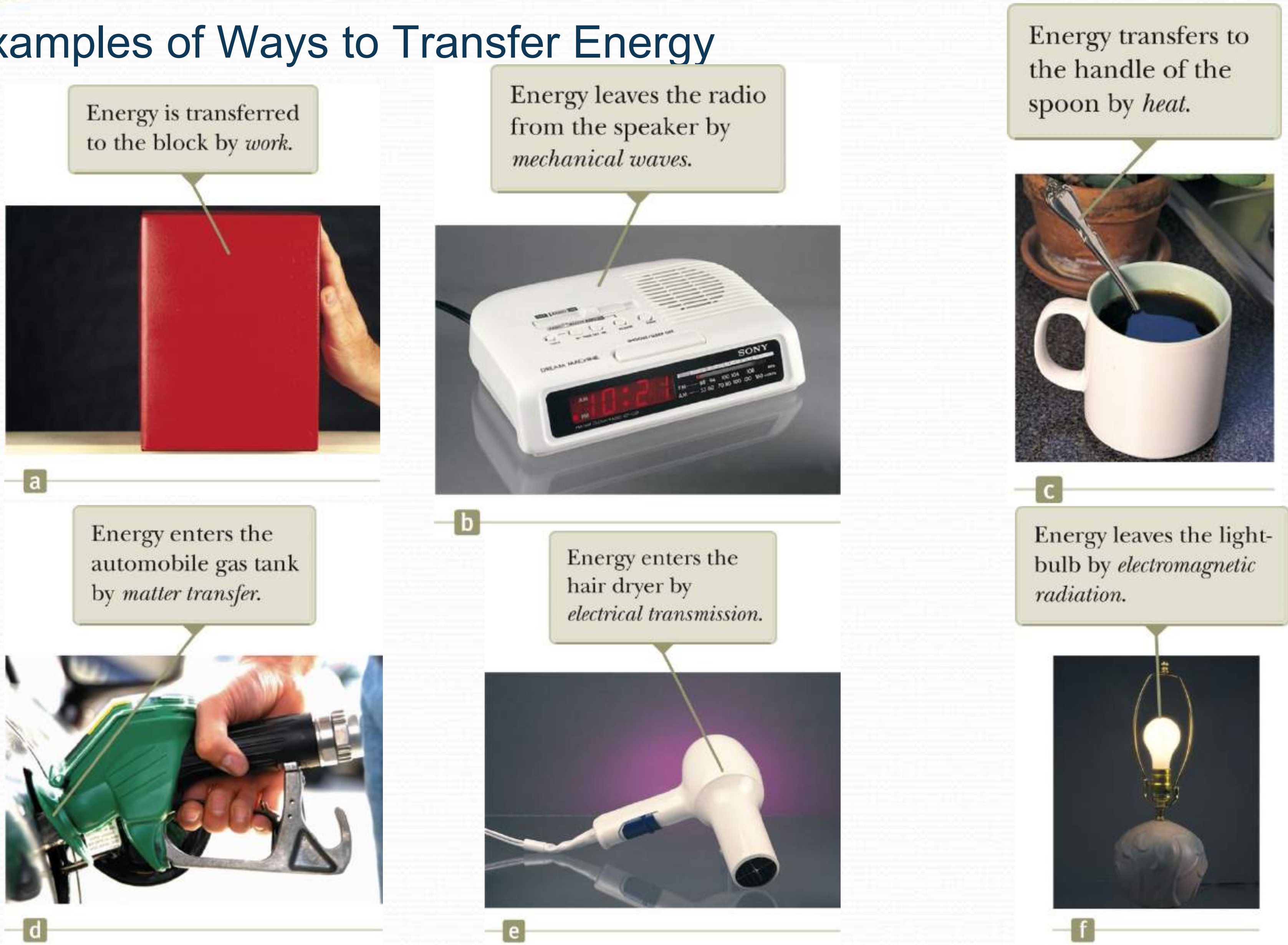
Heat – the mechanism of energy transfer that is driven by a temperature difference between two regions in space.

Matter Transfer – matter physically crosses the boundary of the system, carrying energy with it.

Electrical Transmission – energy transfer into or out of a system by electric current.

Electromagnetic Radiation – energy is transferred by electromagnetic waves.

Examples of Ways to Transfer Energy



Conservation of Energy

Energy is conserved

- This means that energy cannot be created nor destroyed.
- If the total amount of energy in a system changes, it can only be due to the fact that energy has crossed the boundary of the system by some method of energy transfer.

Mathematically, $\Delta E_{\text{system}} = \Sigma T$

- E_{system} is the total energy of the system
- T is the energy transferred across the system boundary by some mechanism
  - Established symbols: $T_{\text{work}} = W$ and $T_{\text{heat}} = Q$

The primarily mathematical representation of the energy version of the analysis model of the non-isolated system is given by the full expansion of the above equation.

- $\Delta K + \Delta U + \Delta E_{int} = W + Q + T_{MW} + T_{MT} + T_{ET} + T_{ER}$
  - T_{MW} – transfer by mechanical waves
  - T_{MT} – by matter transfer
  - T_{ET} – by electrical transmission
  - T_{ER} – by electromagnetic transmission

Isolated System

For an isolated system, $\Delta E_{mech} = 0$

- Remember $E_{mech} = K + U$
- This is ***conservation of energy*** for an isolated system with no non-conservative forces acting.

If non-conservative forces are acting, some energy is transformed into internal energy.

Conservation of Energy becomes $\Delta E_{system} = 0$

- E_{system} is all kinetic, potential, and internal energies
- This is the most general statement of the isolated system model.

The changes in energy can be written out and rearranged.

$\mathbf{K_f + U_f = K_i + U_i}$

- Remember, this applies only to a system in which conservative forces act.

Example – Ball in Free Fall

Determine the speed of the ball at a height *y* above the ground.

Conceptualize: Use energy instead of motion

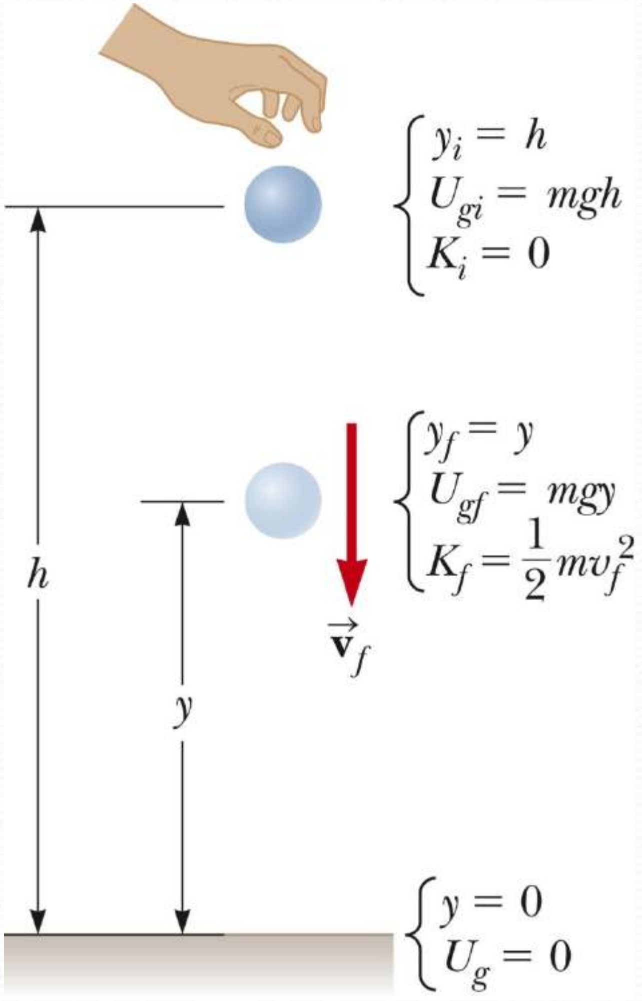
Categorize:

- System is the ball and the Earth
- System is isolated. Use the isolated system model
- Only force is gravitational which is conservative

Analyze

- Apply the Conservation of Mechanical Energy
- $K_f + U_{gf} = K_i + U_{gi}$
  - $K_i = 0$, the ball is dropped
  - Solve for v_f $\quad v_f = \sqrt{2g(h-y)}$

Finalize: The equation for v_f is consistent with the results obtained from the particle under constant acceleration model for a falling object.



Power

Power is the time rate of energy transfer.

The ***instantaneous power*** is defined as $P \equiv \frac{dE}{dt}$

Using work as the energy transfer method, this can also be written as

$$P_{avg} = \frac{W}{\Delta t}$$

The instantaneous power is the limiting value of the average power as Δt approaches zero.

$$P = \lim_{\Delta t \to 0} \frac{W}{\Delta t} = \frac{dW}{dt} = \vec{F} \cdot \frac{d\vec{r}}{dt} = \vec{F} \cdot \vec{v}$$

The SI unit of power is called the watt.

- 1 watt = 1 joule / second = 1 kg · m^2 / s^3

Units of power can also be used to express units of work or energy.

- 1 kWh = (1000 W)(3600 s) = 3.6 x10^6 J

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Chapter 5 - Fluid Mechanics

States of Matter

Solid

- Has a definite volume and shape

Liquid

- Has a definite volume but not a definite shape

Gas – unconfined

- Has neither a definite volume nor shape

Fluids

A fluid is a collection of molecules that are randomly arranged and held together by weak cohesive forces and by forces exerted by the walls of a container.

Both liquids and gases are fluids.

Fluids do not sustain shearing stresses or tensile stresses.

The only stress that can be exerted on an object submerged in a static fluid is one that tends to compress the object from all sides.

The force exerted by a static fluid on an object is always perpendicular to the surfaces of the object.

Viscosity

Real fluids (especially liquids) exhibit a kind of internal friction called *viscosity*. Fluids that flow easily (like water and gasoline) have a fairly low viscosity; liquids like molasses that are “thick” and flow with difficulty have a high viscosity.

There are two different types of viscosity defined. The more common is *dynamic viscosity*, the other is *kinematic viscosity*.

Dynamic Viscosity

When a body is placed under transverse (shear) stress σ = Ft/A, the resulting strain ε is the tangential displacement x divided by the transverse distance l:

$$\sigma = E\varepsilon$$

$$\frac{F_t}{A} = S\,\frac{x}{l}$$

where S is the shear modulus. Fluid flow undergoes a similar kind of shear stress; however, with fluids, we find that the stress is not proportional to the strain, but to the *rate of change* of strain:

$$\frac{F_t}{A} = \mu\frac{d}{dt}\frac{x}{l} = \mu\frac{v}{l}$$

Dynamic Viscosity

where v is the fluid velocity. The proportionality constant , which takes the place of the shear modulus, is the *dynamic viscosity*. The SI units of dynamic viscosity are Pascal-seconds (Pa s). Other common units are the *poise* (1 P = 0.1 Pa s) and the *centipoise* (1 cP = 0.001 Pa s).

Viscosity, especially liquid viscosity, is temperature dependent. You've probably noticed this from everyday experience: refrigerated maple syrup is fairly thick (high viscosity), but if you warm it on the stove it becomes much thinner (low viscosity).

Kinematic Viscosity ν.

The kinematic viscosity is defined as the dynamic viscosity divided by the density:

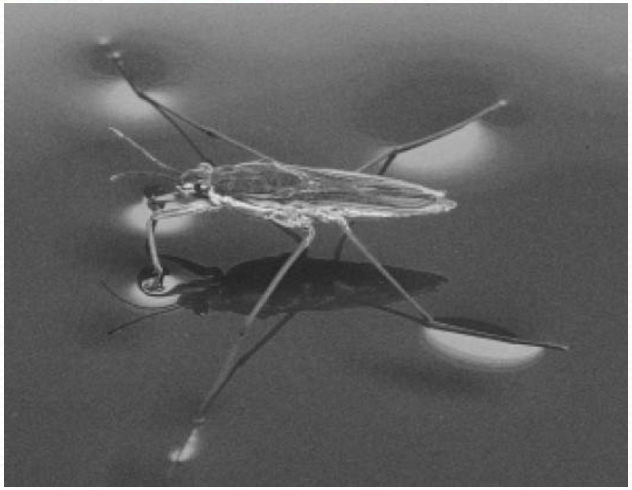
$$\nu = \frac{\mu}{\rho}$$

SI units for kinematic viscosity are m^2/s. Other common units are *stokes* (1 St = 10^{-4} m^2/s) and *centistokes* (1 cSt = 10^{-6} m^2/s).

Viscosities of common liquids (room temperature).

Liquid	Dynamic viscosity μ (Pa s)	(cP)
gasoline	5×10^{-4}	0.5
water	8.9×10^{-4}	0.89
mercury	0.0016	1.6
olive oil	0.09	90
ketchup	1.3	1300
honey	5	5000
molasses	7	7000
peanut butter	250	250,000

Surface tension

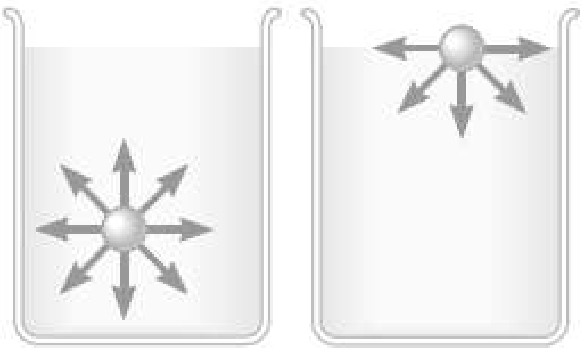


A fluid is matter that has no definite shape and adjusts to the container that it is placed in.

Gases and liquids are both fluids. All fluids are made of molecules. Every molecules attracts other molecules around it.

Liquids exhibit surface tension. A liquid has the property that its free surface tends to contract to minimum possible area and is therefore in a state of tension.

The surface tension of the water allows the insect to walk on the water without sinking.



The molecules of the liquid exerts attractive forces on each other, which is called **cohesive forces**. Deep inside a liquid, a molecule is surrounded by other molecules in all directions. Therefore there is no net force on it. At the surface, a molecule is surrounded by only half as many molecules of the liquid, because there are no molecules above the surface.

Surface tension, definition

The force of contraction is at right angles to an imaginary line of unit length, tangential to the surface of a liquid, is called its **surface tension *T* or *γ***:

$$\gamma = \frac{F}{L}$$

. Here *F* is the force exerted by the "skin" of the Liquid. The SI unit of the surface tension is N/m.

Liquid	Surface Tension γ (N/m)
Benzene (20 °C)	0.029
Blood (37 °C)	0.058
Glycerin (20 °C)	0.063
Mercury (20 °C)	0.47
Water (20 °C)	0.073
Water (100 °C)	0.059

Why are soap bubbles spherical?

Generally, a system under the influence of forces moves towards an equilibrium configuration that corresponds to minimum potential energy. The sphere contains the most volume for the least area ⇒ minimum surface potential energy. There are no cubic raindrops.

Capillary Action

The molecules of the liquid exerts attractive forces on each other, which is called **cohesive forces**.

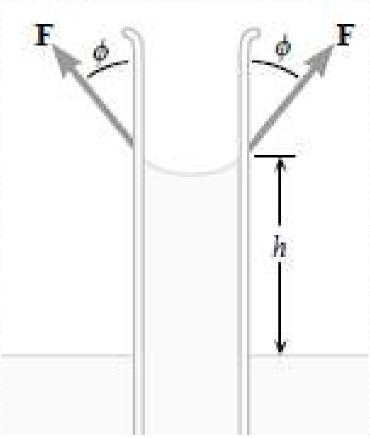
When liquids come into contact with a solid surface, the liquid's molecules are attracted by the solid's molecules (called **adhesive forces**).

If these adhesive forces are stronger than the cohesive forces, the liquid's molecules are pulled towards the solid surface and liquid surface becomes curved inward (e.g. water in a narrow tube).

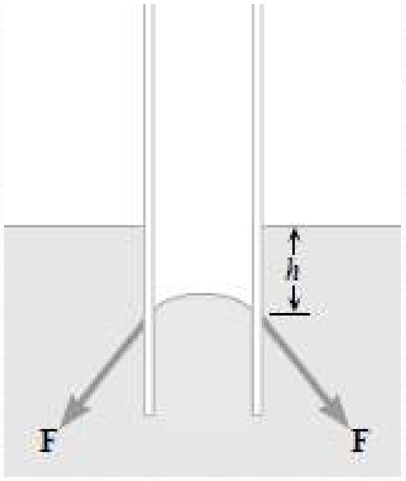
If cohesive forces are stronger the surface becomes curved outwards (e.g. with mercury instead).

This also explains why certain liquids spread when placed on the solid surface and wet it (e.g., water on glass) while others do not spread but form globules (e.g., mercury on glass).

The behavior of the liquids in both Figures is called ***capillary action***.

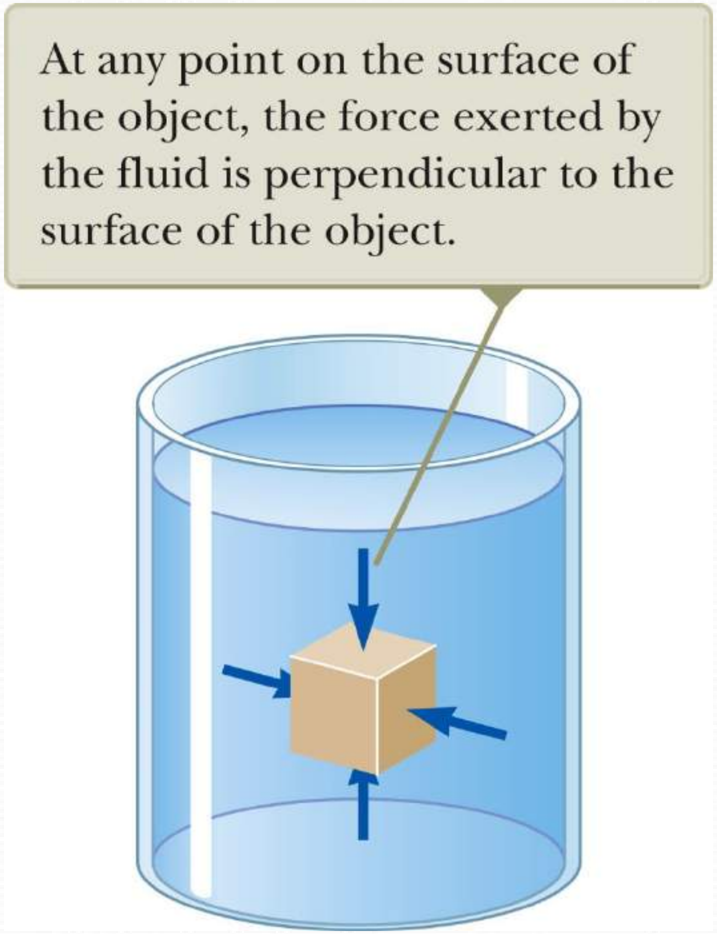


$$h = \frac{2T\cos\theta}{R\rho g}$$



Pressure

The **pressure** *P* of the fluid at the level to which the device has been submerged is the ratio of the force to the area.



Pressure is a scalar quantity.

- Because it is proportional to the magnitude of the force.

If the pressure varies over an area, evaluate dF on a surface of area dA as $dF = P\,dA$.

Unit of pressure is **pascal** (Pa)

$$1\,\text{Pa} = 1\ \text{N/m}^2$$

Density Notes

Density is defined as the mass per unit volume of the substance.

$$\rho = \frac{m}{V}$$

where *r* is the density, *m* is the mass of the substance and *V* is the Volume. The unit of density in SI unit system is kg/m^3.

The values of density for a substance vary slightly with temperature since volume is temperature dependent.

The various densities indicate the average molecular spacing in a gas is much greater than that in a solid or liquid.

Substance	ρ (kg/m^3)	Substance	ρ (kg/m^3)
Ice	0.917×10^3	Water	1×10^3
Aluminum	2.7×10^3	Glycerine	1.26×10^3
Iron	7.86×10^3	Ethyl alcohol	0.8×10^3
Copper	8.92×10^3	Benzene	0.88×10^3
Silver	10.5×10^3	Mercury	13.6×10^3
Lead	11.3×10^3	Air	1.29
Gold	19.3×10^3	Oxygen	1.43
Platinum	21.4×10^3	Hydrogen	910^3
		Helium	1.8×10^3

Variation of Pressure with Depth

If a fluid is at rest in a container, all portions of the fluid must be in static equilibrium.

All points at the same depth must be at the same pressure.

Examine the darker region, a sample of liquid within a cylinder.

- It has a cross-sectional area A.
- Extends from depth d to d + h below the surface.

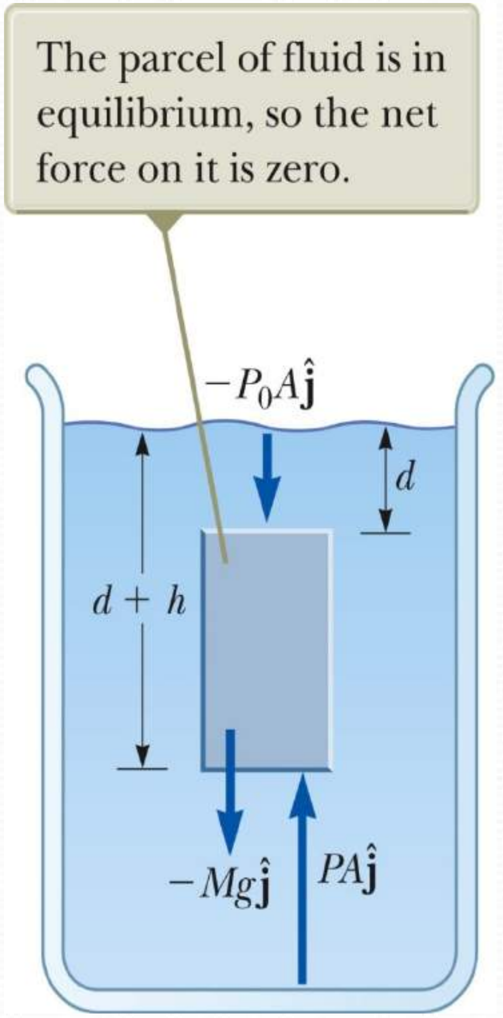
Three external forces act on the region.

The liquid has a density of ρ.

- Assume the density is the same throughout the fluid.

The three forces are:

- Downward force on the top, P_0A
- Upward on the bottom, PA
- Gravity acting downward, Mg
  - The mass can be found from the density: $M = \rho V = \rho A h$.



Pressure and Depth, final

Since the net force must be zero:

$$\sum \vec{\mathbf{F}} = PA\hat{\mathbf{j}} - P_o A\hat{\mathbf{j}} - Mg\hat{\mathbf{j}} = 0$$

- This chooses upward as positive.

Solving for the pressure gives

- $P = P_0 + \rho g h$

The pressure P at a depth h below a point in the liquid at which the pressure is P_0 is greater by an amount $\rho g h$.

Atmospheric Pressure

If the liquid is open to the atmosphere, and P_0 is the pressure at the surface of the liquid, then P_0 is *atmospheric pressure.*

$P_0 = 1.00 \text{ atm} = 1.013 \times 10^5 \text{ Pa}$

Pascal's Law

The pressure in a fluid depends on depth and on the value of P_0.

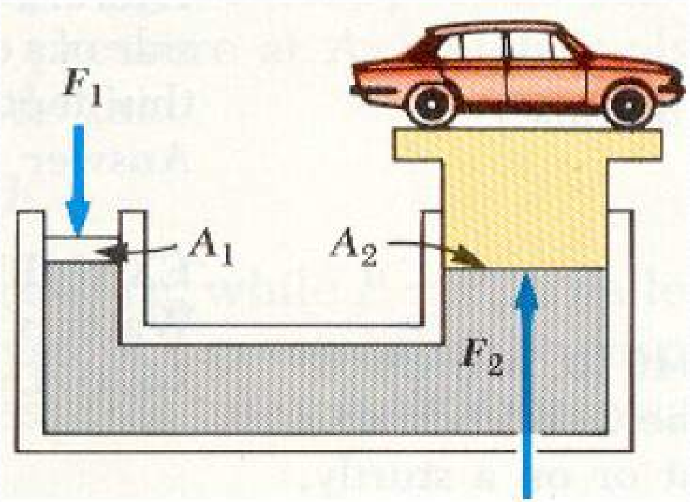
An increase in pressure at the surface must be transmitted to every other point in the fluid.

This is the basis of Pascal's law.

- Named for French science Blaise Pascal.

Pascal's Law states a change in the pressure applied to a fluid is transmitted undiminished to every point of the fluid and to the walls of the container.

$$P_1 = P_2 \qquad \frac{F_1}{A_1} = \frac{F_2}{A_2}$$



Applications to Pascal's Law:

Hydraulic brakes

Car lifts

Hydraulic jacks

Forklifts

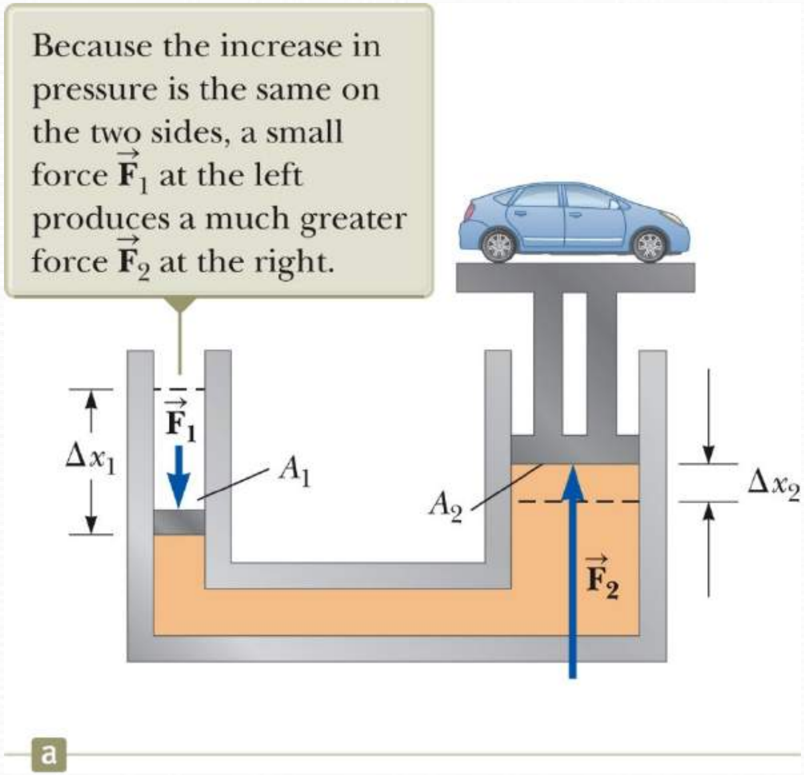
Pascal's Law, Example

An important application of Pascal's Law is a hydraulic press. The volume of liquid pushed down on the left must equal the volume pushed up on the right.

Since the volumes are equal, $A_1\Delta x_1 = A_2\Delta x_2$

Combining the equations,

- $F_1\Delta x_1 = F_2\Delta x_2$ which means Work$_1$ = Work$_2$. This is a consequence of Conservation of Energy.



Example

In a hydrochloric piston of radius 5cm and 50cm for the small and large pistons respectively. Find the weight of a car that can be elevated if the force exerted by the compressed air is (F_1 = 100N).

Solution

As shown in Figure $P = \frac{F_1}{A_2} = \frac{F_2}{A_1}$ $\quad F_2 = \frac{A_1}{A_2}F_1$ $\quad F_2 = \frac{\pi(0.05)^2}{\pi(0.005)^2}100 = 10000\ N$

Pressure Measurements:

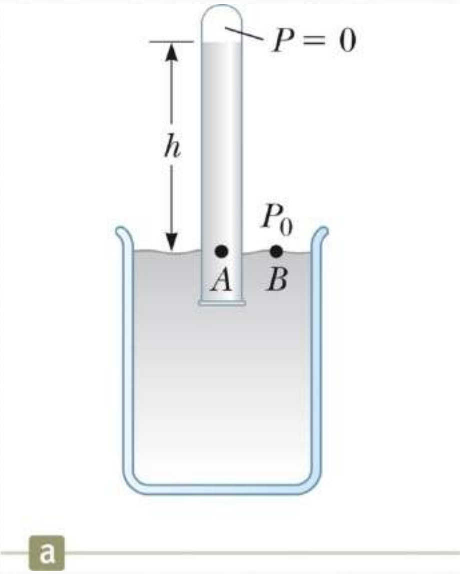
Barometer Invented by Torricelli

A long closed tube is filled with mercury and inverted in a dish of mercury.

- The closed end is nearly a vacuum.

Measures atmospheric pressure as $P_o = \rho_{Hg}\, g\, h$

One 1 atm = 0.760 m (of Hg)



Manometer

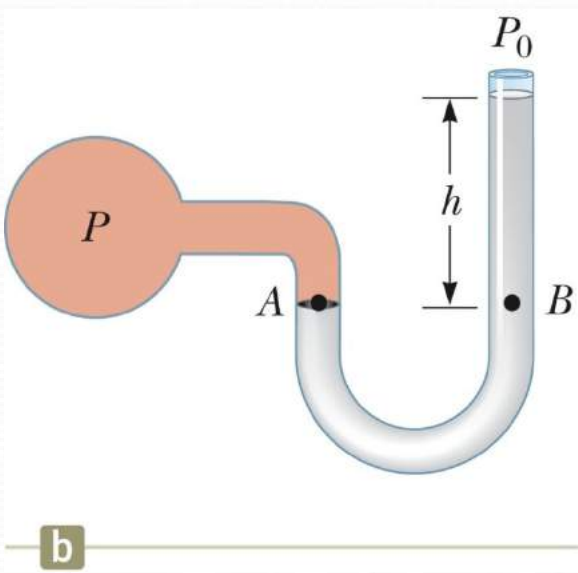
A device for measuring the pressure of a gas contained in a vessel.

One end of the U-shaped tube is open to the atmosphere.

The other end is connected to the pressure to be measured.

Pressure at B is $P = P_o + \rho g h$

The height can be calibrated to measure the pressure.



Manometer

The difference in height, "h," which is the sum of the readings above and below zero, indicates the gauge pressure ($p = \rho g h$)).

- *When a vacuum (low pressure) is applied to one leg, the liquid rises in that leg and falls in the other.*
- *The difference in height, "h," which is the sum of the readings above and below zero, indicates the amount of vacuum.*

The manometer is a part of a device

called a sphygmomanometer

Absolute vs. Gauge Pressure

$P = P_0 + \rho g h$

P is the **absolute pressure.**

The **gauge pressure** is $P - P_0 = \rho g h$. This is what you measure in your tires.

Example: Calculate the pressure at an ocean depth of 500m. Assume the density of water is 10^3kg/m^3 and the atmospheric pressure is 1.01 × 10^5Pa..

Solution

$$\because P = P_a + \rho g h$$

$$\therefore P = 1.01\times10^5 + (10^3 \times 9.8 \times 500)$$

$$= 5\times10^6\ Pa$$

Example: What is the pressure on a swimmer 5 m below the surface of a lake?

Solution: Using the depth of the swimmer is h = 5 mm,

the density for water is ρ = 1000 kgm−3*, and*

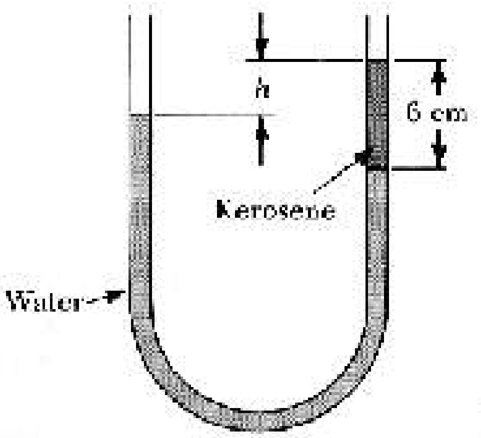
the atmospheric pressure is 1.013 × 105 Pa.

So using equation $p = pa + \rho\ g\ h$ to *calculate the pressure on the swimmer to be:*

$$p = p_a + \rho g h = 1.013\times10^5 + (1000)\,(10)\,5 = 1.5\times10^5\ Pa$$

Example

A simple U-tube that is open at both ends is partially filled with water. Kerosene ($\rho_K = 0.82 \times 10^3 kg/m^3$) is then poured into on arm of the tube, forming a column 6cm height, as shown in Figure. What is the difference h in the heights of the two liquid surfaces?



Solution

The pressure at the doted line is the same *i.e.*

$$P_A = P_B$$

Therefore

$$P_A = \rho_w g h_w \qquad \& \qquad P_B = \rho_k g h_k$$

$$\rho_w g h_w = \rho_k g h_k$$

$$10^3 \times 10 \times h_w = 0.82 \times 10^3 \times 10 \times 0.6$$

hence

$$h_w = 0.498 \text{ m} = 4.98\text{cm}$$

$$h = 6 - 4.98 = 1.02\text{cm}$$

Buoyant Force and Archimedes's Principle

The **buoyant force** is the upward force exerted by a fluid on any immersed object.

The magnitude of the buoyant force always equals the weight of the fluid displaced by the object.

- This is called **Archimedes's Principle.**

The pressure at the bottom of the cube is greater than the pressure at the top of the cube.

The pressure at the top of the cube causes a downward force of P_{top} A.

The pressure at the bottom of the cube causes an upward force of P_{bot} A.

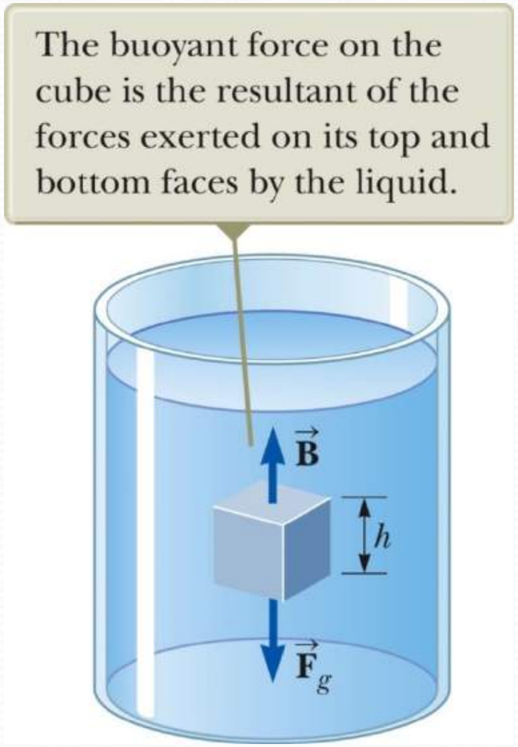
$B = (P_{bot} – P_{top})\ A = (\rho_{fluid}\ g\ h)\ A$

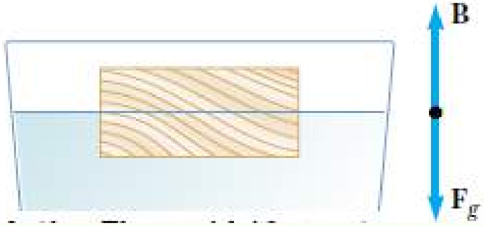
$B = \rho_{fluid}\ g\ V_{disp}$

- V_{disp} = A h is the volume of the fluid displaced by the cube.

$B = M\ g$

- *Mg* is the weight of the fluid displaced by the cube.





Archimedes's Principle: Totally Submerged Object

An object is totally submerged in a fluid of density $\rho_{fluid.}$

The volume V_{disp} of the fluid is equal to the volume of the object, $V_{obj.}$

The upward buoyant force is $B = \rho_{fluid}\, g\, V_{object}$

The downward gravitational force is $F_g = \mathrm{M}g = = \rho_{obj}\, g\, V_{obj}$

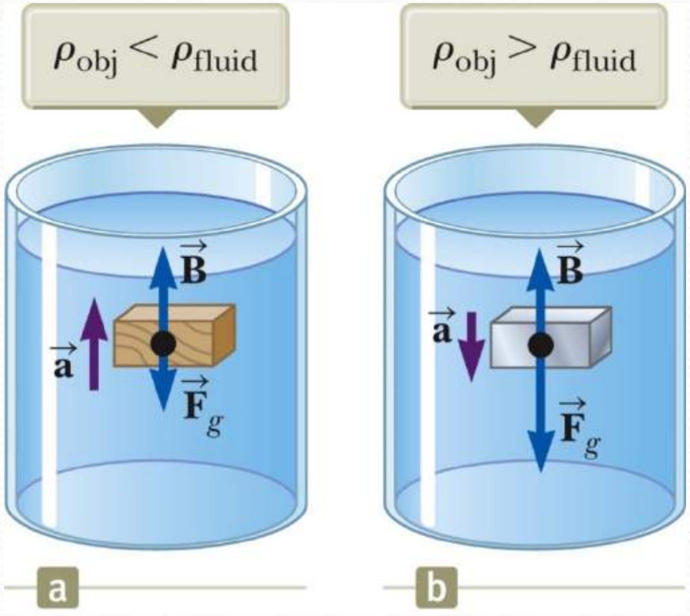
The net force is $B - F_g = (\rho_{fluid} - \rho_{obj})\, g\, V_{obj}$

If the density of the object is less than the density of the fluid, the unsupported object accelerates upward.

If the density of the object is more than the density of the fluid, the unsupported object sinks.

If the density of the submerged object equals the density of the fluid, the object remains in equilibrium.

The direction of the motion of an object in a fluid is determined only by the densities of the fluid and the object.



Archimedes's Principle: Floating Object

The density of the object is less than the density of the fluid.

The object is in static equilibrium.

The object is only partially submerged.

The upward buoyant force is balanced by the downward force of gravity.

Volume of the fluid displaced corresponds to the volume of the object beneath the fluid level.

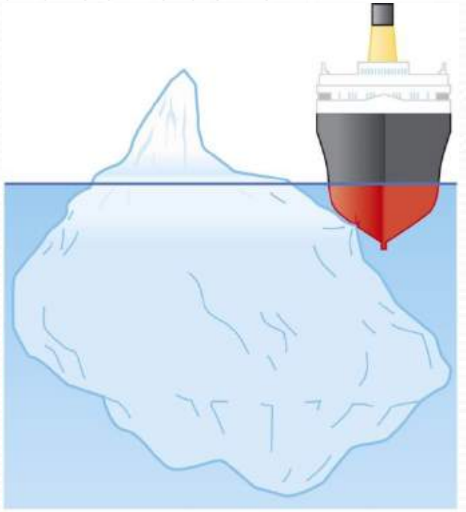
The fraction of the volume of a floating object that is below the fluid surface is equal to the ratio of the density of the object to that of the fluid.

Archimedes's Principle, Iceberg Example

What fraction of the iceberg is below water?

The iceberg is only partially submerged and so $V_{disp} / V_{ice} = \rho_{ice} / \rho_{seawater}$ applies

About 89% of the ice is below the water's surface.



b

Archimedes's Principle, Crown Example

Archimedes was (supposedly) asked, "Is the crown made of pure gold?"

Crown's weight in air = 7.84 N

Weight in water (submerged) = 6.84 N

Buoyant force will equal the apparent weight loss

- Difference in scale readings will be the buoyant force

Categorize the crown as a particle in equilibrium.

$\Sigma F = B + T_2 - F_g = 0$

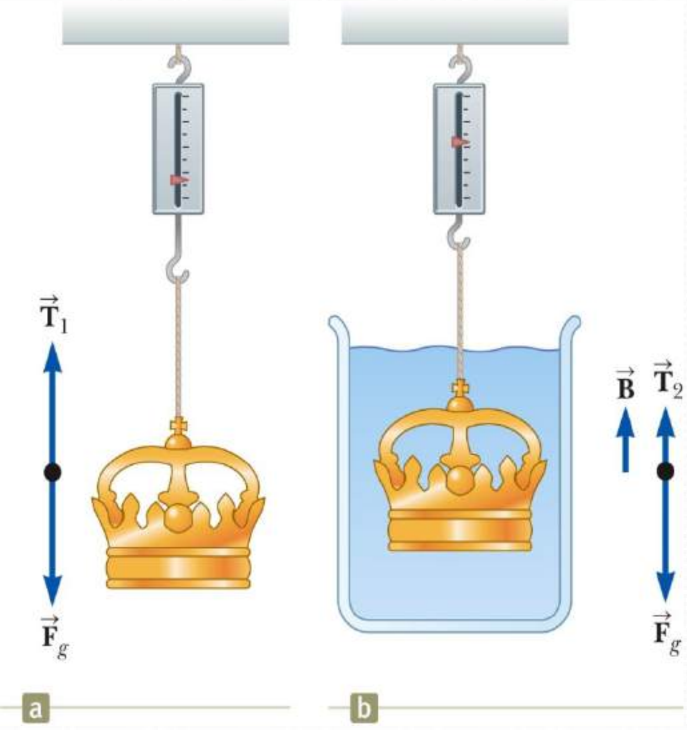
$B = F_g - T_2$

(Weight in air – apparent "weight" in water)

Archimedes's principle says $B = \rho g V$

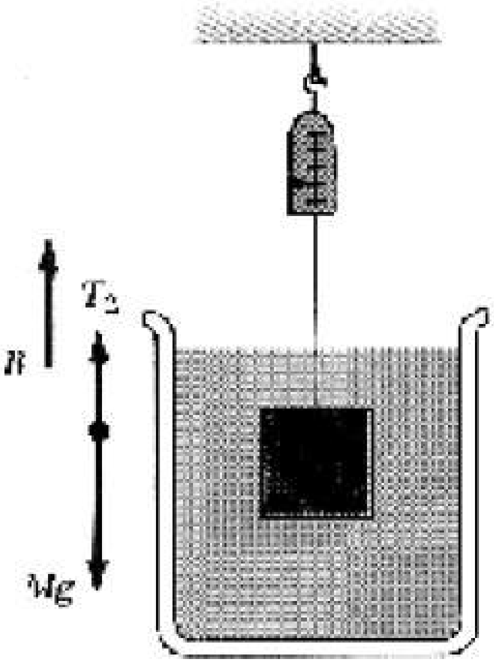
- Find V

Then to find the material of the crown, $\rho_{\text{crown}} = m_{\text{crown in air}} / V$



Example

A solid object has a weight of 5N. When it is suspended from a spring scale and submerged in water, the scale reads 3.5N as shown in Figure. What is the density of the object?



Solution

The buoyant force (B) = the weight of the water displaced (W_{water})

$B = 5 - 3.5 = 1.5\text{N}$

$W_{water} = mg = \rho V g$

hence, $\rho V g = 1.5$

$$V = \frac{1.5}{10^3 \times 9.8} = 1.5\times10^{-4}\text{m}^3$$

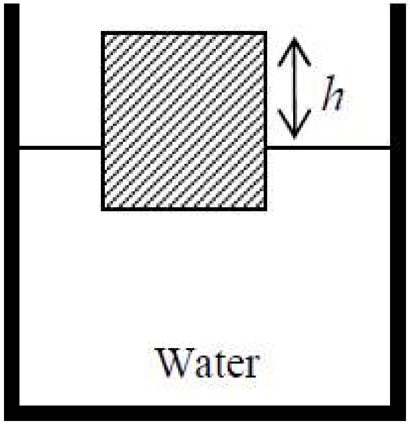
The density of the object is its mass over its volume

$$\rho = \frac{3.5}{1.5\times10^{-4}\times9.8} = 2.3\times10^3\, kg/m^3$$

Example

A cube of wood 20cm on a side and having a density of 0.65×10^3kg/m^3 floats on water. What is the distance from the top of the cube to the water level?

Solution



(a) According to Archimedes principle

$B = \rho_w V g = (1\text{g/cm}^3)\times[20\times20\times(20-h)]g$

but

$B =$ weight of the wood $= mg = \rho_{wood} V_{wood}\, g = (0.65\text{g/cm}^3)(20)^3$

$(1\text{g/cm}^3)\times[20\times20\times(20-h)]g = (0.65\text{g/cm}^3)(20)^3$

$20 - h = 20\times0.65$ then $h = 20(1-0.65) = 7\text{cm}$

(b) $B = W + Mg$ where M is the mass of lead

$1(20)^3 g = (0.65)(20)^3 g + Mg$

$M = 20^3(1- 0.65) = 2800\text{ g} = 2.8\text{kg}$

Types of Fluid Flow

Laminar flow

- Steady flow
- Each particle of the fluid follows a smooth path.
- The paths of the different particles never cross each other.
- Every given fluid particle arriving at a given point has the same velocity.

Turbulent flow

- An irregular flow characterized by small whirlpool-like regions.
- Turbulent flow occurs when the particles go above some critical speed.

Ideal Fluid Flow

- ***The fluid is non-viscous*** – internal friction is neglected
- ***The flow is steady***: all particles passing through a point have the same velocity.
- ***The fluid is incompressible***: the density of the incompressible fluid remains constant.
- ***The flow is irrotational***: the fluid has no angular momentum about any point.

Equation of Continuity

Consider a fluid moving through a pipe of non-uniform size

Consider the small blue-colored portion of the fluid.

At t = 0, the blue portion is flowing through a cross section of area A_1 at speed v_1.

At the end of Δt , the blue portion is flowing through a cross section of area A_2 at speed v_2.

The mass that crosses A_1 in some time interval is the same as the mass that crosses A_2 in that same time interval.

$m_1 = m_2$ or $\rho A_1 v_1 \Delta t = \rho A_2 v_2 \Delta t$

The fluid is incompressible, so ρ is a constant.

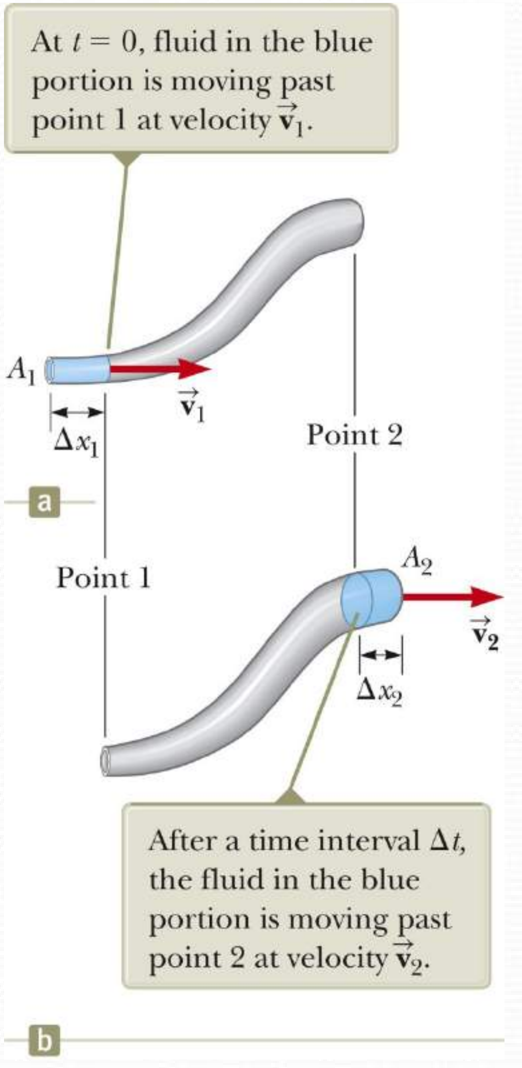
$\mathbf{A_1 v_1 = A_2 v_2 = constant}$

- This is called the **equation of continuity for fluids.**

The speed is high where the tube is constricted (small *A*).

The speed is low where the tube is wide (large *A*).

The product, *Av*, is called the *volume flux* or the *flow rate.*



Example: **A water pipe of radius 3cm is used to fill a 40liter bucket. If it takes 5min to fill the bucket, what is the speed v at which the water leave the pipe?**

Solution:

The cross sectional area of the pipe A is

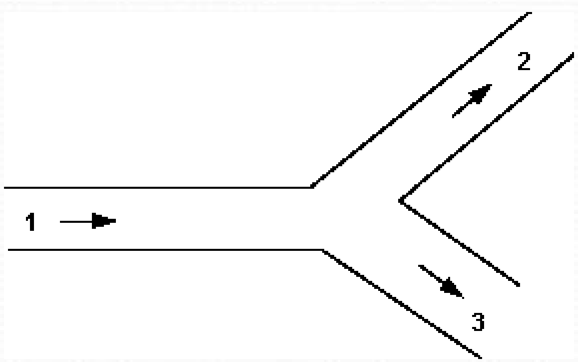
$$A = \pi r^2 = \pi \times 3^2 = 9\pi\, cm^2$$

$$Av = 40\frac{liter}{\min} = \frac{40 \times 10^3\, cm^3}{60s} = 666.6cm^3 / s$$

therefore,

$$v = \frac{666.6}{9\pi} = 23.5cm / s$$

Example: If pipe 1 diameter = 50mm, mean velocity 2m/s, pipe 2 diameter 40mm takes 30% of total discharge and pipe 3 diameter 60mm. What are the values of discharge and mean velocity in each pipe?



$$Q_1 = A_1 u_1 = \left(\frac{\pi d^2}{4}\right) u$$

$$= 0.00392\, m^3 / s$$

$$Q_2 = 0.3 Q_1 = 0.001178 m^3 / s$$

$$Q_1 = Q_2 + Q_3$$

$$Q_3 = Q_1 - 0.3 Q_1 = 0.7 Q_1$$

$$= 0.00275 m^3 / s$$

$$Q_2 = A_2 u_2$$

$$u_2 = 0\ 936 m \quad s$$

$$Q_3 = A_3 u_3$$

$$u_3 = 0\ 972 m \quad s$$

Bernoulli's Equation, 1

Daniel Bernoulli. (1700 – 1782)

Consider the two shaded segments.

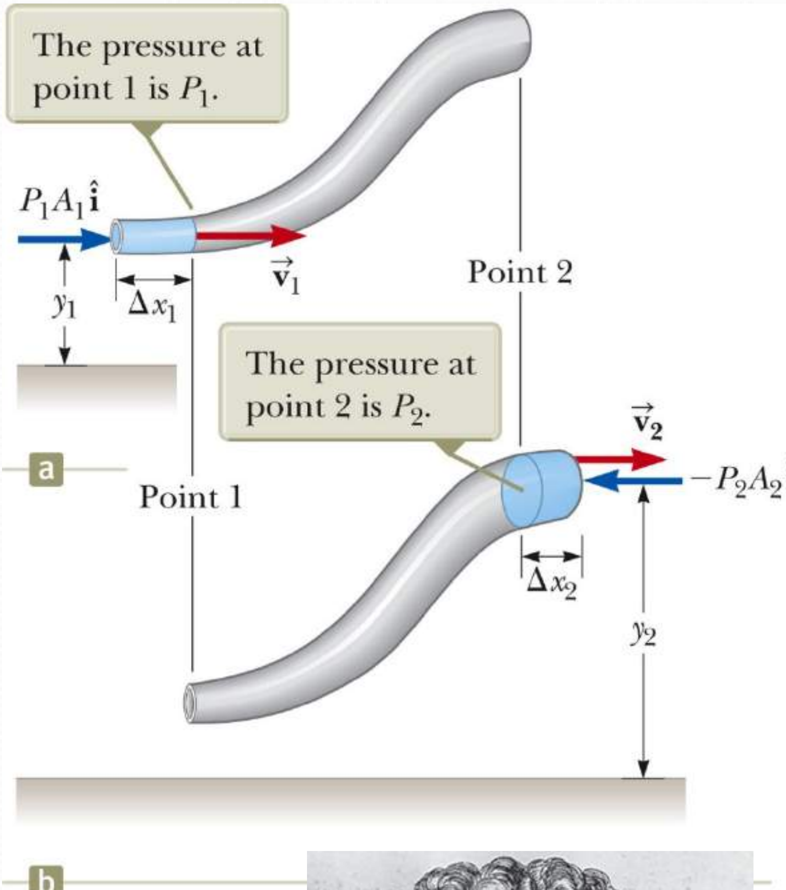
The volumes of both segments are equal.

The net work done on the segment is $W = (P_1 - P_2)\, V$.

Part of the work goes into changing the kinetic energy and some to changing the gravitational potential energy.

The work is negative because the force on the segment of fluid is to the left and the displacement of the point of application of the force is to the right. Part of the work goes into changing in kinetic energy of the segment of fluid:

- $\Delta K = ½\, m v_2^2 - ½\, m v_1^2$
- The masses are the same since the volumes are the same.



Bernoulli's Equation, 2

- There is no change in the kinetic energy of the gray portion since we are assuming streamline flow.

The change in gravitational potential energy:

- $\Delta U = mgy_2 - mgy_1$

The work also equals the change in energy.

Combining:

- $(P_1 - P_2)V = \frac{1}{2} mv_2^2 - \frac{1}{2} mv_1^2 + mgy_2 - mgy_1$

Rearranging and expressing in terms of density:

$$\boldsymbol{P_1 + \tfrac{1}{2}\rho v_1^2 + \rho g y_1 = P_2 + \tfrac{1}{2}\rho v_2^2 + \rho g y_2}$$

This is Bernoulli's Equation as applied to an ideal fluid and is often expressed as

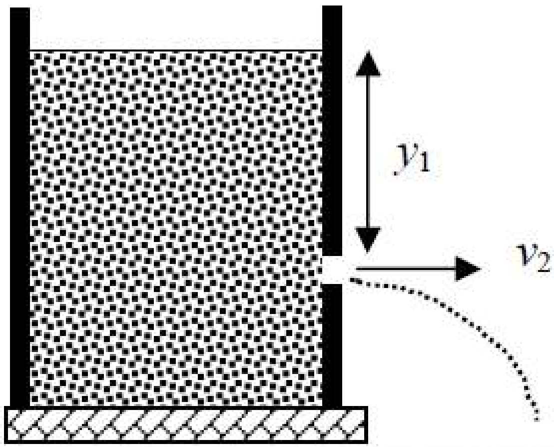
$$P + \tfrac{1}{2}\rho v^2 + \rho g y = constant$$

When the fluid is at rest, this becomes $P_1 - P_2 = \rho g h$ which is consistent with the pressure variation with depth we found earlier .

- As the speed increases, the pressure decreases.

Example

A large storage tank filled with water develops a small hole in its side at a point 16m below the water level. If the rate of flow from the leak is 2.5×10^{-3}m^3/min, determine (a) the speed at which the water leaves the hole and (b) the diameter of the hole.



Solution

(a) The top of the tank is open then $P_1 = P_a$

The water flow rate is 2.5×10^{-3}m^3/min = 4.167×10^{-5}m^3/s

Assuming the speed $v_1 = 0$, and $P_1=P_2=P_a$

$$P_1 + \frac{1}{2}\rho v_1^{\,2} + \rho g y_1 = P_2 + \frac{1}{2}\rho v_2^{\,2} + \rho g y_2$$

$$v_2 = \sqrt{2gy_1} = \sqrt{2\times9.8\times16} = 17.7 m/s$$

(b) The flow rate = $A_2 v_2 = \dfrac{\pi d^2}{4}\times17.7 = 4.167\times10^{-5} m^3/s$

then,

$d = 1.73\times10^{-3}$m = 1.73 mm

Applications of Fluid Dynamics – Airplane Wing

Streamline flow around a moving airplane wing.

Lift is the upward force on the wing from the air.

Drag is the resistance.

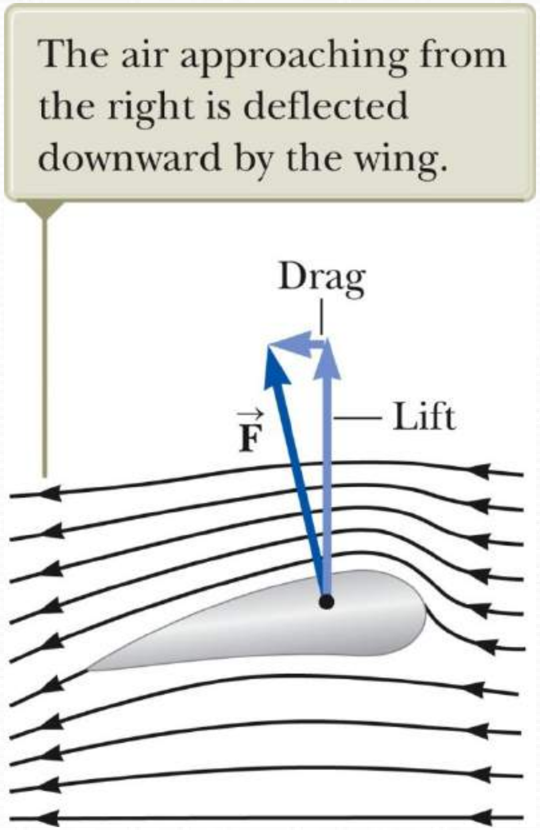
The curvature of the wing surfaces causes the pressure above the wing to be lower than that below the wing due to the Bernoulli effect.

The lift depends on the speed of the airplane, the area of the wing, its curvature, and the angle between the wing and the horizontal.

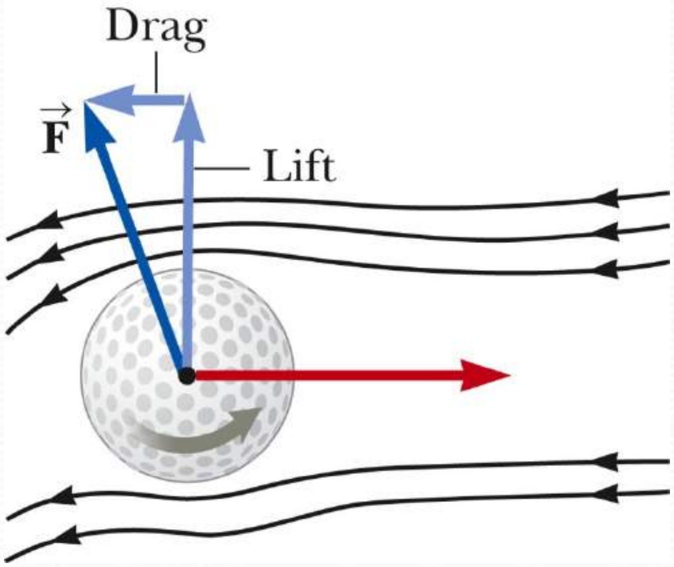
In general, an object moving through a fluid experiences lift as a result of any effect that causes the fluid to change its direction as it flows past the object.

Some factors that influence lift are:

- The shape of the object
- The object's orientation with respect to the fluid flow
- Any spinning of the object
- The texture of the object's surface



Golf Ball Example



The ball is given a rapid backspin.

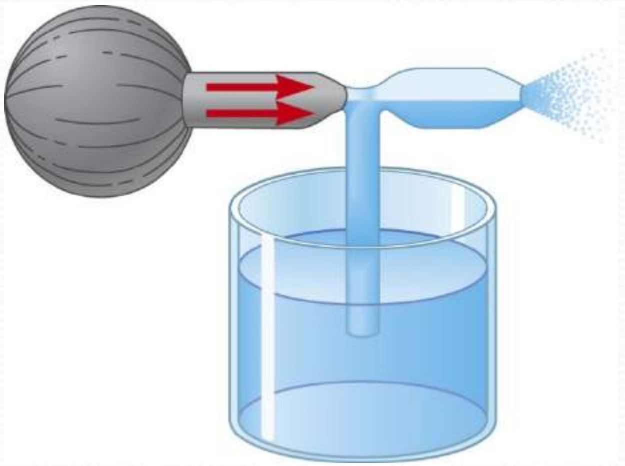
The dimples increase friction.

- Increases lift

It travels farther than if it was not spinning.

The lift gained by spinning the ball more than compensates for the loss of range due to the effect of friction on the translational motion of the ball.

Atomizer Example



A stream of air passes over one end of an open tube.

The other end is immersed in a liquid.

The moving air reduces the pressure above the tube.

The fluid rises into the air stream.

The liquid is dispersed into a fine spray of droplets.

General Physics

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Chapter 6 – Heat and Temperature

Thermal Contact and Thermal Equilibrium

Two objects are in **thermal contact** with each other if energy can be exchanged between them.

The energy is exchanged due to a temperature difference.

Thermal equilibrium is a situation in which two objects would not exchange energy by heat or electromagnetic radiation if they were placed in thermal contact. They are at the same temperature.

Zeroth Law of Thermodynamics

If objects A and B are separately in thermal equilibrium with a third object C, then A and B are in thermal equilibrium with each other.

- Let object C be the thermometer. Since they are in thermal equilibrium with each other, there is no energy exchanged among them.

Temperature can be thought of as the property that determines whether an object is in thermal equilibrium with other objects.

A **thermometer** is a device that is used to measure the temperature of a system.

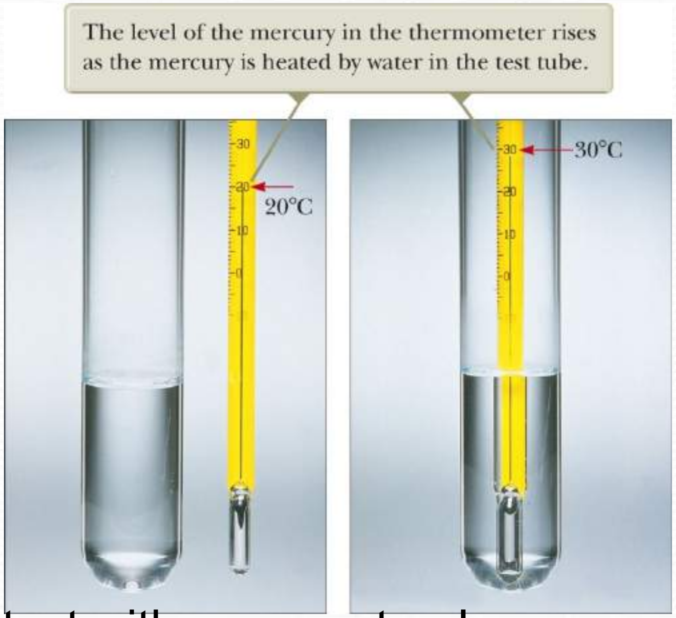
Thermometers are based on the principle that some physical property of a system changes as the system's temperature changes.

Thermometer, Liquid in Glass

A common type of thermometer is a liquid-in-glass.

The material in the capillary tube expands as it is heated.

The liquid is usually mercury or alcohol.



Calibrating a Thermometer

A thermometer can be calibrated by placing it in contact with some natural systems that remain at constant temperature.

Common systems involve water

- A mixture of ice and water at atmospheric pressure
  - Called the *ice point* of water
- A mixture of water and steam in equilibrium
  - Called the *steam point* of water

Once these points are established, the length between them can be divided into a number of segments.

Celsius Scale

The ice point of water is defined to be 0^o C.

The steam point of water is defined to be 100^o C.

The length of the column between these two points is divided into 100 increments, called degrees.

Problems with Liquid-in-Glass Thermometers

An alcohol thermometer and a mercury thermometer may agree only at the calibration points.

The discrepancies between thermometers are especially large when the temperatures being measured are far from the calibration points.

The thermometers also have a limited range of values that can be measured.

- Mercury cannot be used under -39^o C
- Alcohol cannot be used above 85^o C

Absolute Zero

The thermometer readings are virtually independent of the gas used.

If the lines for various gases are extended, the pressure is always zero when the temperature is –273.15^{o} C.

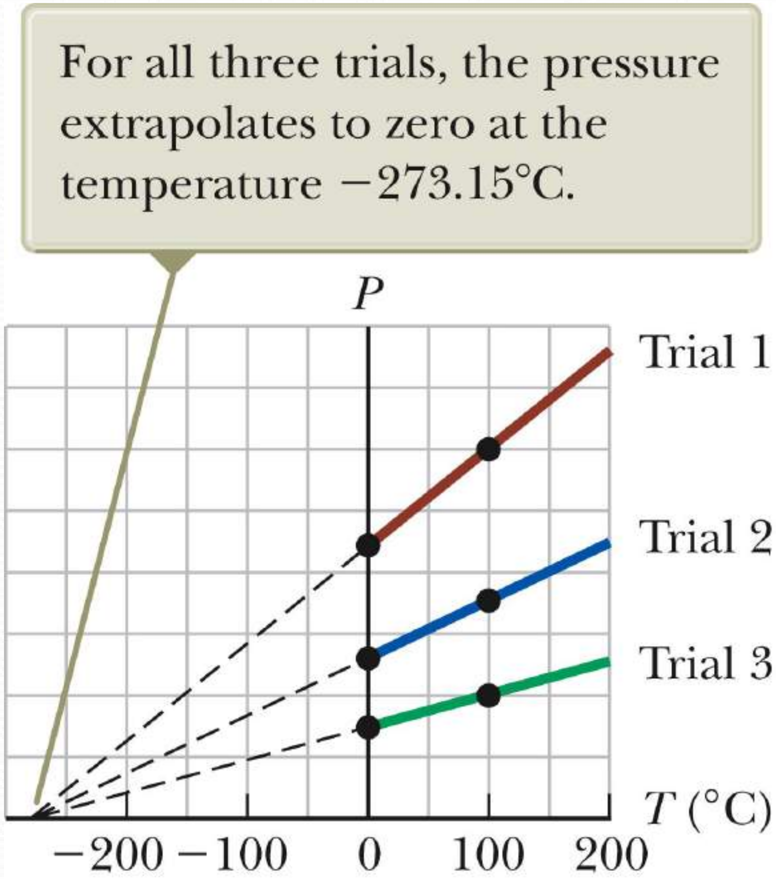
This temperature is called **absolute zero.**

Absolute zero is used as the basis of the **absolute temperature scale.**

The size of the degree on the absolute scale is the same as the size of the degree on the Celsius scale.

To convert: $T_C = T - 273.15$

The units of the absolute scale are **kelvins.** The absolute scale is also called the Kelvin scale. Named for William Thomson, Lord Kelvin



Fahrenheit Scale

A common scale in everyday use in the US. Named for Daniel Fahrenheit

Temperature of the ice point is 32^{o}F.

Temperature of the steam point is 212^o.

There are 180 divisions (degrees) between the two reference points.

$$\Delta T_C = \Delta T = \frac{5}{9} \Delta T_F$$

Comparison of Scales

Celsius and Kelvin have the same size degrees, but different starting points.

- $T_C = T - 273.15$

Celsius and Fahrenheit have different sized degrees and different starting points.

$$T_F = \frac{9}{5} T_C + 32^\circ.$$

To compare changes in temperature

Ice point temperatures 0^{o}C = 273.15 K = 32^o F

Steam point temperatures 100^{o}C = 373.15 K = 212^o F

Thermal Expansion

Thermal expansion is the increase in the size of an object with an increase in its temperature.

Linear Expansion

Assume an object has an initial length *L.*

That length increases by ΔL as the temperature changes by ΔT.

We define the **coefficient of linear expansion** as

$$\alpha = \frac{\Delta L / L_i}{\Delta T}$$

A convenient form is $\boldsymbol{\Delta L = \alpha L_i \Delta T}$

This equation can be written in terms of the initial and final conditions of the object:

- $L_f - L_i = \alpha\, L_i (T_f - T_i)$

The coefficient of linear expansion, α, has units of $(^{o}C)^{-1}$

Some materials expand along one dimension, but contract along another as the temperature increases. Since the linear dimensions change, it follows that the surface area and volume also change with a change in temperature.

Some Coefficients

TABLE 19.1 *Average Expansion Coefficients for Some Materials Near Room Temperature*

Material (Solids)	Average Linear Expansion Coefficient $(\alpha)(^\circ C)^{-1}$	Material (Liquids and Gases)	Average Volume Expansion Coefficient $(\beta)(^\circ C)^{-1}$
Aluminum	24×10^{-6}	Acetone	1.5×10^{-4}
Brass and bronze	19×10^{-6}	Alcohol, ethyl	1.12×10^{-4}
Concrete	12×10^{-6}	Benzene	1.24×10^{-4}
Copper	17×10^{-6}	Gasoline	9.6×10^{-4}
Glass (ordinary)	9×10^{-6}	Glycerin	4.85×10^{-4}
Glass (Pyrex)	3.2×10^{-6}	Mercury	1.82×10^{-4}
Invar (Ni–Fe alloy)	0.9×10^{-6}	Turpentine	9.0×10^{-4}
Lead	29×10^{-6}	Air[a] at 0°C	3.67×10^{-3}
Steel	11×10^{-6}	Helium[a]	3.665×10^{-3}

[a]Gases do not have a specific value for the volume expansion coefficient because the amount of expansion depends on the type of process through which the gas is taken. The values given here assume the gas undergoes an expansion at constant pressure.

Example: Expansion of a railroad track

(a) A steel railroad track has a length of 30.0 m when the temperature is 0 ^{o}C. What is the length on a hot day when the temperature is 40.0 ^{o}C?

(b) (b) What is the stress caused by this expansion?

Solution:

(a) The change in length due to the temperature change,

$$\begin{aligned}\Delta L &= \alpha L_0 \Delta T \\ \Delta L &= (11 \times 10^{-6}\ /^{\circ}\mathrm{C})(30.0\ \mathrm{m})(40.0\ ^{\circ}\mathrm{C}) \\ \Delta L &= 0.013\ \mathrm{m}.\end{aligned}$$

So the new length is 30.013 m.

(b) The railroad undergoes a linear expansion, so this is a tensile strain,

$$\begin{aligned}\frac{F}{A} &= Y\frac{\Delta L}{L} \\ \frac{F}{A} &= (2.0 \times 10^{11}\ \mathrm{Pa}\left(\frac{0.013\ \mathrm{m}}{30.0\ \mathrm{m}}\right) \\ \frac{F}{A} &= 8.7 \times 10^{7}\ \mathrm{Pa}.\end{aligned}$$

Volume Expansion

The change in volume is proportional to the original volume and to the change in temperature.

$\Delta V = \beta V_i \Delta T$

- β is the coefficient of volume expansion.
- For a solid, $\beta = 3\alpha$
- For a liquid or gas, β is given in the table

Area Expansion

The change in area is proportional to the original area and to the change in temperature:

- $\Delta A = 2\alpha A_i \Delta T$

An Ideal Gas

For gases, the interatomic forces within the gas are very weak.

State variables describe the state of a system.

Variables may include:

- Pressure, temperature, volume, internal energy

The state of an isolated system can be specified only if the system is in thermal equilibrium internally.

- For a gas in a container, this means every part of the gas must be at the same pressure and temperature.

It is useful to know how the volume, pressure, and temperature of the gas of mass m are related.

The equation that interrelates these quantities is called the **equation of state.**

The **ideal gas model** can be used to make predictions about the behavior of gases.

The Mole

The amount of gas in a given volume is conveniently expressed in terms of the number of moles, *n.*

One **mole** of any substance is that amount of the substance that contains **Avogadro's number** of constituent particles.

- Avogadro's number is $N_A = 6.022 \times 10^{23}$
- The constituent particles can be atoms or molecules.

The number of moles can be determined from the mass of the substance:

$$n = \frac{m}{M}$$

- M is the molar mass of the substance.
  - Can be obtained from the periodic table
  - Is the atomic mass expressed in grams/mole
    - Example: He has mass of 4.00 u so M = 4.00 g/mol
- m is the mass of the sample.
- n is the number of moles.

Gas Laws

When a gas is kept at a constant temperature, its pressure is inversely proportional to its volume (Boyle's law).

When a gas is kept at a constant pressure, its volume is directly proportional to its temperature (Charles and Gay-Lussac's law).

When the volume of the gas is kept constant, the pressure is directly proportional to the temperature (Guy-Lussac's law).

Ideal Gas Law

The equation of state for an ideal gas combines and summarizes the other gas laws:

$$PV = nRT$$

This is known as the **ideal gas law.**

R is a constant, called the Universal Gas Constant.

- $R = 8.314\ \text{J/mol} \cdot \text{K} = 0.08214\ \text{L} \cdot \text{atm/mol} \cdot \text{K}$

From this, you can determine that 1 mole of any gas at atmospheric pressure and at 0^{o} C is 22.4 L.

It is common to call P, V, and T the **thermodynamic variables** of an ideal gas.

Example

Pure helium gas is admitted into a tank containing a movable piston. The initial volume, pressure and temperature of the gas are $15x10^{-3}m^3$, 200kPa and 300K respectively. If the volume is decreased to $12x10^{-3}m^3$ and the pressure is increased to 350KPa, find the final temperature of the gas.

 Solution

Since the gas can not escape from the tank then the number of moles is constant,

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

$$T_2 = (\frac{p_2V_2}{p_1V_1})T_1 = \frac{3.5\, atm\,.12\, liters}{2\, atm\,.15\, liters}(300K) = 420\, K$$

Internal Energy

Internal energy is all the energy of a system that is associated with its microscopic components.

- These components are its atoms and molecules.
- The system is viewed from a reference frame at rest with respect to the center of mass of the system.

The kinetic energy due to its motion through space is not included.

Internal energy does include kinetic energies due to:

- Random translational motion
- Rotational motion
- Vibrational motion

Internal energy also includes potential energy between molecules

Heat

Heat is defined as the transfer of energy across the boundary of a system due to a temperature difference between the system and its surroundings.

The term heat will also be used to represent the amount of energy transferred by this method.

There are many common phrases that use the word “heat” incorrectly.

Heat, internal energy, and temperature are all different quantities.

- Be sure to use the correct definition of heat.
- **One calorie** is the amount of energy transfer necessary to raise the temperature of 1 g of water from 14.5^{o}C to 15.5^{o}C.
  - The “Calorie” used for food is actually 1 kilocalorie.
  - The standard in the text is to use Joules.

more precise, measurements determined the amount of mechanical energy needed to raise the temperature of water from 14.5^{o}C to 15.5^{o}C.

1 cal = 4.186 J

- This is known as the **mechanical equivalent of heat.**

Heat Capacity

The **heat capacity**, C, of a particular sample is defined as the amount of energy needed to raise the temperature of that sample by 1°C.

If energy Q produces a change of temperature of ΔT, then $Q = C\,\Delta T$.

Specific Heat

Specific heat, c, is the heat capacity per unit mass.

If energy Q transfers to a sample of a substance of mass m and the temperature changes by ΔT, then the specific heat is

$$c \equiv \frac{Q}{m\,\Delta T}$$

The specific heat is essentially a measure of how thermally insensitive a substance is to the addition of energy.

- The greater the substance's specific heat, the more energy that must be added to a given mass to cause a particular temperature change.

The equation is often written in terms of Q : $Q = m\,c\,\Delta T$

Water has the highest specific heat of common materials.

Some Specific Heat Values

TABLE 20.1 *Specific Heats of Some Substances at 25°C and Atmospheric Pressure*

Substance	Specific Heat (J/kg · °C)	Substance	Specific Heat (J/kg · °C)
Elemental solids		*Other solids*	
Aluminum	900	Brass	380
Beryllium	1 830	Glass	837
Cadmium	230	Ice (−5°C)	2 090
Copper	387	Marble	860
Germanium	322	Wood	1 700
Gold	129	*Liquids*	
Iron	448	Alcohol (ethyl)	2 400
Lead	128	Mercury	140
Silicon	703	Water (15°C)	4 186
Silver	234	*Gas*	
		Steam (100°C)	2 010

Note: To convert values to units of cal/g · °C, divide by 4 186.

Example

A quantity of hot water at 91° C and another cold one at 12° C. How much kilogram of each one is needed to make an 800 liter of water bath at temperature of 35° C.

Solution

Assume the mass of hot water m_H and cold one is m_C,

800 liter of water is equivalent to 800 kg, *So* $m_H + m_C = 800$,

From the conservation of energy $m_H C_w (T_H - T_f) = m_C C_w (T_f - T_C)$

$T_H = 92°C$, $T_C = 12°C$, $T_f = 35°C$,

$$56\, m_H = 23\, m_C,$$

- So

$$m_C = 2.43\, m_H$$

- So by substitution

$$3.43\, m_H = 800,$$

$$m_H = 233\ kg, \text{ and } m_C = 567\ kg$$

Supercooling

If liquid water is held perfectly still in a very clean container, it is possible for the temperature to drop below 0^{o} C without freezing.

This phenomena is called **supercooling.**

It arises because the water requires a disturbance of some sort for the molecules to move apart and start forming the open ice crystal structures.

- This structure makes the density of ice less than that of water.

If the supercooled water is disturbed, it immediately freezes and the energy released returns the temperature to 0^{o} C.

Superheating

Water can rise to a temperature greater than 100^{o} C without boiling.

This phenomena is called **superheating.**

The formation of a bubble of steam in the water requires nucleation site.

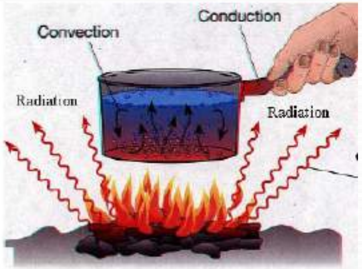
- This could be a scratch in the container or an impurity in the water.

When disturbed, the superheated water can become explosive.

- The bubbles will immediately form and hot water is forced upward and out of the container.

Mechanisms of Energy Transfer In Thermal Processes

- The heat is a transfer of the energy from a high temperature object to a lower temperature one. There are various mechanisms responsible for the transfer: Conduction, Convection, Radiation



Conduction

It is an exchange of kinetic energy between microscopic particles by collisions.

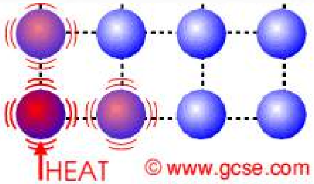
- The microscopic particles can be atoms, molecules or free electrons.

- Less energetic particles gain energy during collisions with more energetic particles.

Rate of conduction depends upon the characteristics of the substance.

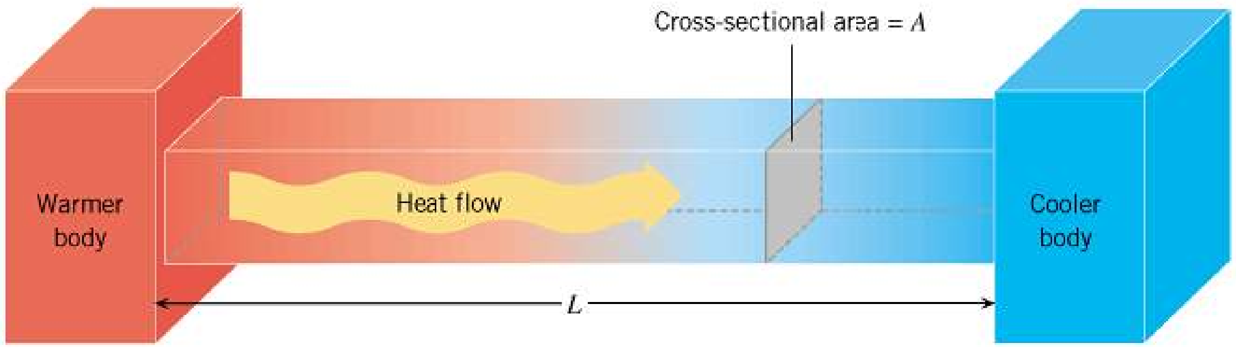
In general, metals are good thermal conductors.

- They contain large numbers of electrons that are relatively free to move through the metal.
- They can transport energy from one region to another.



Poor conductors include asbestos, paper, and gases.Conduction can occur only if there is a difference in temperature between two conducting medium.

Conduction, equation



The slab at right allows energy to transfer from the region of higher temperature to the region of lower temperature.

The rate of transfer is given by:

$$H = \frac{Q}{t} = kA\left(\frac{\Delta T}{L}\right)$$

A is the cross-sectional area. L is the length of a rod

H (or P) = rate of conduction heat transfer (Watt)

k is the thermal conductivity of the material.

- Good conductors have high k values and good insulators have low k values

TABLE 20.3

Thermal Conductivities

Substance	Thermal Conductivity (W/m · °C)
Metals (at 25°C)	
Aluminum	238
Copper	397
Gold	314
Iron	79.5
Lead	34.7
Silver	427
Nonmetals (approximate values)	
Asbestos	0.08
Concrete	0.8
Diamond	2 300
Glass	0.8
Ice	2
Rubber	0.2
Water	0.6
Wood	0.08
Gases (at 20°C)	
Air	0.023 4
Helium	0.138
Hydrogen	0.172
Nitrogen	0.023 4
Oxygen	0.023 8

Example

- An aluminum pot contains water that is kept steadily boiling (100 ºC). The bottom surface of the pot, which is 12 mm thick and $1.5x10^4$ mm^2 in area, is maintained at a temperature of 102° C by an electric heating unit. Find the rate at which heat is transferred through the bottom surface. Compare this with a copper based pot.

$$H = kA\left(\frac{\Delta T}{L}\right)$$

Solution

- For the aluminum base: $T_H = 102\ °C, T_C = 100\ °C,\ L=12\ mm = 0.012\ m,\ K_{Al} = 238\, Wm^{-1}K^{-1}$, Base area $A = 1.5x10^4\ mm^2 = 0.015\ m^2$.

$$H_{Al} = 238\,(0.015)\,\frac{(102-100)}{0.012} = 588W$$

- For the copper base $K_{Cu} = 397\, Wm^{-1}K^{-1}$.

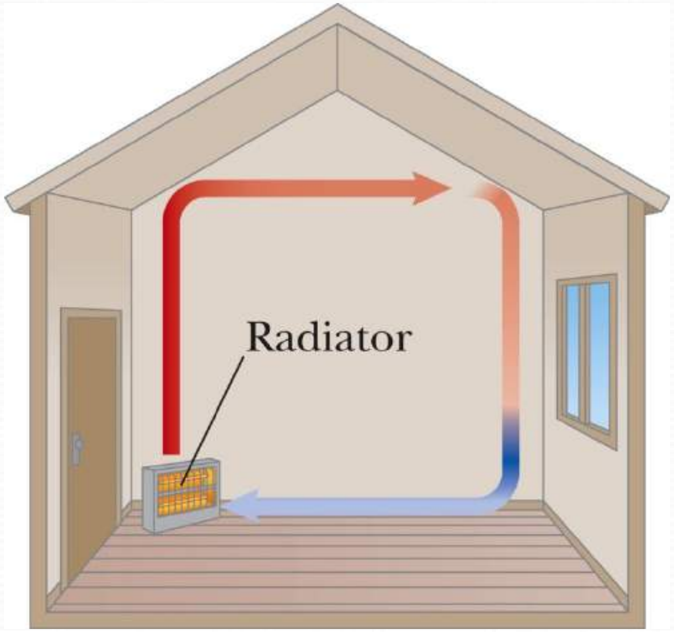
$$H_{Cu} = 397\,(0.015)\,\frac{(102-100)}{0.012} = 1003W$$

Convection

Energy transferred by the movement of a substance.

It is a form of matter transfer:

- When the movement results from differences in density, it is called *natural convection.*
- When the movement is forced by a fan or a pump, it is called *forced convection.*



Example

Air directly above the radiator is warmed and expands.

The density of the air decreases, and it rises.

A continuous air current is established

Radiation

Radiation does not require physical contact.

All objects radiate energy continuously in the form of electromagnetic waves due to thermal vibrations of their molecules.

Rate of radiation is given by **Stefan's law.**

$P = \sigma A e T^4$

- P is the rate of energy transfer, in Watts.
- $\sigma = 5.6696 \times 10^{-8}\ W/m^2 \cdot K^4$
- A is the surface area of the object.
- e is a constant called the emissivity.
  - e varies from 0 to 1
  - The emissivity is also equal to the absorptivity.
- T is the temperature in Kelvins.

An ***ideal absorber*** is defined as an object that absorbs all of the energy incident on it. $e = 1$

This type of object is called a **black body.**

Energy Absorption and Emission by Radiation

With its surroundings, the rate at which the object at temperature T with surroundings at T_o radiates is

- $P_{net} = \sigma A e\,(T^4 - T_o^4)$
- When an object is in equilibrium with its surroundings, it radiates and absorbs at the same rate.
  - Its temperature will not change

Example: A student tries to decide what to wear is staying in a room that is at 20° C. If the skin temperature is 37° C, how much heat is lost from the body in 10 minutes? Assume that the emissivity of the body is 0.9 and the surface area of the student is 1.5 m2.

Solution

Using the Stefan-Boltzmann's law

$$P_{net} = e\,\sigma\,A\,(T^4 - T_s^4) = (5.67\times10^{-8})(0.9)(1.5)(310^4 - 293^4) = 143\,watt.$$

The total energy lost during 10 min is

$$Q = P_{net}\,\Delta t = 143\times600 = 85.8\,kJ$$

The Dewar Flask

A Dewar flask is a container designed to minimize the energy losses by conduction, convection, and radiation.

- Invented by Sir James Dewar (1842 – 1923)

It is used to store either cold or hot liquids for long periods of time.

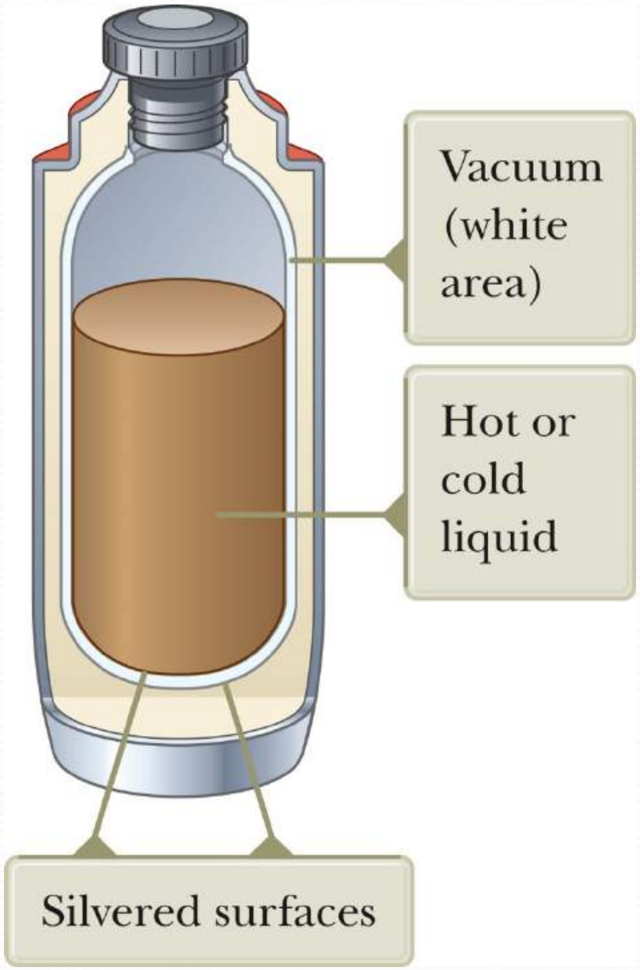
- A Thermos bottle is a common household equivalent of a Dewar flask.

The space between the walls is a vacuum to minimize energy transfer by conduction and convection.

The silvered surface minimizes energy transfers by radiation.

- Silver is a good reflector.

The size of the neck is reduced to further minimize energy losses.



General Physics

for Science and Engineering Faculties

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Chapter 7 - Sound Waves

Types of Waves

Example of a wave

- A pebble hits the water's surface.
- The resulting circular wave moves outward from the creation point.
- An object floating on the disturbed water will move vertically and horizontally about its original position, but does not undergo any net displacement.

In wave motion, energy is transferred over a distance.

Matter is not transferred over a distance.

There are two main types of waves.

- Mechanical waves
  - Some physical medium is being disturbed.
  - The wave is the propagation of a disturbance through a medium.
- Electromagnetic waves
  - No medium required.
  - Examples are light, radio waves, x-rays

Pulse on a String

The wave is generated by a flick on one end of the string.

The string is under tension.

A single bump is formed and travels along the string.

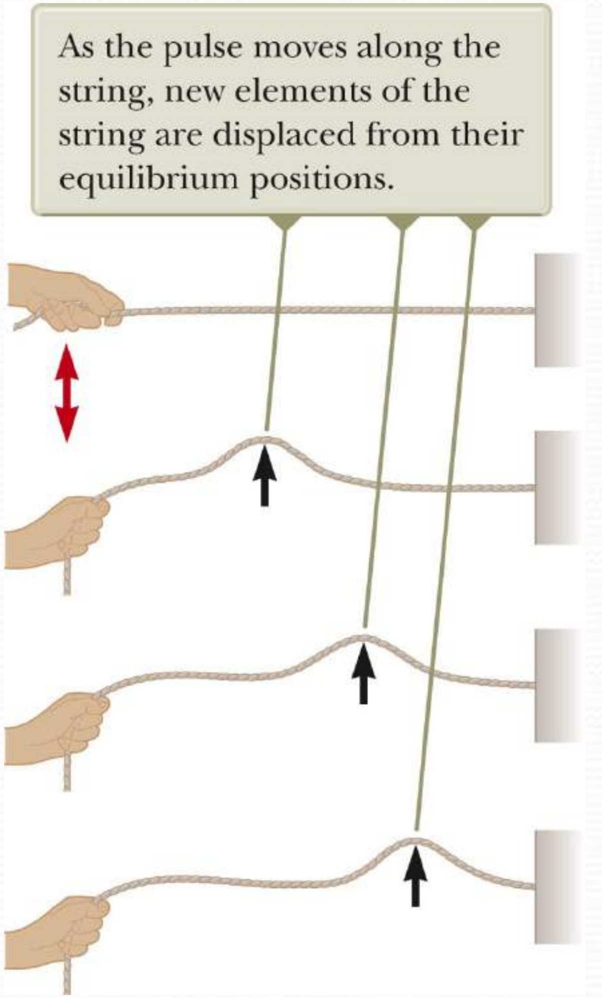
- The bump is called a **pulse.**
- The speed of the pulse is *v.*

The string is the medium through which the pulse travels.

- Individual elements of the string are disturbed from their equilibrium position.

The pulse has a definite height. It has a definite speed of propagation along the medium.

The shape of the pulse changes very little as it travels along the string.

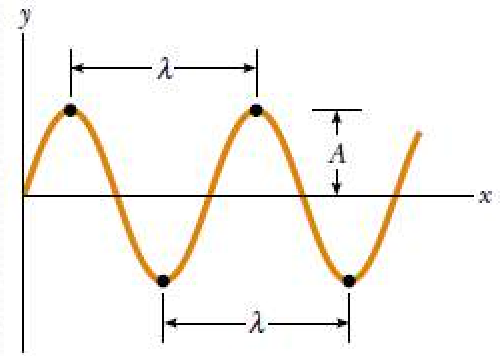


Terminology: Amplitude and Wavelength

The **crest** of the wave is the location of the maximum displacement of the element from its normal position.

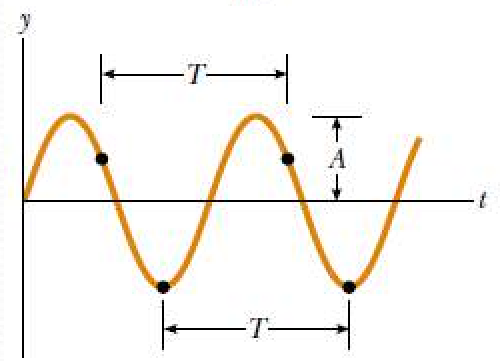
- This distance is called the **amplitude**, *A.*

The **wavelength**, λ, is the distance from one crest to the next.



(a)

The **period**, T , is the time interval required for two identical points of adjacent waves to pass by a point.

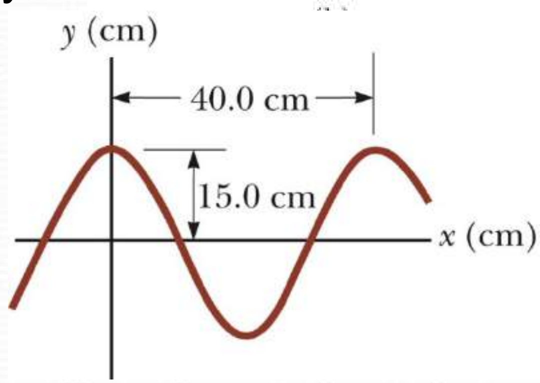


The **frequency**, f, is the number of crests (or any point on the wave) that pass a given point in a unit time interval.

$$f = \frac{1}{T}$$

When the time interval is the second, the units of frequency are s^{-1} = Hz. Hz is a hertz

Example



The wavelength, λ, is 40.0 cm

The amplitude, *A*, is 15.0 cm

The wave function can be written as $y = A\cos(kx - \omega t)$.

Speed of Waves

Since speed is distance divided by time,

$$v = \lambda / T = \lambda f$$

- The speed depends on the properties of the medium being disturbed.

The wave function is given by

$$y(x,t) = A\sin\left[\frac{2\pi}{\lambda}(x - vt)\right]$$

- This is for a wave moving to the right.
- For a wave moving to the left, replace x – vt with x + vt.

We can also define the angular wave number (or just wave number), *k.*

$$k = \frac{2\pi}{\lambda}$$

The angular frequency can also be defined.

$$\omega = \frac{2\pi}{T} = 2\pi f$$

The wave function can be expressed as $y = A \sin (k x - \omega t)$.

If $x \neq 0$ at $t = 0$, the wave function can be generalized to $y = A \sin (k x - \omega t + \phi)$ where ϕ is called the **phase constant.**

Example

A sinusoidal wave traveling in the positive *x* direction has an amplitude of 15.0 cm, a wavelength of 40.0 cm, and a frequency of 8.00 Hz. The vertical position of an element of the medium at *t* ! 0 and *x* ! 0 is also 15.0 cm, as shown in Figure. Find the wave number *k*, period *T*, angular frequency w

and speed *v* of the wave.

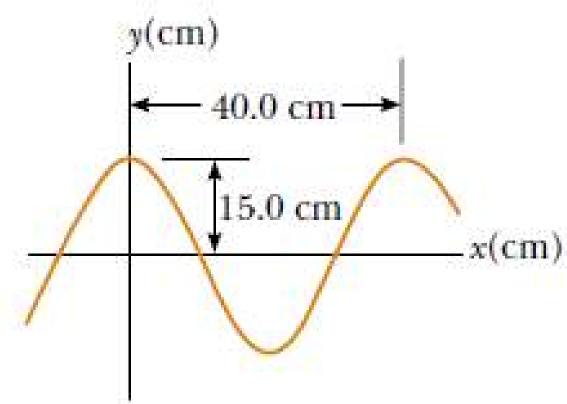
Solution

$$k = \frac{2\pi}{\lambda} = \frac{2\pi \text{ rad}}{40.0 \text{ cm}} = \boxed{0.157 \text{ rad/cm}}$$

$$T = \frac{1}{f} = \frac{1}{8.00 \text{ s}^{-1}} = \boxed{0.125 \text{ s}}$$

$$\omega = 2\pi f = 2\pi(8.00 \text{ s}^{-1}) = \boxed{50.3 \text{ rad/s}}$$

$$v = \lambda f = (40.0 \text{ cm})(8.00 \text{ s}^{-1}) = \boxed{320 \text{ cm/s}}$$



Speed of a Wave on a String

The speed of the wave depends on the physical characteristics of the string and the tension to which the string is subjected.

$$v = \sqrt{\frac{\text{tension}}{\text{mass/length}}} = \sqrt{\frac{T}{\mu}}$$

This assumes that the tension is not affected by the pulse.

Energy in Waves in a String

Waves transport energy when they propagate through a medium. Every element has the same total energy.

the total kinetic energy in one wavelength is $K_\lambda = \frac{1}{4}\mu\,\omega^2 A^2\lambda$.

The total potential energy in one wavelength is $U_\lambda = \frac{1}{4}\mu\,\omega^2 A^2\lambda$.

This gives a total energy of $E_\lambda = K_\lambda + U_\lambda = \frac{1}{2}\mu\,\omega^2 A^2\lambda$

Power Associated with a Wave

- The power is the rate at which the energy is being transferred:

$$P = \frac{E_\lambda}{T} = \frac{\frac{1}{2}\mu\omega^2 A^2\lambda}{T} = \frac{1}{2}\mu\omega^2 A^2 v$$

Introduction to Sound Waves

Waves can move through three-dimensional bulk media.

Sound waves are longitudinal waves.

Sound waves cannot be transmitted through vacuum. The transmission of sound requires at least a medium, which can be solid, liquid, or gas.

- Commonly experienced as the mechanical waves traveling through air that result in the human perception of hearing
- As the sound wave travels through the air, elements of air are disturbed from their equilibrium positions.
- Accompanying these movements are changes in density and pressure of the air.

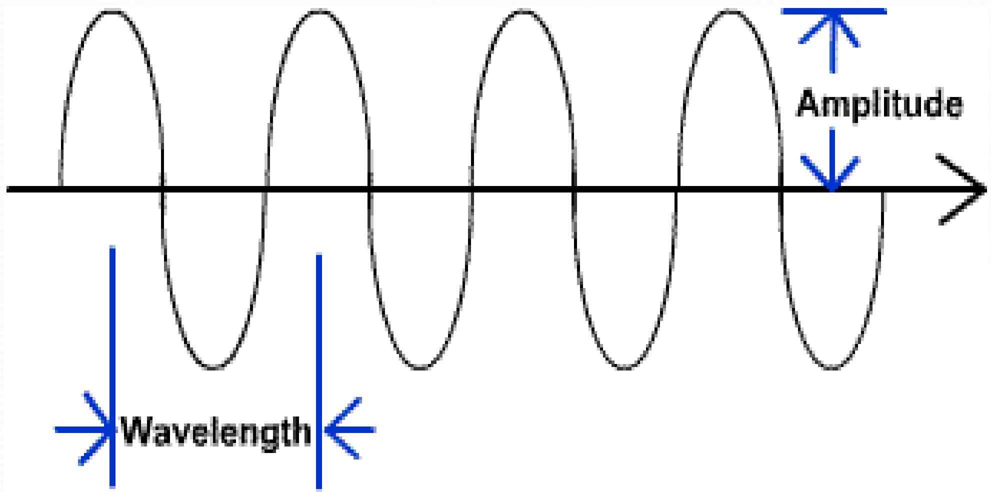
The mathematical description of sinusoidal sound waves is very similar to sinusoidal waves on a string.

The categories cover different frequency ranges.

Audible waves are within the sensitivity of the human ear. [20Hz - 20kHz]

Infrasonic waves have frequencies below the audible range. [less than 20kHz]

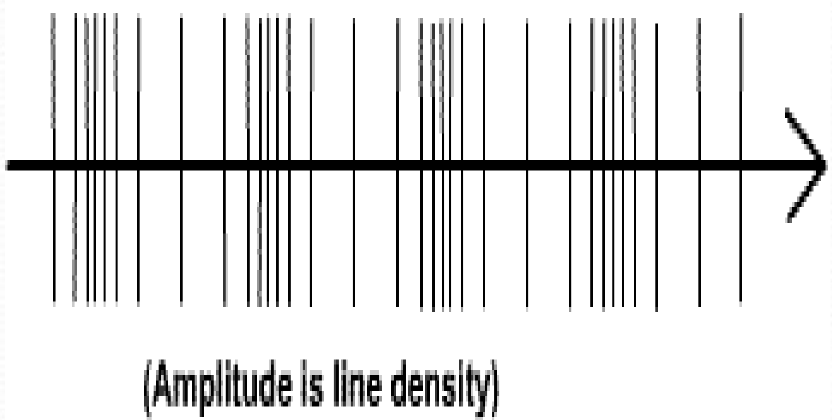
Ultrasonic waves have frequencies above the audible range. [larger than 20kHz]



Transverse Wave
(water wave)

compression
(increase in pressure)

rarefaction
(Decrease in pressure)



Compression Wave
(sound)

The illustration above shows a comparison of a transverse wave such as a water wave and the compression wave sound wave.

Characteristics of sound

A sound wave has characteristics just like any other type of wave, including amplitude, velocity, wavelength and frequency.

Amplitude

The amplitude of a sound wave is the same thing as its loudness. Since sound is a compression wave, its loudness or amplitude would correspond to how much the wave is compressed. It is sometimes called pressure amplitude

Wavelength (λ)

Wavelength is the distance from one crest to another of a wave. Since sound is a compression wave, the wavelength is the distance between maximum compressions

Frequency (f)

The frequency of sound is the rate at which the waves pass a given point. It is also the rate at which a guitar string or a loud speaker vibrates.

Period (T) :is the time taken by a crest to move forward one wave length.

Speed or velocity of sound

The relationship between velocity, wavelength and frequency is:

velocity = wavelength x frequency

Since a crest moves forward a distance λ in

a time T .

velocity (v) = $\lambda / T = \lambda f$

Where $T = 1 / f$

$$V = \lambda f \text{ m/sec}$$

Resonance : The ability of an object to vibrate by absorbing energy of its own natural frequency is called *resonance*

Producing a Periodic Sound Wave

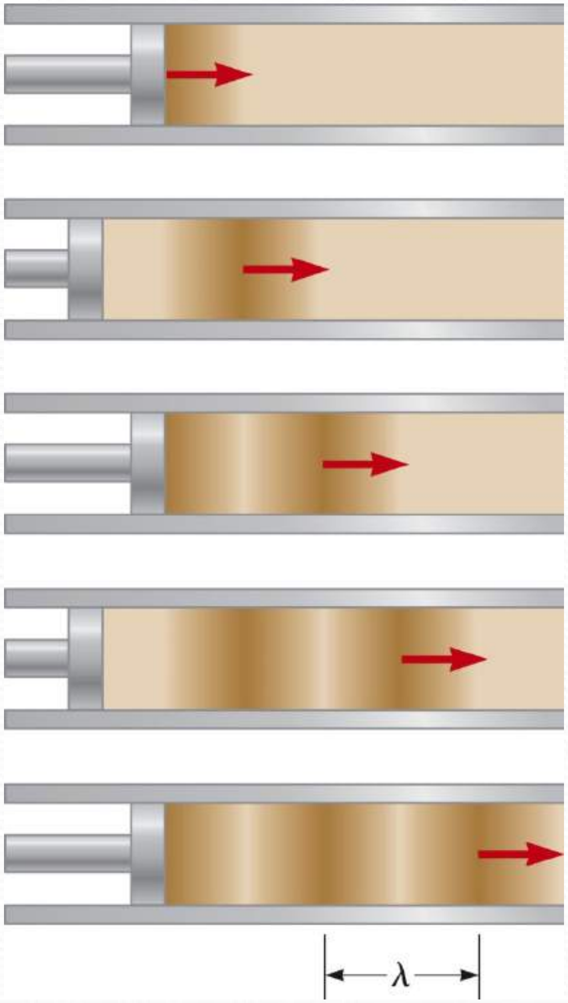
A one-dimensional periodic sound wave can be produced by causing the piston to move in simple harmonic motion.

The darker parts of the areas in the figures represent areas where the gas is compressed. The compressed region is called a **compression.**

When the piston is pulled back, the gas in front of it expands. The low-pressure regions are called **rarefactions.**

Both regions move at the speed of sound in the medium.

The distance between two successive compressions (or rarefactions) is the wavelength.

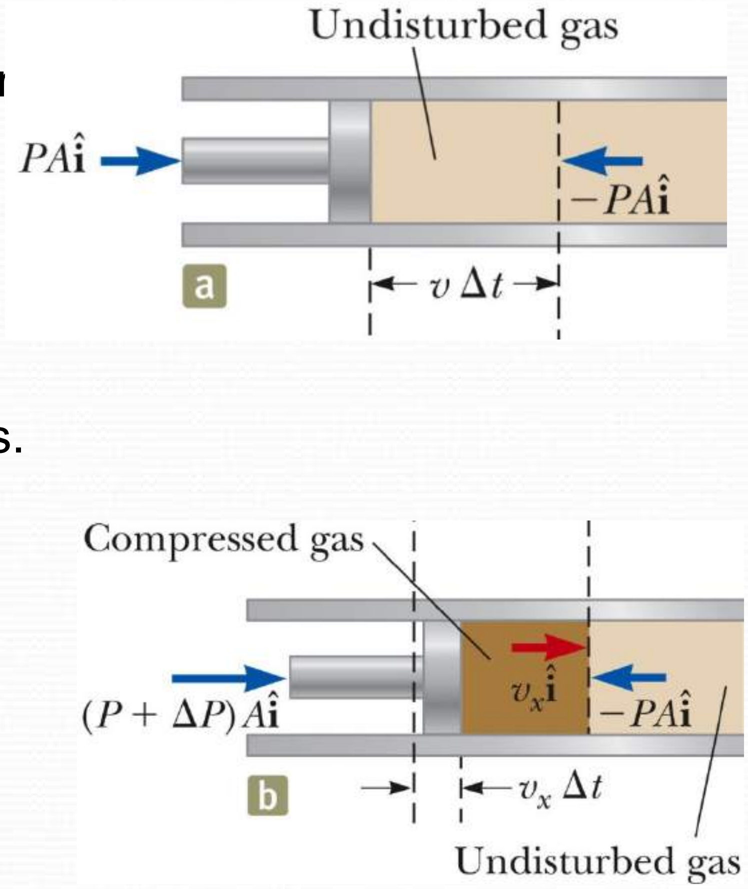


Speed of Sound in a Gas

Consider an element of the gas between the piston and the dashed line.

Initially, this element is in equilibrium under the influence of forces of equal magnitude.

- There is a force from the piston on left.
- There is another force from the rest of the gas.
- These forces have equal magnitudes of *PA.*
  - P is the pressure of the gas.
  - A is the cross-sectional area of the tube.



The change in pressure can be related to the volume change and the bulk modulus:

$$\Delta P = -B\frac{\Delta V}{V} = B\frac{v_x}{v}$$

Speed of Sound in a Gas, cont.

The speed of sound in a gas is

$$v = \sqrt{\frac{B}{\rho}}$$

- The bulk modulus of the material is B.
- The density of the material is ρ.

Example Find the speed of sound in water, which has a bulk modulus of 2.1 & 10_9 N/m_2 at a temperature of 0° C and a density of 1.00 & 10_3 kg/m_3.

Solution

$$v_{\text{water}} = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.1 \times 10^9 \text{ N/m}^2}{1.00 \times 10^3 \text{ kg/m}^3}} = \boxed{1.4 \text{ km/s}}$$

Speed of Sound Waves, General

The speed of sound waves in a medium depends on the compressibility and the density of the medium.

The speed of *all mechanical waves* follows a general form:

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

For a solid rod, the speed of sound depends on Young's modulus and the density of the material.

Speed of Sound in Air

The speed of sound also depends on the temperature of the medium.

- This is particularly important with gases.

For air, the relationship between the speed and temperature is

$$v = (331\ \text{m/s})\sqrt{1 + \frac{T_C}{273}}$$

- The 331 m/s is the speed at 0^{o} C.
- T_C is the air temperature in Celsius.

Speed of Sound in Gases, Example Values

TABLE 17.1 *Speed of Sound in Various Media*

Medium	v (m/s)	Medium	v (m/s)	Medium	v (m/s)
Gases		**Liquids at 25°C**		**Solids**[a]	
Hydrogen (0°C)	1 286	Glycerol	1 904	Pyrex glass	5 640
Helium (0°C)	972	Seawater	1 533	Iron	5 950
Air (20°C)	343	Water	1 493	Aluminum	6 420
Air (0°C)	331	Mercury	1 450	Brass	4 700
Oxygen (0°C)	317	Kerosene	1 324	Copper	5 010
		Methyl alcohol	1 143	Gold	3 240
		Carbon tetrachloride	926	Lucite	2 680
				Lead	1 960
				Rubber	1 600

[a]Values given are for propagation of longitudinal waves in bulk media. Speeds for longitudinal waves in thin rods are smaller, and speeds of transverse waves in bulk are smaller yet.

A Point Source

A **point source** will emit sound waves equally in all directions. This can result in a **spherical wave.**

This can be represented as a series of circular arcs concentric with the source.

Each surface of constant phase is a **wave front.**

The radial distance between adjacent wave fronts that have the same phase is the wavelength λ of the wave.

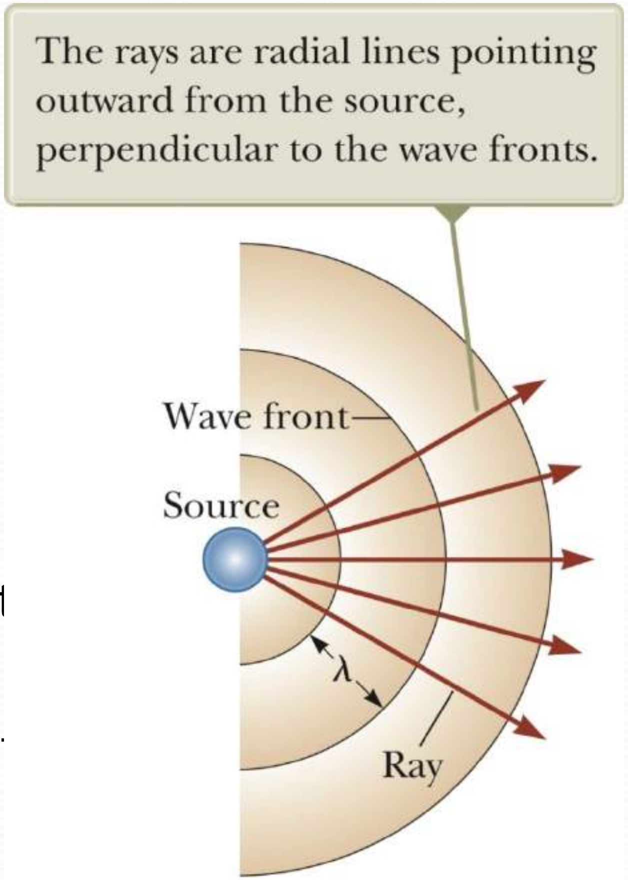
Radial lines pointing outward from the source, representing the direction of propagation, are called **rays.**

The power will be distributed equally through the area of the sphere.

The wave intensity at a distance *r* from the source is

$$I = \frac{(Power)_{avg}}{A} = \frac{(Power)_{avg}}{4\pi r^2}$$

This is an inverse-square law.The intensity decreases in proportion to the square of the distance from the source.



Example: Intensity Variations of a Point Source

A point source emits sound waves with an average power output of 80.0 W.

(A) Find the intensity 3.00 m from the source.

SOLUTION

Because a point source emits energy in the form of spherical waves

$$I = \frac{\mathcal{P}_{\text{avg}}}{4\pi r^2} = \frac{80.0\ \text{W}}{4\pi(3.00\ \text{m})^2} = \boxed{0.707\ \text{W/m}^2}$$

(B) Find the distance at which the intensity of the sound is 1.00 108 W/m2.

$$r = \sqrt{\frac{\mathcal{P}_{\text{avg}}}{4\pi I}} = \sqrt{\frac{80.0\ \text{W}}{4\pi(1.00 \times 10^{-8}\ \text{W/m}^2)}}$$
$$= \boxed{2.52 \times 10^4\ \text{m}}$$

Sound Level

The range of intensities detectible by the human ear is very large.

It is convenient to use a logarithmic scale to determine the intensity level, β.

$$\beta = 10\log\left(\frac{I}{I_o}\right)$$

I_0 is called the **reference intensity.**

- It is taken to be the threshold of hearing. $I_0 = 1.00 \times 10^{-12}$ W/ m^2
- I is the intensity of the sound whose level is to be determined.

β is in decibels (dB)

Threshold of pain: I = 1.00 W/m^2; β = 120 dB

Threshold of hearing: $I_0 = 1.00 \times 10^{-12}$ W/ m^2 corresponds to β = 0 dB

What is the sound level that corresponds to an intensity of 2.0×10^{-7} W/m^2 ?

$$\beta = 10 \log (2.0 \times 10^{-7} \text{ W/m}^2 / 1.0 \times 10^{-12} \text{ W/m}^2)$$

$$= 10 \log 2.0 \times 10^5 = 53 \text{ dB}$$

Rule of thumb: A doubling in the loudness is approximately equivalent to an increase of 10 dB.

Sound Levels

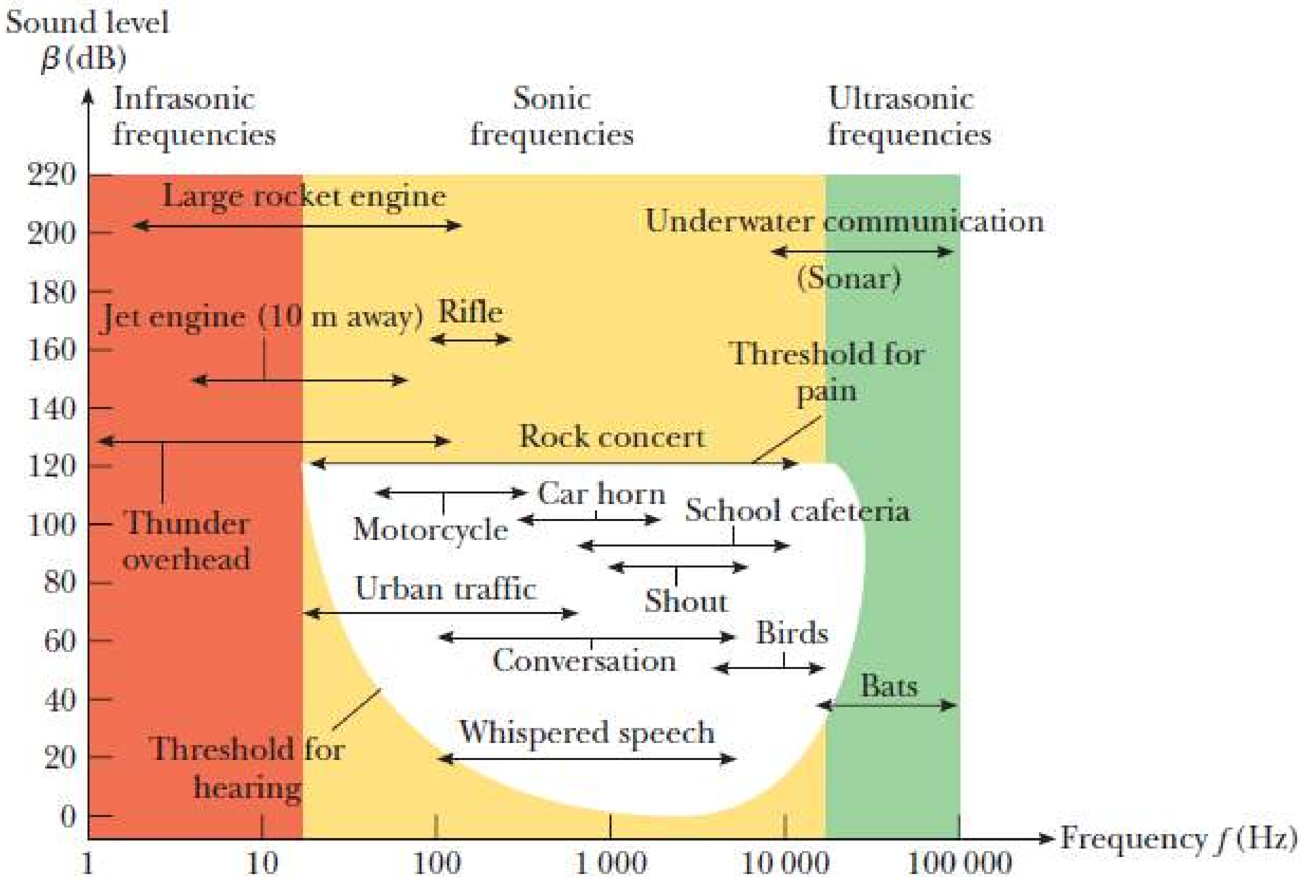


TABLE 17.2

Sound Levels

·ce of Sound	β (dB)
rby jet airplane	150
hammer;	
achine gun	130
n; rock concert	120
way; power	
wn mower	100
y traffic	80
uum cleaner	70
mal conversation	60
quito buzzing	40
sper	30
tling leaves	10
eshold of hearing	0

The Doppler Effect

The **Doppler effect** is the apparent change in frequency (or wavelength) that occurs because of motion of the source or observer of a wave.

- When the relative speed of the source and observer is higher than the speed of the wave, the frequency appears to increase.
- When the relative speed of the source and observer is lower than the speed of the wave, the frequency appears to decrease.

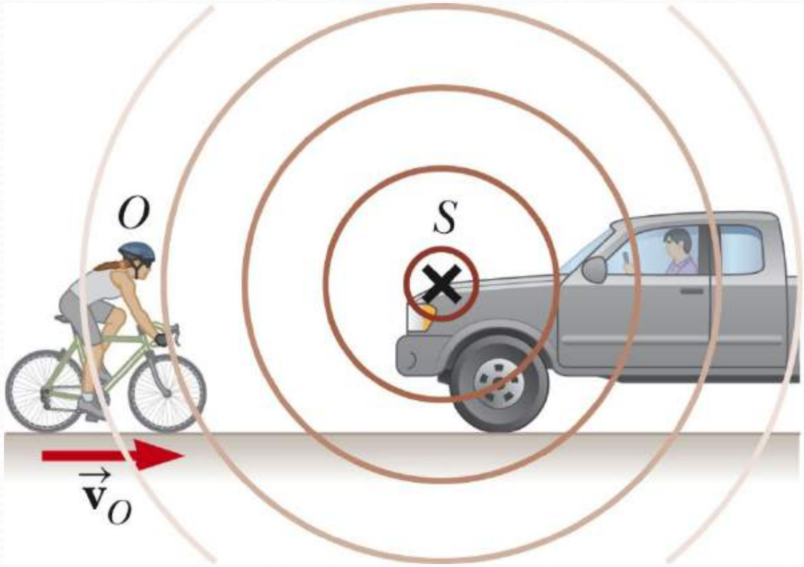
Doppler Effect, Observer Moving

The observer moves with a speed of v_o.

Assume a point source that remains stationary relative to the air.

It is convenient to represent the waves as wave fronts.

- These surfaces are called wave fronts.
- The distance between adjacent wave fronts is the wavelength.



Doppler Effect, Observer Moving, cont

The speed of the sound is v, the frequency is f, and the wavelength is λ.

When the observer moves toward the source, the speed of the waves relative to the observer is $v' = v + v_o$.

- **The wavelength is unchanged.**

The frequency heard by the observer, f', appears higher when the observer approaches the source.

$$f' = \left(\frac{v + v_o}{v}\right) f$$

The frequency heard by the observer, f', appears lower when the observer moves away from the source.

$$f' = \left(\frac{v - v_o}{v}\right) f$$

Doppler Effect, Source Moving

Consider the source being in motion while the observer is at rest.

As the source moves toward the observer, the wavelength appears shorter.

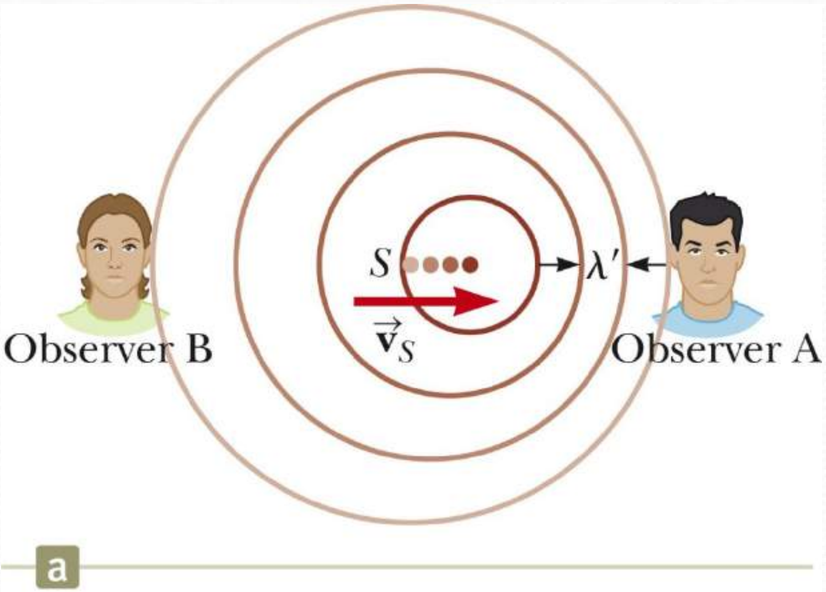
As the source moves away, the wavelength appears longer.

When the source is moving toward the observer, the apparent frequency is higher.

$$f' = \left(\frac{v}{v - v_s}\right) f$$

When the source is moving away from the observer, the apparent frequency is lower.

$$f' = \left(\frac{v}{v + v_s}\right) f$$



Doppler Effect, General

Combining the motions of the observer and the source

$$f' = \left(\frac{v + v_o}{v - v_s}\right) f$$

The signs depend on the direction of the velocity.

- A positive value is used for motion of the observer or the source *toward* the other.
- A negative sign is used for motion of one *away from* the other.

Convenient rule for signs.

- The word “toward” is associated with an increase in the observed frequency.
- The words “away from” are associated with a decrease in the observed frequency.

The Doppler effect is common to all waves.

Doppler Effect, Submarine Example

Sub A (source) travels at 8.00 m/s emitting at a frequency of 1400 Hz.

The speed of sound in the water is 1533 m/s.

Sub B (observer) travels at 9.00 m/s.

What is the apparent frequency heard by the observer as the subs approach each other? Then as they recede from each other?

pproaching each other:

$$f' = \left(\frac{v + v_o}{v - v_s}\right) f = \left(\frac{1533\ \text{m/s} + (+9.00\ \text{m/s})}{1533\ \text{m/s} - (+8.00\ \text{m/s})}\right)(1400\,Hz)$$

$$= 1416\,Hz$$

Receding from each other:

$$f' = \left(\frac{v + v_o}{v - v_s}\right) f = \left(\frac{1533\ \text{m/s} + (-9.00\ \text{m/s})}{1533\ \text{m/s} - (-8.00\ \text{m/s})}\right)(1400\,Hz)$$

$$= 1385\,Hz$$

Shock Waves and Mach Number

The speed of the source can *exceed* the speed of the wave.

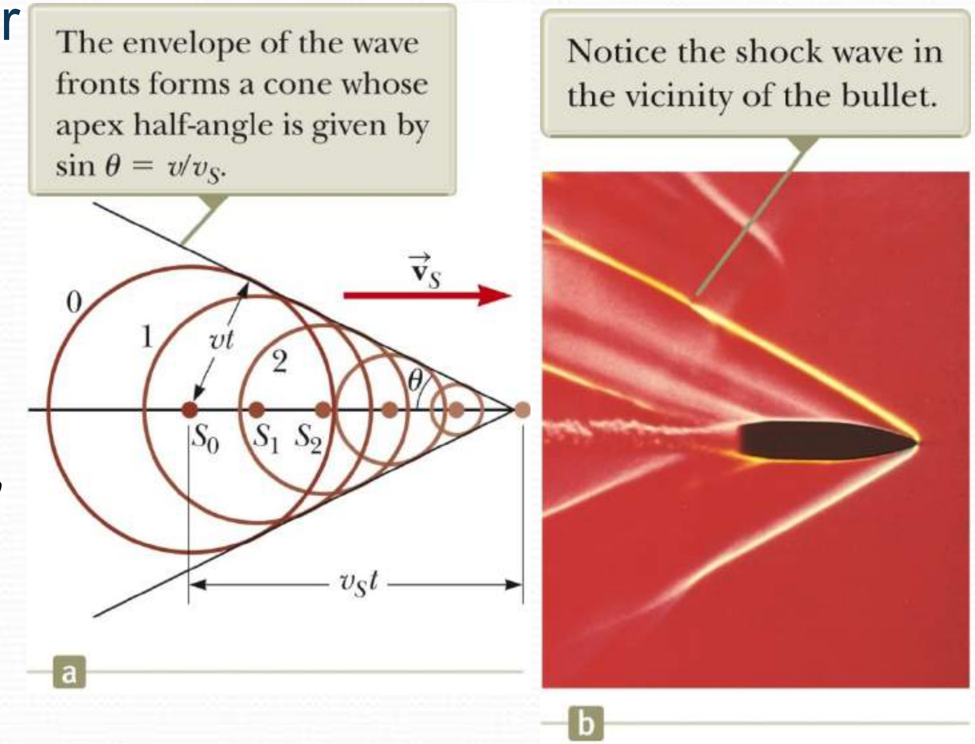
The envelope of these wave fronts is a cone whose apex half-angle is given by sin $\theta = v/v_{S.}$

- This is called the *Mach angle.*

The ratio v_s / v is referred to as the *Mach number* .

The relationship between the Mach angle and the Mach number is

$$\sin\theta = \frac{vt}{v_s t} = \frac{v}{v_s}$$



The conical wave front produced when $v_s > v$ is known as a shock wave.

- This is a supersonic speed.

The shock wave carries a great deal of energy concentrated on the surface of the cone. There are correspondingly great pressure variations.

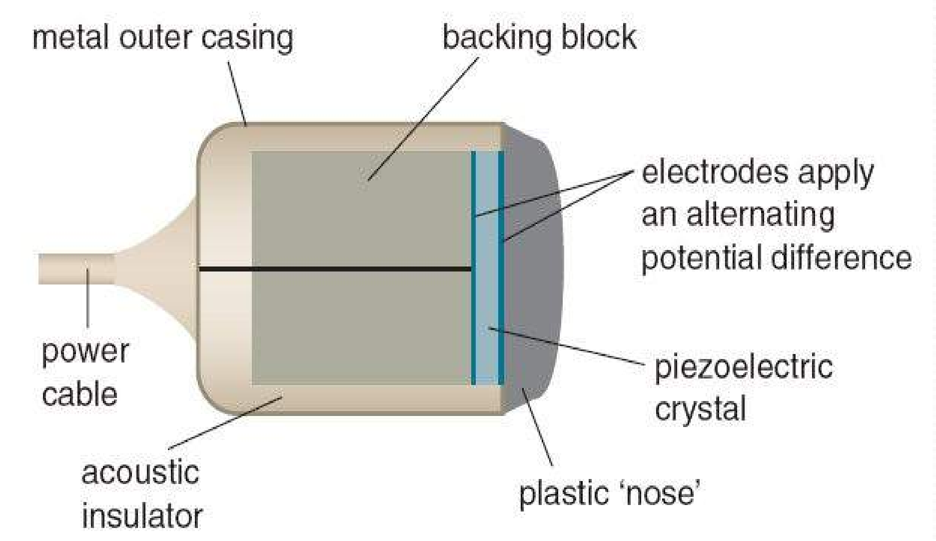
What is Ultrasound?

Ultrasound is defined as any sound wave above 20000Hz. Sound waves of this frequency are above the human audible range and therefore cannot be heard by humans. All sound waves, including ultrasound are longitudinal waves. Medical ultrasounds are usually of the order of MEGAHERTZ (1-15MHz). Ultrasound as all sound waves are caused by vibrations and therefore cause no ionisation and are safe to use on pregnant women. Ultrasound is also able to distinguish between muscle and blood and show blood movement.

When an ultrasound wave meets a boundary between two different materials some of it is refracted and some is reflected. The reflected wave is detected by the ultrasound scanner and forms the image.

producing a sound wave

Ultrasound waves are produced by a transducer. A transducer is a device that takes power from one source and converts into another form ,i.e electricity into sound waves. The sound waves begin with the mechanical movement (oscillations) of a crystal that has been excited by electrical pulses.



Ultrasound Equipment

Screen/Display

Transducer pulse controls

Computer

Various Transducers

Portable

General Physics

for Science and Engineering Faculties

Hasan Maridi
https://www.hasanmaridi.com

Chapter 8 - Light and Optics

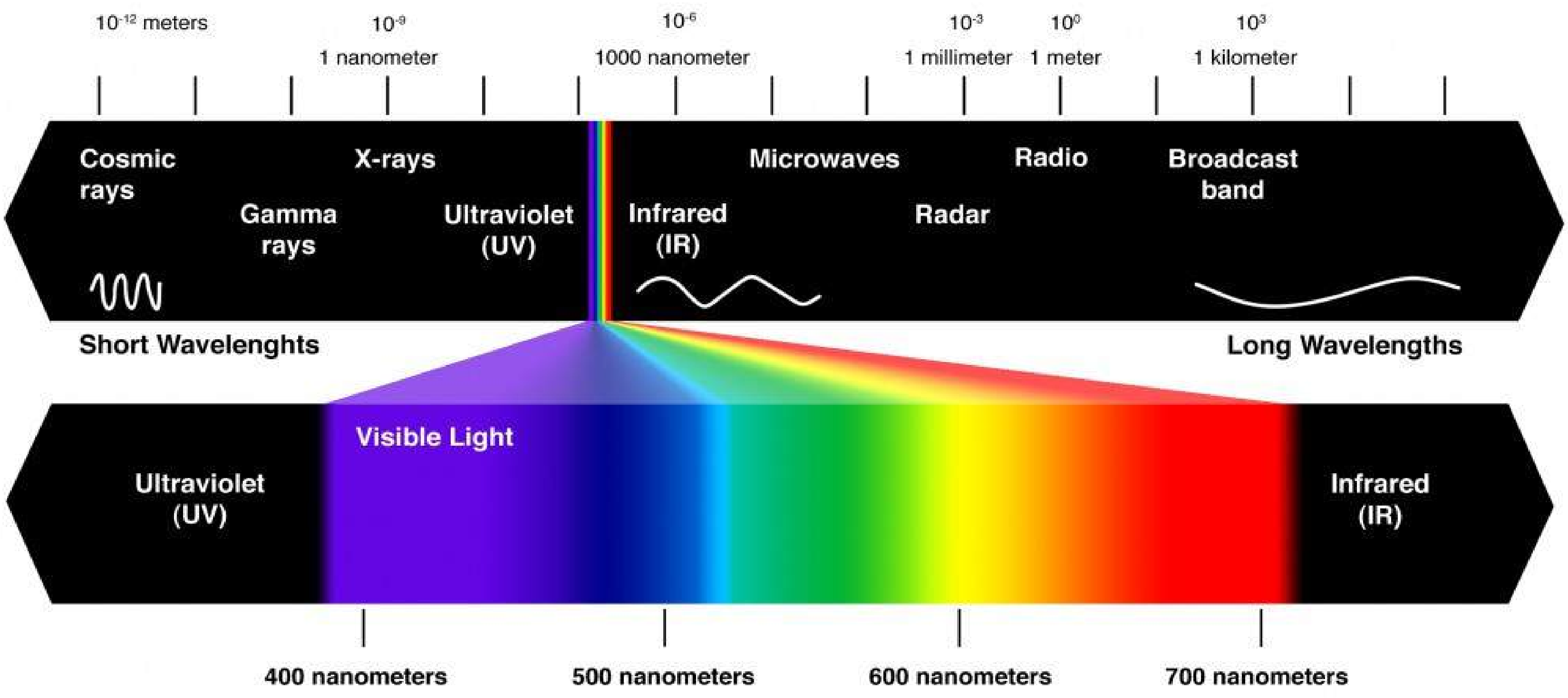
Introduction to Light

Light is a form of electromagnetic radiation.

Speed of light = 3×10^8 m/s

Light represents energy transfer from the source to the observer.

Spectrum of light



The Nature of Light

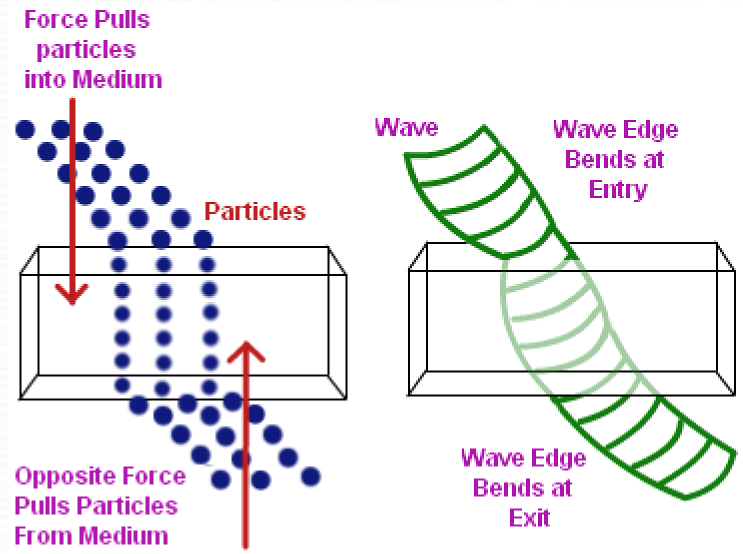
Before the beginning of the nineteenth century, light was considered to be a stream of particles.

During the nineteenth and 20th century, other

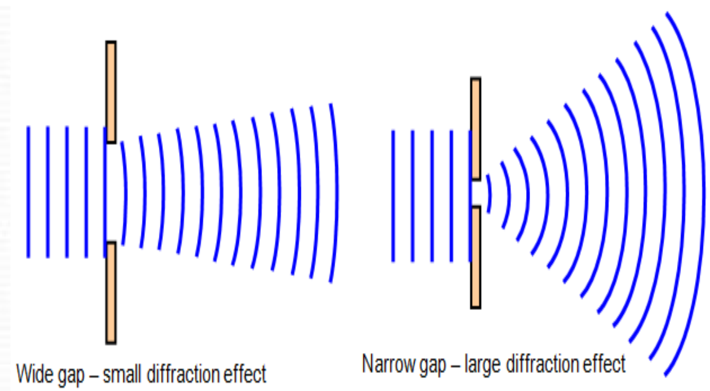
In view of other developments in the 20th century, light must be regarded as having a dual nature.

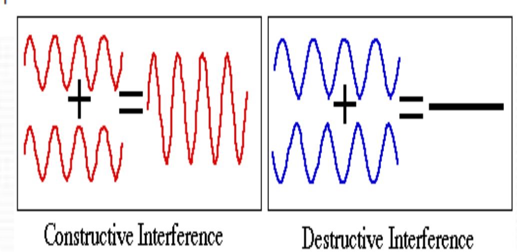
- Light behaves both as a wave and as a particle. As a wave it produces interference and diffraction, which are of minor importance in medicine. As a particle it can be absorbed by a single molecule. When a light photon is absorbed its energy is used in a various ways. It can cause an electrical change.

Ray optics (sometimes called *geometric* optics) involves the study of the propagation of light. It uses the assumption that light travels in a straight-line path in a uniform medium and changes its direction when it meets the surface of a different medium



Refraction of Particles and Wave





Reflection of Light

A ray of light, the *incident ray*, travels in a medium.

When it encounters a boundary with a second medium, part of the incident ray is reflected back into the first medium.

- There are two types of reflection:

Specular reflection is reflection from a smooth surface.

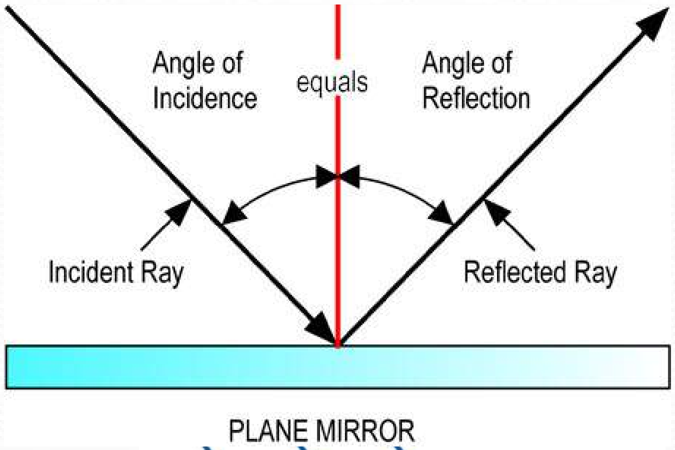
The reflected rays are parallel to each other.

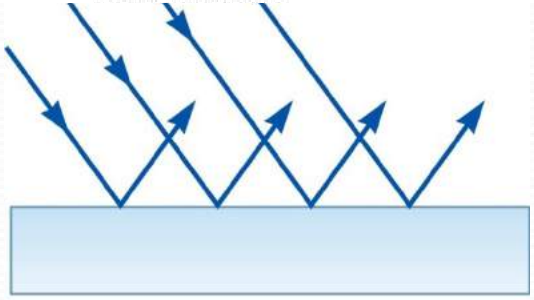
All reflection in this text is assumed to be specular.

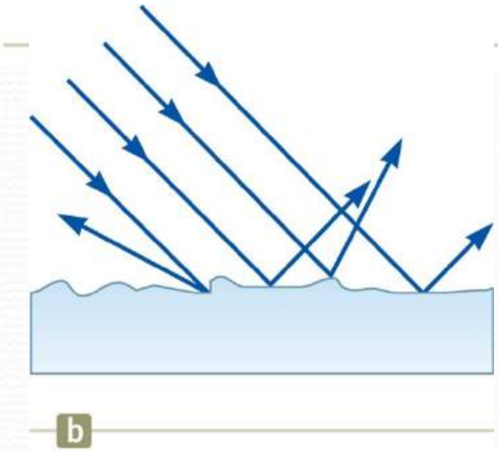
Diffuse reflection is reflection from a rough surface.

The reflected rays travel in a variety of directions.

A surface behaves as a smooth surface as long as the surface variations are much smaller than the wavelength of the light.







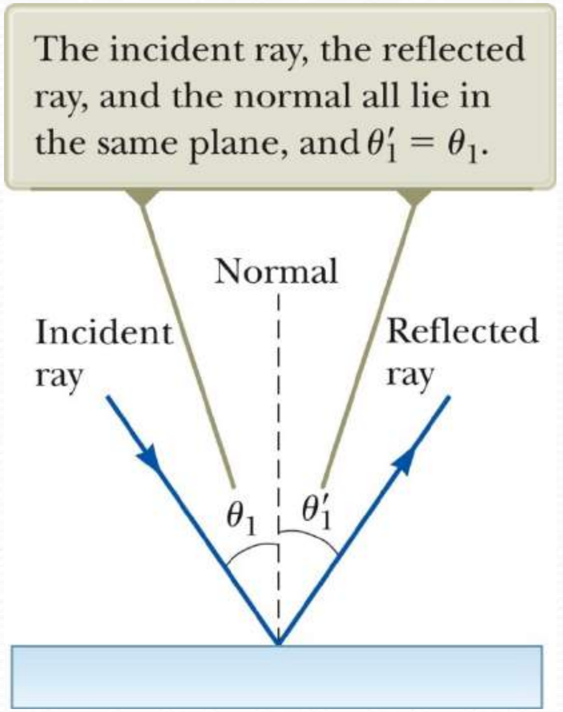
Law of Reflection

The *normal* is a line perpendicular to the surface.

The angle of reflection is equal to the angle of incidence.

$\theta_1' = \theta_1$ This relationship is called the Law of Reflection.

- The incident ray, the reflected ray and the normal are all in the same plane.



Multiple Reflections

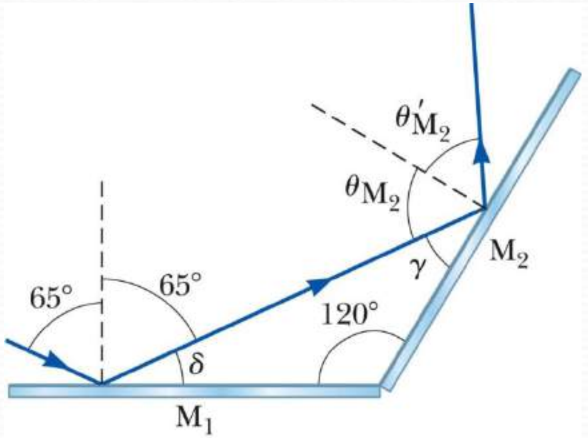
The incident ray strikes the first mirror. The reflected ray is directed toward the second mirror. There is a second reflection from the second mirror.

Retroreflection

Assume the angle between two mirrors is 90º .The reflected beam returns to the source parallel to its original path.

This phenomenon is called *retroreflection. It iis used in*

- Measuring the distance to the Moon
- Automobile taillights and Traffic signs



Refraction of Light

When a ray of light traveling through a transparent medium encounters a boundary leading into another transparent medium, part of the energy is reflected and part enters the second medium and changes its direction of propagation at the boundary.

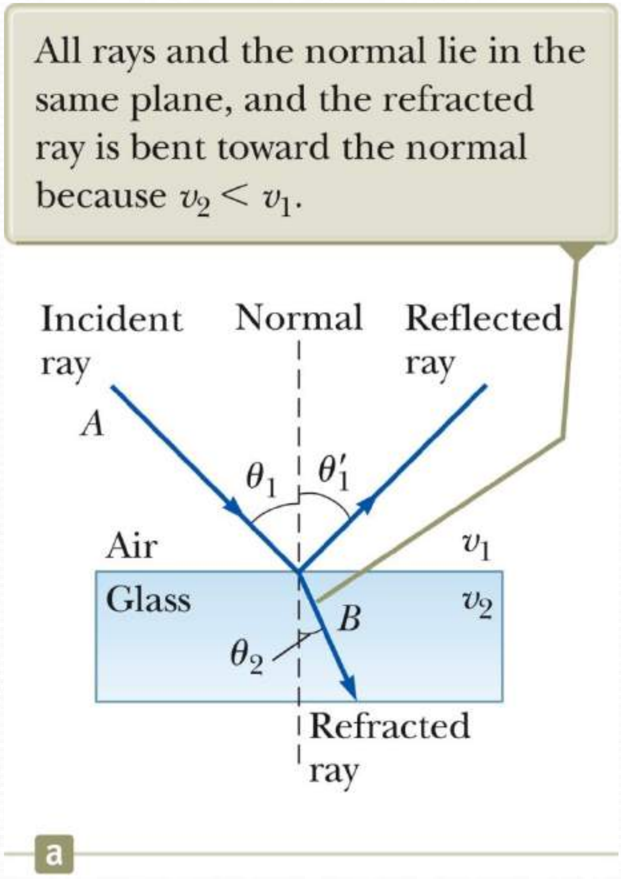
- This bending of the ray is called *refraction.*

The incident ray, the reflected ray, the refracted ray, and the normal all lie on the same plane.

The angle of refraction depends upon the material and the angle of incidence.

$$\frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$$

- v_1 is the speed of the light in the first medium and v_2 is its speed in the second.



Light in a Medium

The light enters from the left.

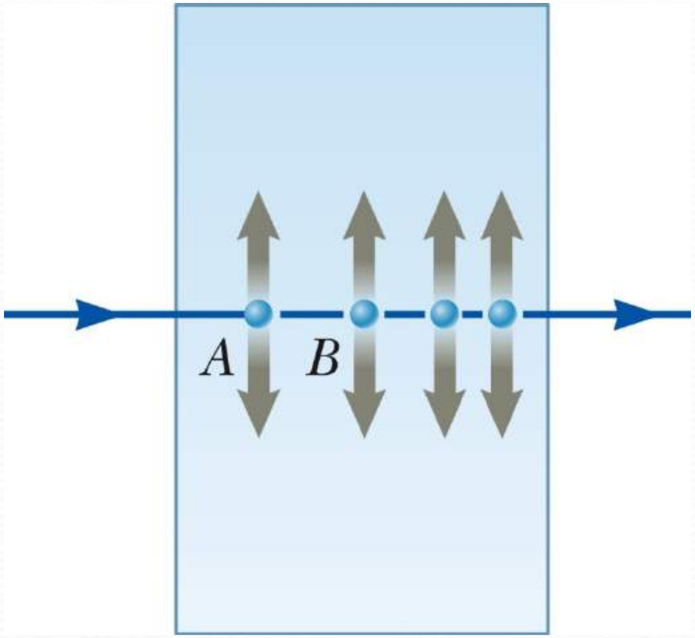
The light may encounter an electron.

The electron may absorb the light, oscillate, and reradiate the light.

The absorption and radiation cause the average speed of the light moving through the material to decrease.

When light is absorbed, its energy generally appears as heat. This property is the basis for the use in medicine.

Sometime when a light photon is absorbed ,a lower energy light photon is emitted. This property is known a fluorescence.



The Index of Refraction

The speed of light in any material is less than its speed in vacuum.

The **index of refraction**, n, of a medium can be defined as

$$n \equiv \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} \equiv \frac{c}{v}$$

For a vacuum, n = 1

- We assume n = 1 for air also

For other media, n > 1

n is a dimensionless number greater than unity and is not necessarily an integer.

Snell's Law of Refraction

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

- θ_1 is the angle of incidence
- θ_2 is the angle of refraction

The experimental discovery of this relationship is usually credited to Willebrord Snell and is therefore known as **Snell's law of refraction.**

Some Indices of Refraction

Indices of Refraction

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

The Rainbow

A ray of light strikes a drop of water in the atmosphere.

It undergoes both reflection and refraction.

- First refraction at the front of the drop
  - Violet light will deviate the most.
  - Red light will deviate the least.

At the back surface the light is reflected.

It is refracted again as it returns to the front surface and moves into the air.

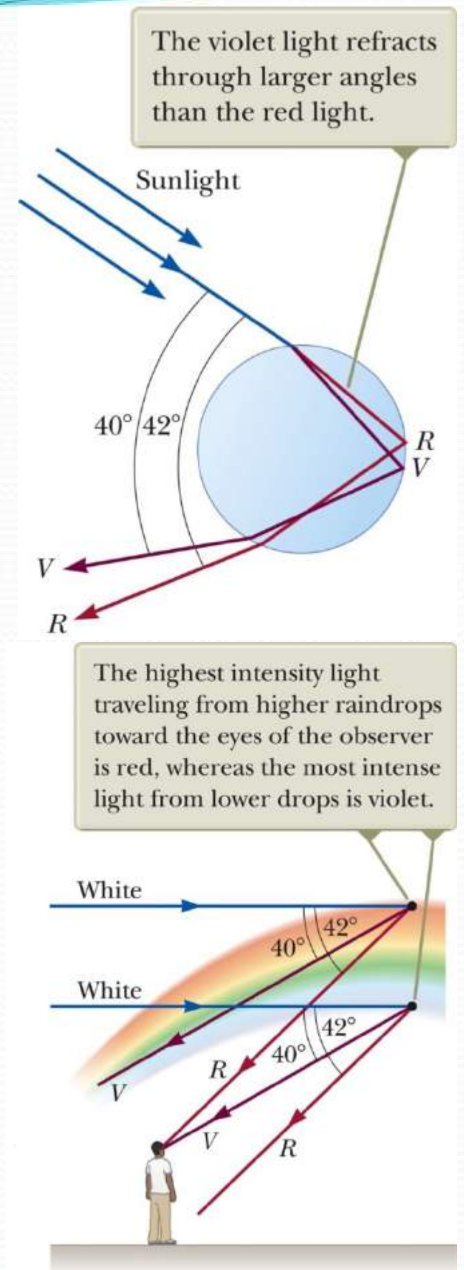
The rays leave the drop at various angles.

- The angle between the white light and the most intense violet ray is 40° .
- The angle between the white light and the most intense red ray is 42°

If a raindrop high in the sky is observed, the red ray is seen.

A drop lower in the sky would direct violet light to the observer.

The other colors of the spectra lie in between the red and the violet..



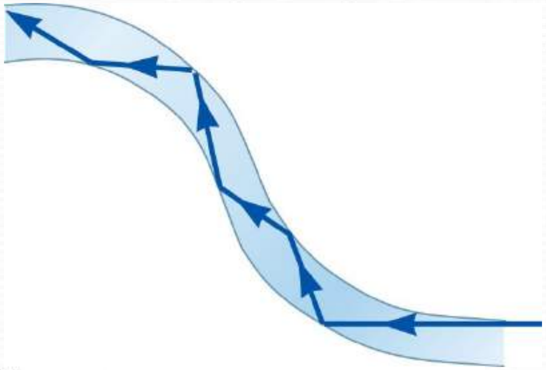
Fiber Optics

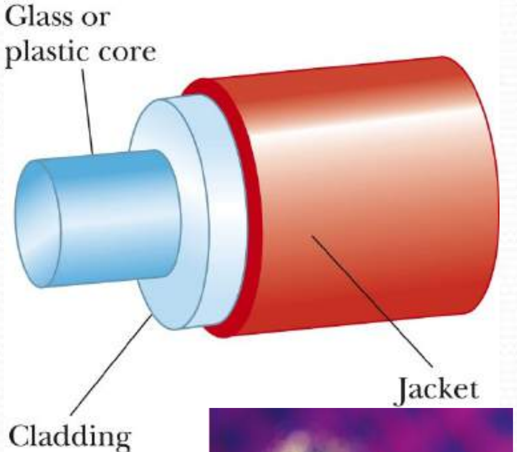
An application of internal reflection. Plastic or glass rods are used to “pipe” light from one place to another.

Applications include:

- Medical examination of internal organs
- Telecommunications

Construction of an Optical Fiber





The transparent core is surrounded by *cladding.*

- The cladding has a lower n than the core.
- This allows the light in the core to experience total internal reflection.

The combination is surrounded by the jacket.

A flexible light pipe is called an **optical fiber.**

A bundle of parallel fibers (shown) can be used to construct an optical transmission line.

Image of Formation

Images can result when light rays encounter surfaces between two media.

Images can be formed either by reflection or refraction due to these surfaces.

Mirrors and lenses can be designed to form images with desired characteristics.

Notation for Mirrors and Lenses

The **object distance** is the distance from the object to the mirror or lens.

- Denoted by p

The **image distance** is the distance from the image to the mirror or lens.

- Denoted by q

The **lateral magnification** of the mirror or lens is the ratio of the image height to the object height.

- Denoted by M

When the object is very far away, then $p \rightarrow \infty$ and the incoming rays are essentially parallel, the image point is called the **focal point.** The distance from the mirror to the focal point is called the **focal length.** Denoted by f

- The focal length is ½ the radius of curvature.

Ray Diagrams

A *ray diagram* can be used to determine the position and size of an image.

They are graphical constructions which reveal the nature of the image.

They can also be used to check the parameters calculated from the mirror and magnification equations.

To draw a ray diagram, you need to know:

- The position of the object
- The locations of the focal point and the center of curvature.

Three rays are drawn. They all start from the same position on the object.

The intersection of any two of the rays at a point locates the image.

The third ray serves as a check of the construction.

Ray 1 is drawn from the top of the object parallel to the principal axis and is reflected through the focal point, *F*.

Ray 2 is drawn from the top of the object through the focal point and is reflected parallel to the principal axis.

Ray 3 is drawn through the center of curvature, C, and is reflected back on itself.

Image Formed by a Thin Lens

A thin lens is one whose thickness is small compared to the radii of curvature. It used in optical instruments: Cameras, Telescopes, Microscopes

Thin Lens Equation

The relationship among the focal length, the object distance and the image distance is the same as for a mirror.

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f}$$

Diopters

Optometrists and ophthalmologists usually prescribe lenses measured in *diopters.* The power *P* of a lens in diopters equals the inverse of the focal length in meters.

- P = 1/f

The **lateral magnification** of the image is

$$M=\frac{h'}{h}=-\frac{q}{p}$$

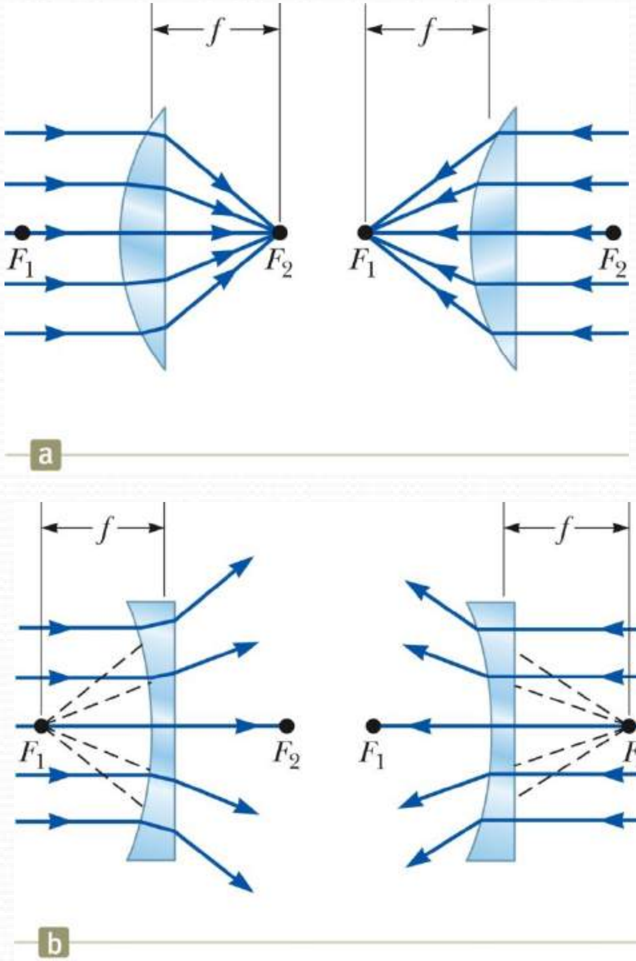
Notes on Focal Length and Focal Point of a Thin Lens

Because light can travel in either direction through a lens, each lens has two focal points. One focal point is for light passing in one direction through the lens and one is for light traveling in the opposite direction.

However, there is only one focal length.

Each focal point is located the same distance

from the lens.



Focal Length of a Converging Lens

The parallel rays pass through the lens and converge at the focal point.

The parallel rays can come from the left or right of the lens.

Focal Length of a Diverging Lens

The parallel rays diverge after passing through the diverging lens.

The focal point is the point where the rays appear to have originated.

Ray Diagrams for Thin Lenses – Converging

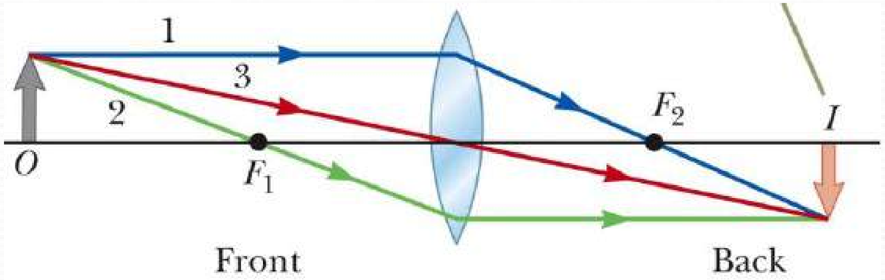
Ray diagrams are convenient for locating the images formed by thin lenses or systems of lenses. For a converging lens, the following three rays are drawn:

- Ray 1 is drawn parallel to the principal axis and then passes through the focal point on the back side of the lens.
- Ray 2 is drawn through the center of the lens and continues in a straight line.
- Ray 3 is drawn through the focal point on the front of the lens (or as if coming from the focal point if $p < f$) and emerges from the lens parallel to the principal axis.

<u>Ray Diagram for Converging Lens, $p > f$</u>

The image is real and inverted.

The image is on the back side of the lens.

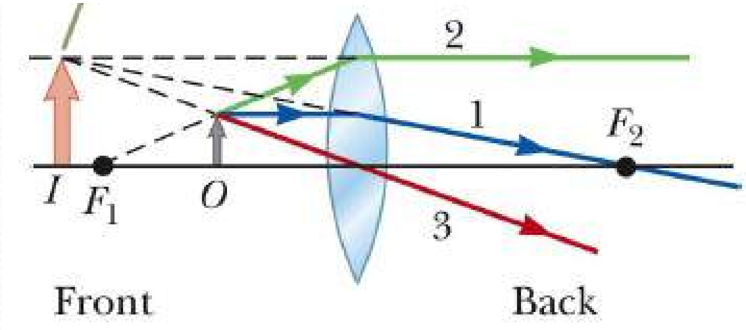


<u>Ray Diagram for Converging Lens, $p < f$</u>

The image is virtual and upright.

The image is larger than the object.

The image is on the front side of the lens.



Ray Diagrams for Thin Lenses – Diverging

For a diverging lens, the following three rays are drawn:

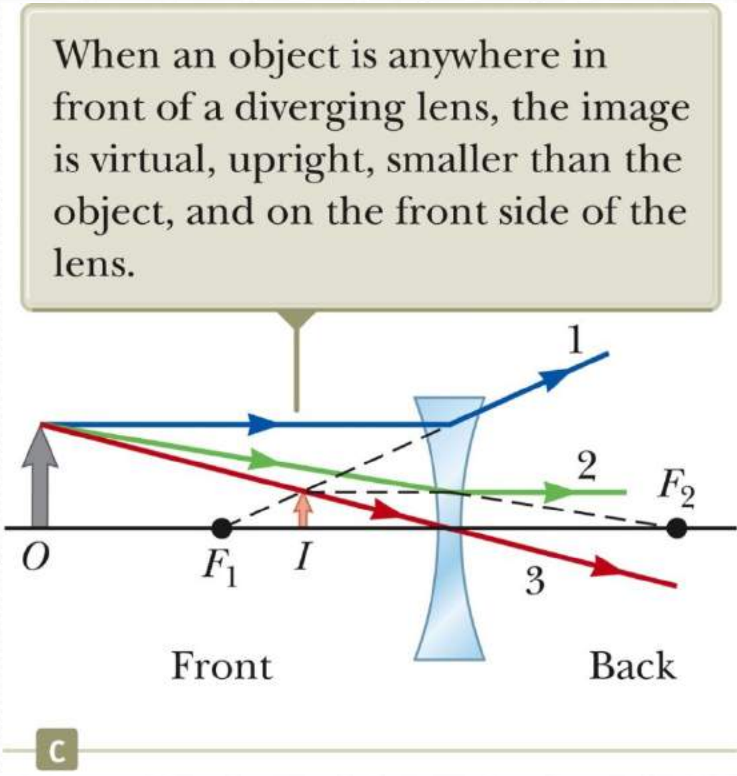
- Ray 1 is drawn parallel to the principal axis and emerges directed away from the focal point on the front side of the lens.
- Ray 2 is drawn through the center of the lens and continues in a straight line.
- Ray 3 is drawn in the direction toward the focal point on the back side of the lens and emerges from the lens parallel to the principal axis.

The image is virtual.

The image is upright.

The image is smaller.

The image is on the front side of the lens.



Combinations of Thin Lenses

The image of the first lens is treated as the object of the second lens.

The image formed by the second lens is the final image of the system.

Then a ray diagram is drawn for the second lens.

The same procedure can be extended to a system of three or more lenses.

The overall magnification is the product of the magnification of the separate lenses.

Two Lenses in Contact

Consider a case of two lenses in contact with each other:

- The lenses have focal lengths of f_1 and f_2.

For the combination of the two lenses

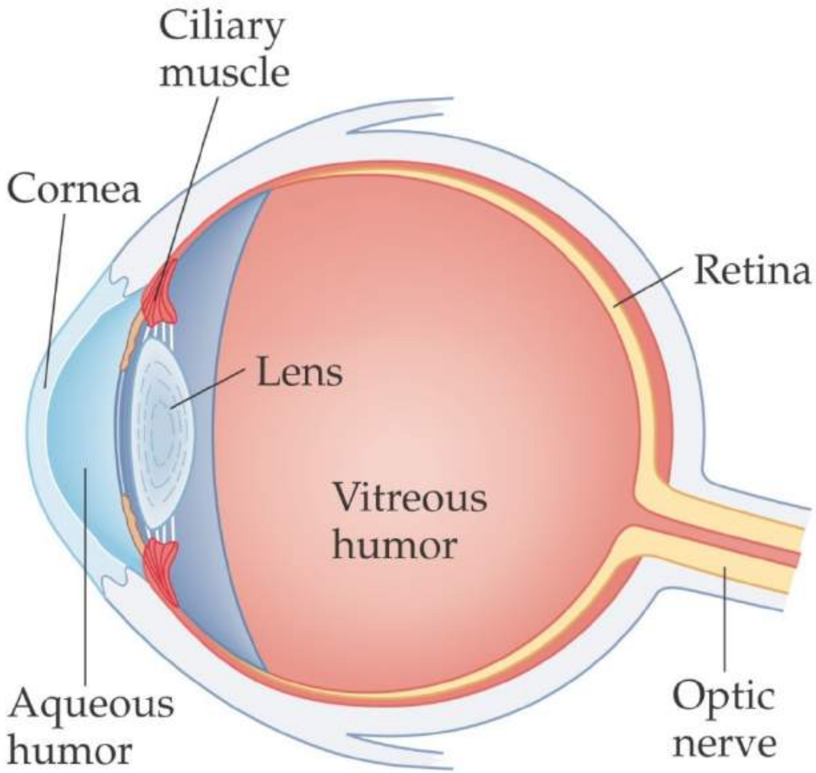
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

Two thin lenses in contact with each other are equivalent to a single thin lens having a focal length given by the above equation.

Eye and vision, The Human Eye

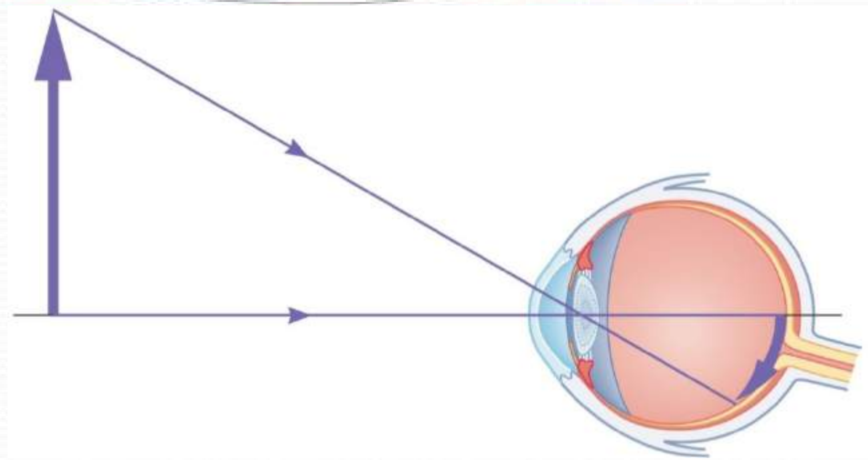
Light passes through the cornea of the human eye and is focused by the lens on the retina. The ciliary muscles change the shape of the lens, so it can focus at different distances. The vitreous and aqueous humors are transparent. Rods and cones on the retina convert the light into electrical impulses, which travel down the optic nerve to the brain.

The cornea focuses by bending (refracting) the light rays. The amount of bending depends on the curvatures of its surfaces and the speed of light in the lens compared with that in the surrounding material.

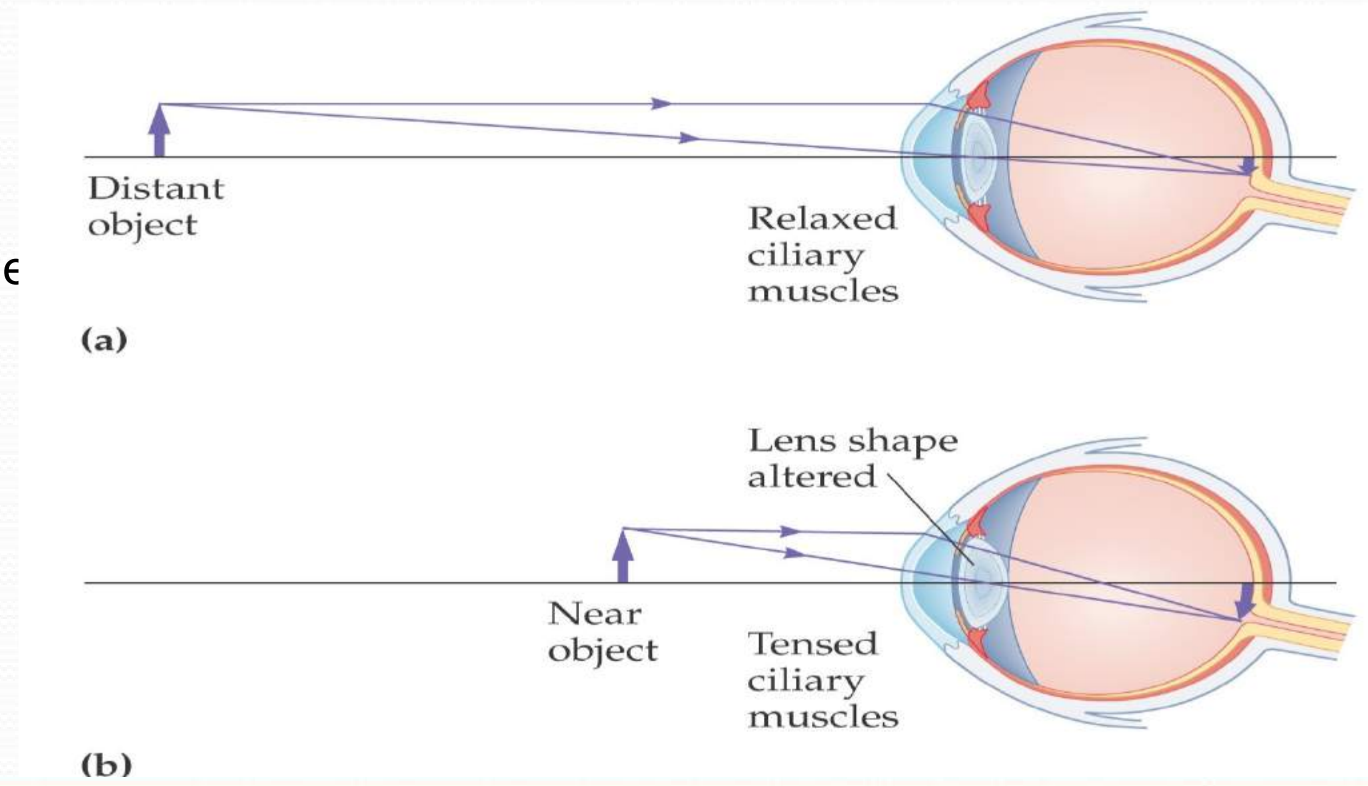


The Human Eye

The eye produces a real, inverted image on the retina. Why don’t things look upside down to us? The brain adjusts the image to appear properly.

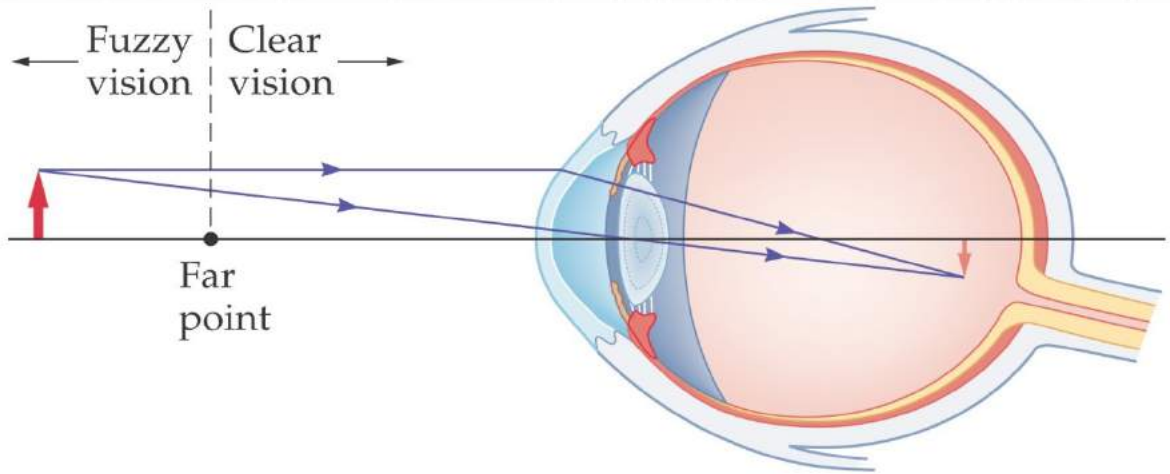


The ciliary muscles adjust the shape of the lens to accommodate near and far vision.

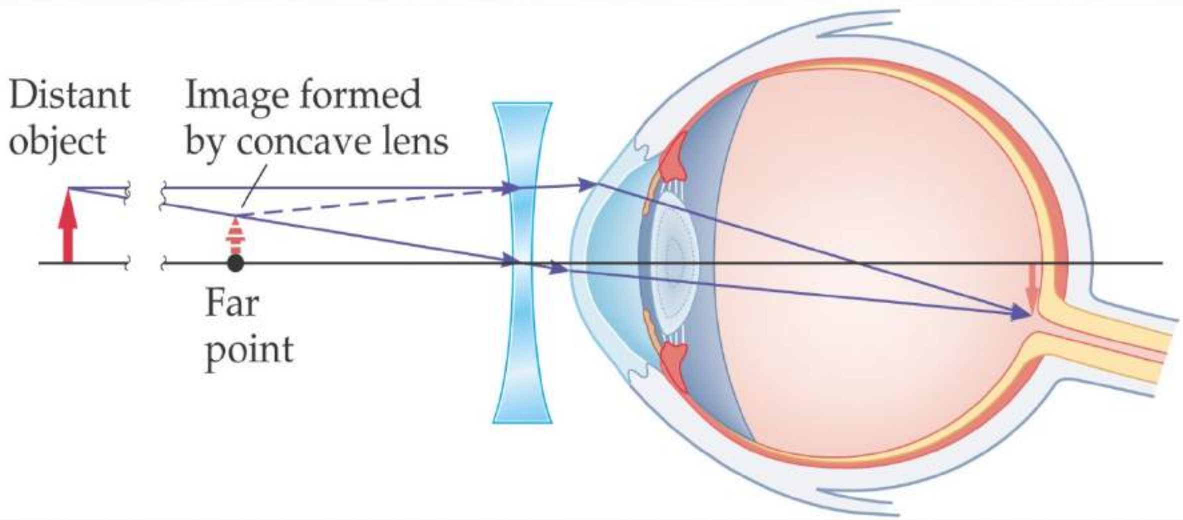


Myopia
Farsightedness

A nearsighted person has a far point that is a finite distance away; objects farther away will appear blurry. This is due to the lens focusing too strongly, so the image is formed in front of the retina.



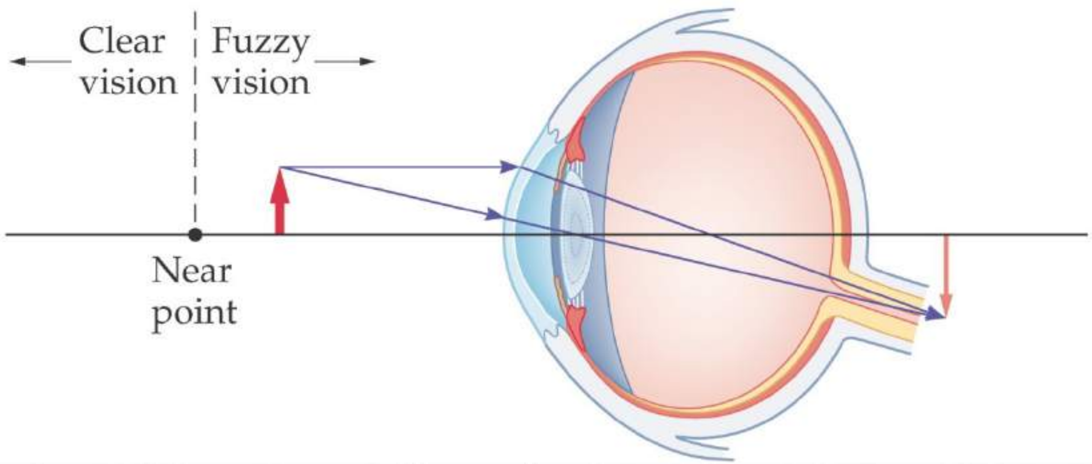
To correct this, a diverging lens is used. Its focal length is such that a distant object forms an image at the far point:



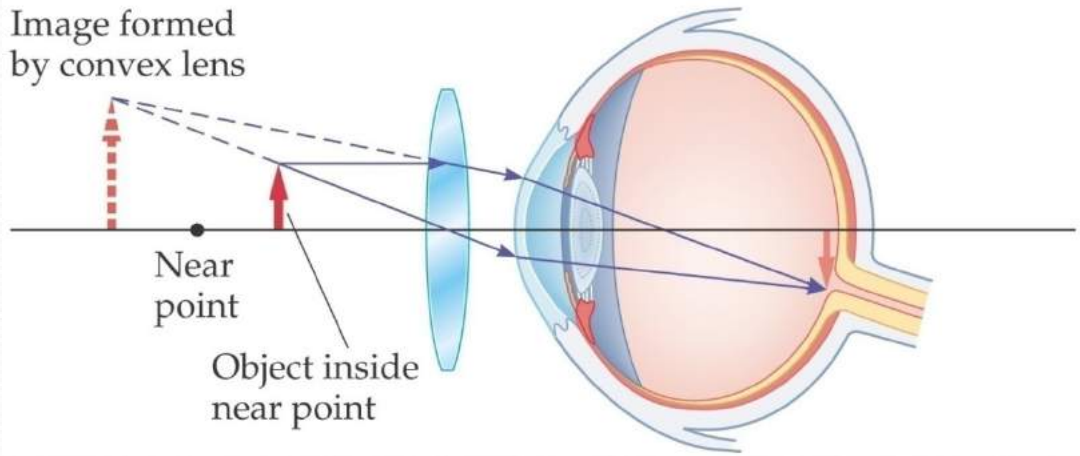
Hyperemia

Nearsightedness

A person who is farsighted can see distant objects clearly, but cannot focus on close objects – the near point is too far away. The lens of the eye is not strong enough, and the image focus is behind the retina.



To correct farsightedness, a converging lens is used to augment the converging power of the eye. The final image is past the near point:



The Camera

The photographic camera is a simple optical instrument.

Proper focusing will result in sharp images.

The camera is focused by varying the distance between the lens and the CCD.

- The lens-to-CCD distance will depend on the object distance and on the focal length of the lens.

The shutter is a mechanical device that is opened for selected time intervals.

- The time interval that the shutter is opened is called the *exposure time.*

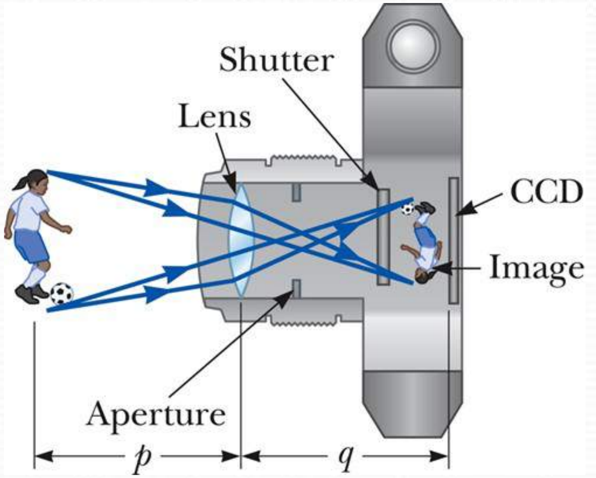
Light intensity is a measure of the rate at which energy is received by the CCD per unit area of the image.

- The intensity of the light reaching the CCD is proportional to the area of the lens.

The brightness of the image formed on the CCD depends on the light intensity.

Components

- Light-tight chamber
- Converging lens
  - Produces a real image
- Light sensitive component behind the lens
  - Where the image is formed
  - Could be a CCD or film

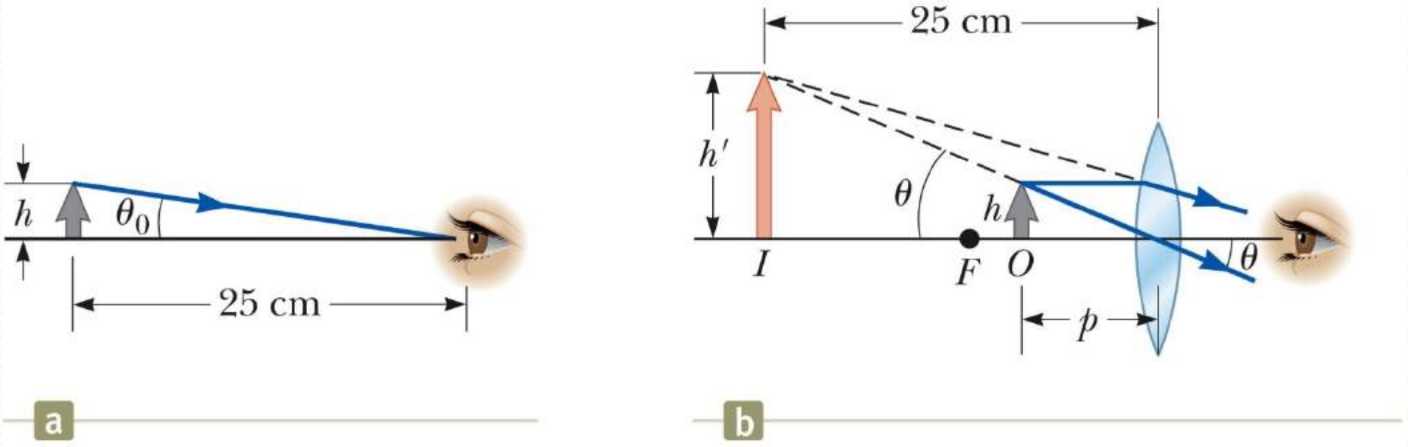


Simple Magnifier

A simple magnifier consists of a single converging lens.

This device is used to increase the apparent size of an object.

The size of an image formed on the retina depends on the angle subtended by the eye.



When an object is placed at the near point, the angle subtended is a maximum.

- The near point is about 25 cm.

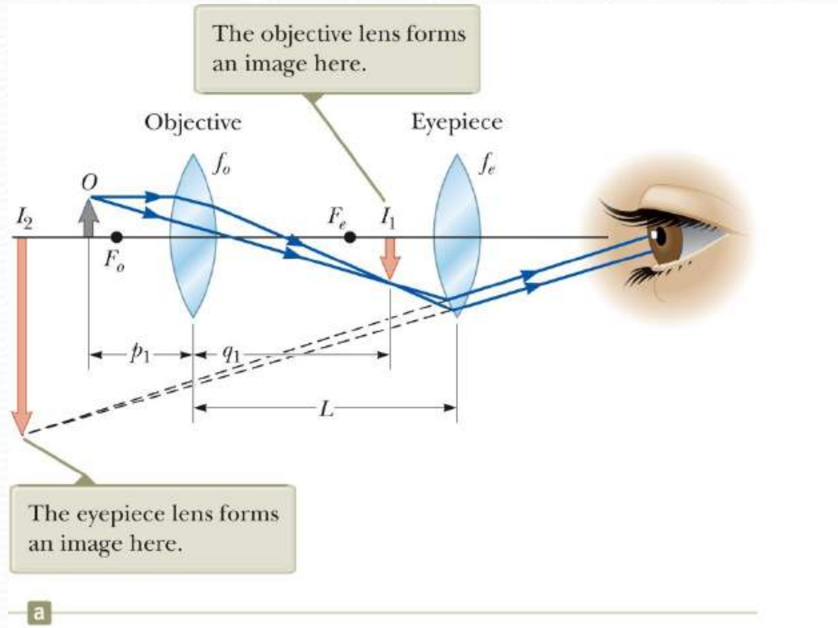
When the object is placed near the focal point of a converging lens, the lens forms a virtual, upright, and enlarged image.

Compound Microscope

A compound microscope consists of two lenses.

- Gives greater magnification than a single lens
- The objective lens has a short focal length,

  $f_o < 1$ cm
- The eyepiece has a focal length, f_e of a few cm.



The lenses are separated by a distance *L.*

- *L* is much greater than either focal length.

The object is placed just outside the focal point of the objective.

- This forms a real, inverted image
- This image is located at or close to the focal point of the eyepiece.

This image acts as the object for the eyepiece.

- The image seen by the eye, I_2, is virtual, inverted and very much enlarged.

General Physics

for Science and Engineering Faculties

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Chapter 9 - Electricity

Electric Charges

There are two kinds of electric charges

- Called positive and negative

Conductors

Electrical conductors are materials in which some of the electrons are free electrons.

- Examples of good conductors include copper, aluminum and silver.

Insulators

Electrical insulators are materials in which all of the electrons are bound to atoms.

- Examples of good insulators include glass, rubber and wood..

Semiconductors

The electrical properties of semiconductors are somewhere between those of insulators and conductors.

Examples of semiconductor materials include silicon and germanium.

- Semiconductors made from these materials are commonly used in making electronic chips.

Point Charge

The term **point charge** refers to a particle of zero size that carries an electric charge.

- The electrical behavior of electrons and protons is well described by modeling them as point charges.

The force is attractive if the charges are of opposite sign.

The force is repulsive if the charges are of like sign.

Quantization of Electric Charges

The electric charge, *q*, is said to be quantized.

The SI unit of charge is the **coulomb** ©.

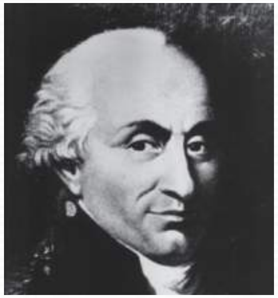
- Electric charge exists as discrete packets.
- $q = \pm Ne$
  - *N* is an integer
  - *e* is the fundamental unit of charge
  - $|e| = 1.6 \times 10^{-19}$ C
  - Electron: $q = -e$
  - Proton: $q = +e$

The electrical force

Charles Coulomb (1736 – 1806 French physicist) measured the magnitudes of electric forces between two small charged spheres.

The electrical force between two point charges is given by Coulomb's Law. Mathematically,

$$F_e = k_e \frac{|q_1||q_2|}{r^2}$$



the **Coulomb constant,** k_e = 8.9876 x 10^9 N·m^2/C^2 = $1/(4\pi e_o)$

- e_o = 8.8542 x 10^{-12} C^2 / N·m^2 is the **permittivity of free space.**

Electric Field

An **electric field** is said to exist in the region of space around a charged object This charged object is the **source charge.**

When another charged object, the **test charge**, enters this electric field, an electric force acts on it.

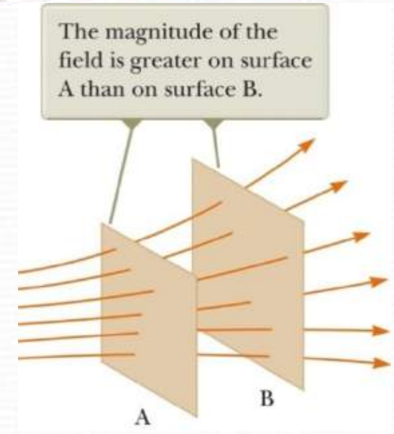
The electric field vector, $\vec{E}$, at a point in space is defined as the electric force acting on a positive test charge, q_o placed at that point divided by the test charge:

The SI units of $\vec{E}$ are N/C.

$$\vec{E} = \frac{\vec{F}}{q_o} = k_e \frac{q}{r^2}\hat{\mathbf{r}}$$

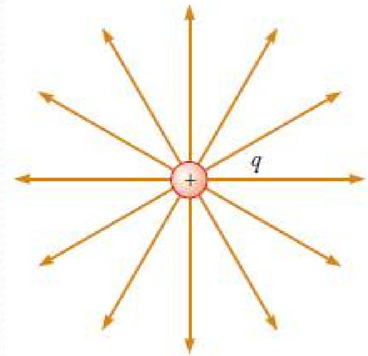
Electric Field Lines

The number of lines per unit area through a surface perpendicular to the lines is proportional to the magnitude of the electric field in that region.



For a positive point charge:

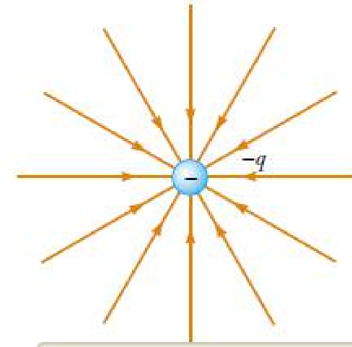
The field lines are directed away from the source charge in all directions.



(a)

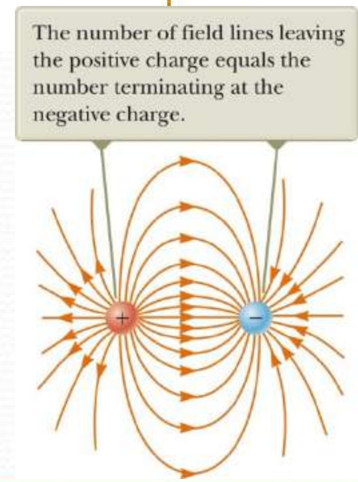
For a negative point charge:

The field lines are directed toward the source charge in all directions.



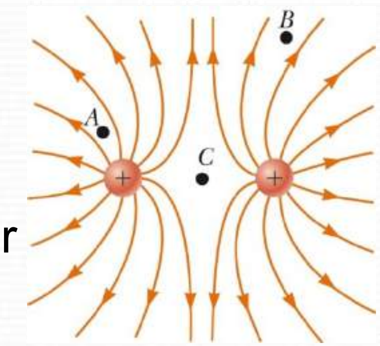
Electric Field Lines – Dipole

The charges are equal and opposite. The number of field lines leaving the positive charge equals the number of lines terminating on the negative charge.



Electric Field Lines – Like Charges

The charges are equal and positive.The same number of lines leave each charge since they are equal in magnitude.



Electrical Potential Energy

When a test charge is placed in an electric field, it experiences a force. $\vec{F}_e = q_o\vec{E}$

For a finite displacement of the charge from A to B, the work is done by the field or **the change in potential energy** is $\Delta U = U_B - U_A = -q_o\int_A^B \vec{E}\cdot d\vec{s}$

Electric Potential

The potential energy per unit charge, U/q_o, is the **electric potential.**

The electric potential is $V = \frac{U}{q_o}$

The potential is a scalar quantity. Because energy is a scalar.

Units of the electric potential is volt. **1 V ≡ 1 J/C**. In addition, 1 N/C = 1 V/m

As a charged particle moves in an electric field,

The equations for electric potential between two points A and B can be simplified if the electric field is uniform:

$$V_B - V_A = \Delta V = -\int_A^B \vec{E}\cdot d\vec{s} = -E\int_A^B d\mathbf{s} = -Ed$$

Then the potential due to a point charge at some point *r* is: $V = k_e\frac{q}{r}$

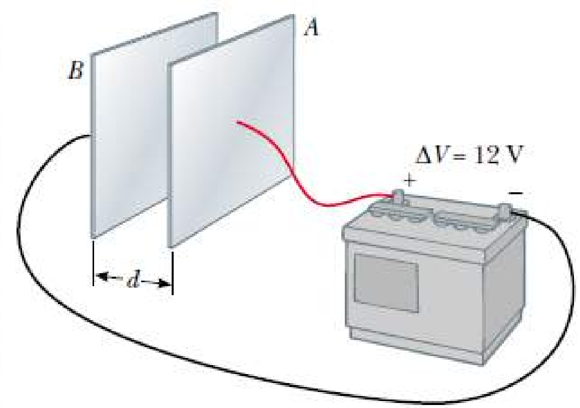
The electric potential due to several point charges is: $V = k_e\sum_i \frac{q_i}{r_i}$

Voltage: Electric potential is also called *voltage which is* applied to a device or across a device is the same as the potential difference across the device.

Electron-Volts: Another unit of energy that is commonly used in atomic and nuclear physics is the electron-volt. One ***electron-volt*** is defined as the energy a charge-field system gains or loses when a charge of magnitude *e* (an electron or a proton) is moved through a potential difference of 1 volt. 1 eV = 1.60×10^{-19} J

Example: A battery produces a specified potential difference ΔV between conductors attached to the battery terminals. A 12-V battery is connected between two parallel plates, as shown in Figure. The separation between the plates is d = 0.30 cm, and we assume the electric field between the plates to be uniform. Find the magnitude of the electric field between the plates.

Solution The potential difference between the plates must equal the potential difference between the battery terminals, because all points on a conductor in equilibrium are at the same electric potential. Therefore, the magnitude of the electric field between the plates is



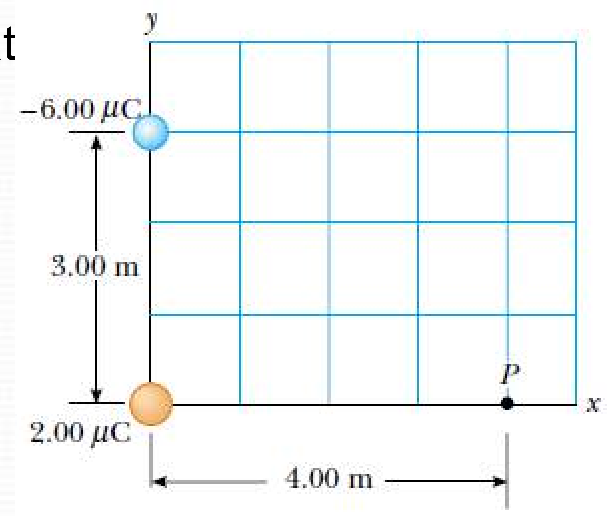
$$E = \frac{|V_B - V_A|}{d} = \frac{12\ \text{V}}{0.30 \times 10^{-2}\ \text{m}} = \boxed{4.0 \times 10^{3}\ \text{V/m}}$$

This configuration of plates is called a *parallel-plate capacitor*

Example: **The Electric Potential Due to Two Point Charges**

A charge $q_1 = 2.00\ \mu C$ is located at the origin, and a charge $q_2 = 6.00\ \mu C$ is located at (0, 3.00) m, as shown in Figure

(A) Find the total electric potential due to these charges at the point *P*, whose coordinates are (4.00, 0) m.



Solution

$$V_P = k_e\left(\frac{q_1}{r_1} + \frac{q_2}{r_2}\right)$$

$$V_P = (8.99 \times 10^9\ \mathrm{N \cdot m^2/C^2})$$
$$\times\left(\frac{2.00 \times 10^{-6}\ \mathrm{C}}{4.00\ \mathrm{m}} - \frac{6.00 \times 10^{-6}\ \mathrm{C}}{5.00\ \mathrm{m}}\right)$$
$$= -6.29 \times 10^3\ \mathrm{V}$$

(B) Find the electric force between the two charges

$$F_e = k_e \frac{|q_1|\,|q_2|}{r^2}$$

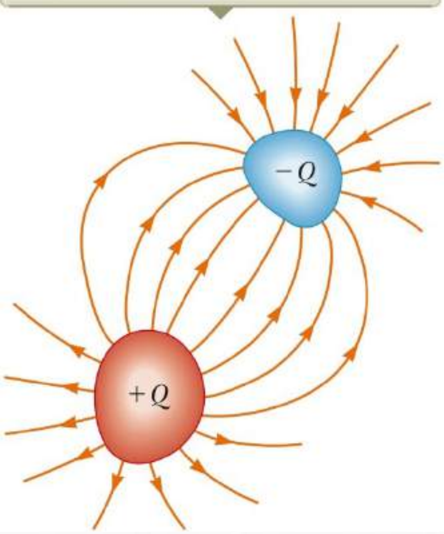
Capacitors

Capacitors are devices that store electric charge.

Examples of where capacitors are used include:

- radio receivers
- filters in power supplies
- to eliminate sparking in automobile ignition systems
- energy-storing devices in electronic flashes

When the capacitor is charged, the conductors carry charges of equal magnitude and opposite sign.



Makeup of a Capacitor

A capacitor consists of two conductors.

- These conductors are called plates.
- When the conductor is charged, the plates carry charges of equal magnitude and opposite directions.

A potential difference exists between the plates due to the charge.

Definition of Capacitance

The **capacitance**, C, of a capacitor is defined as the ratio of the magnitude of the charge on either conductor to the potential difference between the conductors.

The capacitance of a given capacitor is constant.

$$C \equiv \frac{Q}{\Delta V}$$

The SI unit of capacitance is the **farad** (F).

The farad is a large unit, typically you will see microfarads (mF) and picofarads (pF).

For a parallel capacitor:

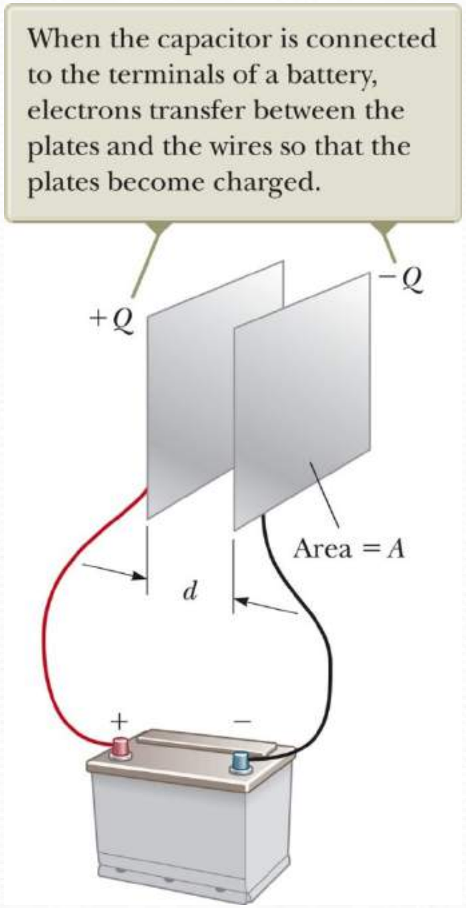
$$C = \frac{Q}{\Delta V} = \frac{Q}{Ed} = \frac{Q}{Qd/\varepsilon_o A} = \frac{\varepsilon_o A}{d}$$

- A is the area of each plate, the area of each plate is equal
- Q is the charge on each plate, equal with opposite signs

A dielectric is a nonconducting material that, when placed between the plates of a capacitor, increases the capacitance and Increase the maximum operating voltage. Dielectrics include rubber, glass, and waxed paper.

For a parallel-plate capacitor, $C = \kappa\,(\varepsilon_o A)\,/\,d$

κ is the dielectric constant of the material.



Capacitance – Parallel Plates

Each plate is connected to a terminal of the battery (source of potential difference).

The charge density on the plates is $\sigma = Q/A$.

- A is the area of each plate, the area of each plate is equal
- Q is the charge on each plate, equal with opposite signs

The electric field is uniform between the plates and zero elsewhere. $E = \dfrac{\sigma}{\epsilon_0} = \dfrac{Q}{\epsilon_0 A}$

$$C = \frac{Q}{\Delta V} = \frac{Q}{Ed} = \frac{Q}{Qd/\varepsilon_o A} = \frac{\varepsilon_o A}{d}$$

Example

A parallel-plate capacitor with air between the plates has an area $A = 2.00 \times 10^{-4}\ \mathrm{m}^2$ and a plate separation $d = 1.00$ mm. Find its capacitance.

Solution

$$C = \frac{\epsilon_0 A}{d} = \frac{(8.85 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2})(2.00 \times 10^{-4}\ \mathrm{m^2})}{1.00 \times 10^{-3}\ \mathrm{m}}$$

$$= 1.77 \times 10^{-12}\ \mathrm{F} = \boxed{1.77\ \mathrm{pF}}$$

Capacitors in Parallel

The potential difference across the capacitors is the same.

- And each is equal to the voltage of the battery $\Delta V_1 = \Delta V_2 = \Delta V$
  - ΔV is the battery terminal voltage

The total charge is equal to the sum of the charges on the capacitors. $Q_{tot} = Q_1 + Q_2$

$$Q_1 = C_1 \Delta V \qquad Q_2 = C_2 \Delta V$$

The capacitors can be replaced with one capacitor with a capacitance of $C_{eq.}$

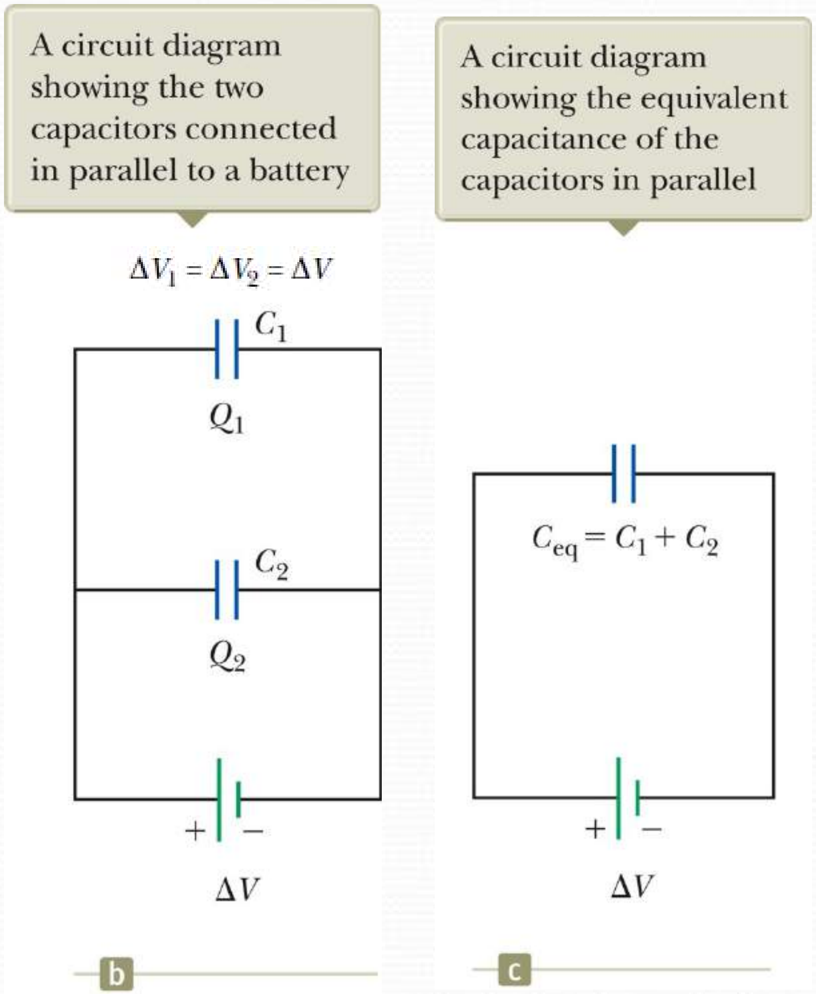
- The *equivalent capacitor* must have exactly the same external effect on the circuit as the original capacitors.

$$C_{eq} = C_1 + C_2$$

$$C_{eq} \Delta V = C_1 \Delta V + C_2 \Delta V$$

- For more capacitors

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



Capacitors in Series

An equivalent capacitor can be found that performs the same function as the series combination.

The charges are all the same.

$$Q_1 = Q_2 = Q$$

The potential differences add up to the battery voltage.

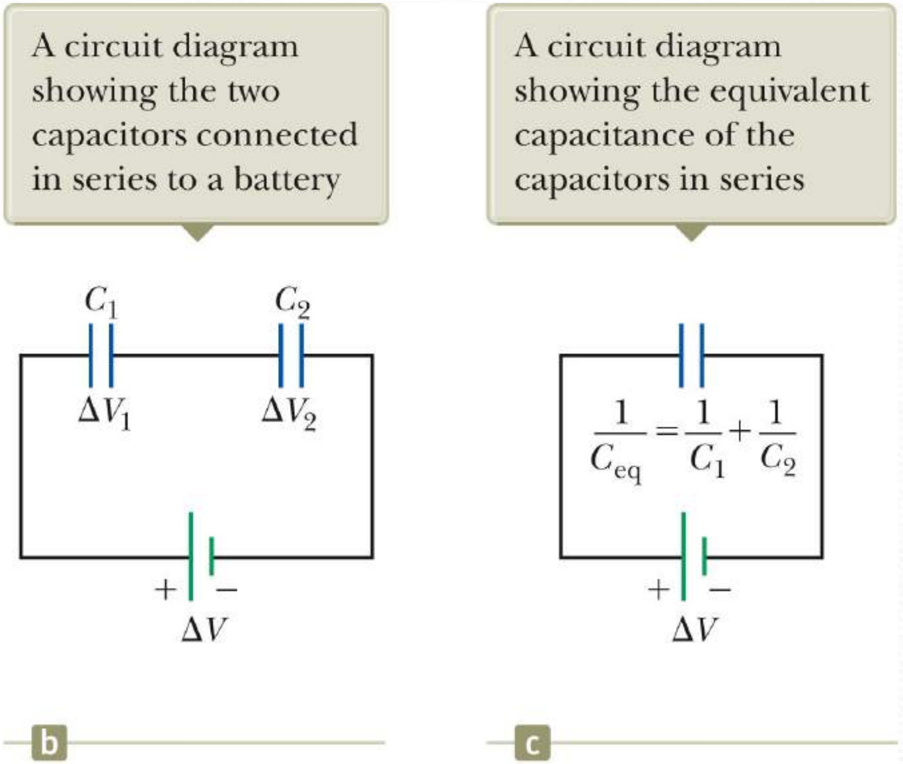
$$\Delta V_{tot} = \Delta V_1 + \Delta V_2 + \ldots$$

$$\Delta V = \frac{Q}{C_{eq}} \qquad \Delta V_1 = \frac{Q}{C_1} \qquad \Delta V_2 = \frac{Q}{C_2}$$

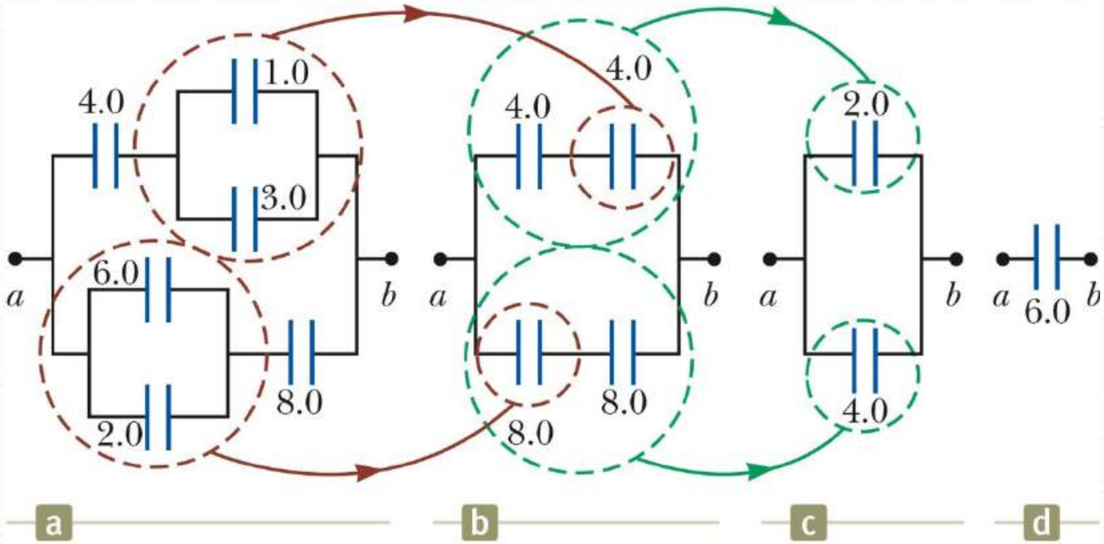
The equivalent capacitance is

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

The equivalent capacitance of a series combination is always less than any individual capacitor in the combination.



Equivalent Capacitance, Example



The 1.0-μF and 3.0-μF capacitors are in parallel as are the 6.0-μF and 2.0-μF capacitors.

These parallel combinations are in series with the capacitors next to them.

The series combinations are in parallel and the final equivalent capacitance can be found.

Capacitors with Dielectrics

A dielectric is a nonconducting material that, when placed between the plates of a capacitor, increases the capacitance and Increase the maximum operating voltage. Dielectrics include rubber, glass, and waxed paper

With a dielectric, the capacitance becomes $C = \kappa C_o$.

- κ is the dielectric constant of the material.

For a parallel-plate capacitor, $C = \kappa (\varepsilon_o A) / d$

In theory, d could be made very small to create a very large capacitance.

Example: A parallel-plate capacitor has plates of dimensions 2.0 cm by 3.0 cm separated by a 1.0-mm thickness of paper, $\kappa = 3.7$ for paper. Find its capacitance.

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

$$= 3.7 \left(\frac{(8.85 \times 10^{-12}\,\mathrm{C^2/N \cdot m^2})(6.0 \times 10^{-4}\,\mathrm{m^2})}{1.0 \times 10^{-3}\,\mathrm{m}} \right)$$

$$= 20 \times 10^{-12}\,\mathrm{F} = \boxed{20\,\mathrm{pF}}$$

Some Dielectric Constants and Dielectric Strengths

TABLE 26.1 *Approximate Dielectric Constants and Dielectric Strengths of Various Materials at Room Temperature*

Material	Dielectric Constant κ	Dielectric Strength[a] (10^6 V/m)
Air (dry)	1.000 59	3
Bakelite	4.9	24
Fused quartz	3.78	8
Mylar	3.2	7
Neoprene rubber	6.7	12
Nylon	3.4	14
Paper	3.7	16
Paraffin-impregnated paper	3.5	11
Polystyrene	2.56	24
Polyvinyl chloride	3.4	40
Porcelain	6	12
Pyrex glass	5.6	14
Silicone oil	2.5	15
Strontium titanate	233	8
Teflon	2.1	60
Vacuum	1.000 00	—
Water	80	—

[a]The dielectric strength equals the maximum electric field that can exist in a dielectric without electrical breakdown. These values depend strongly on the presence of impurities and flaws in the materials.

Types of Capacitors

Tubular: Metallic foil may be interlaced with thin sheets of paraffin-impregnated paper or Mylar.

The layers are rolled into a cylinder to form a small package for the capacitor.

Oil Filled: Common for high-voltage capacitors

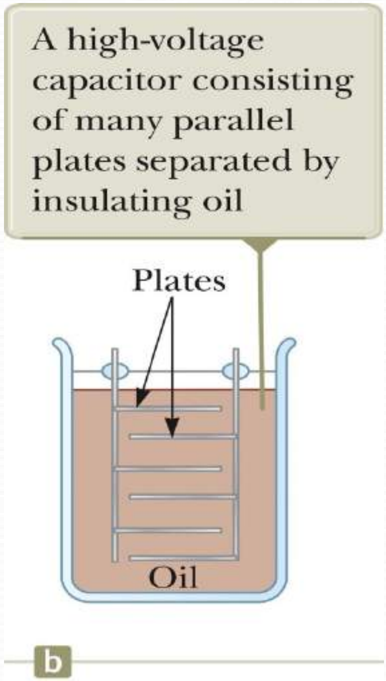
A number of interwoven metallic plates are immersed in silicon oil.

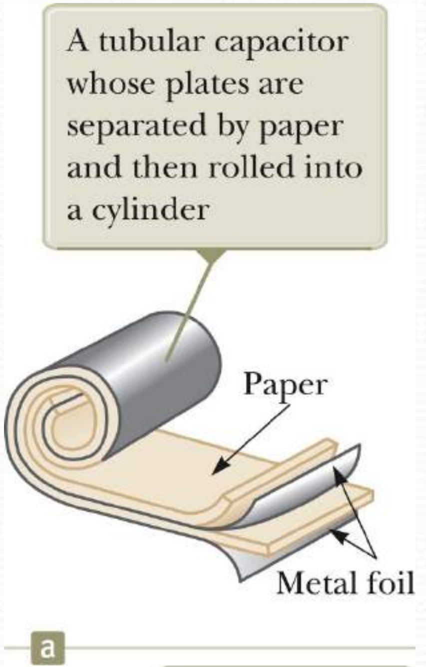
Electrolytic: Used to store large amounts of charge at relatively low voltages

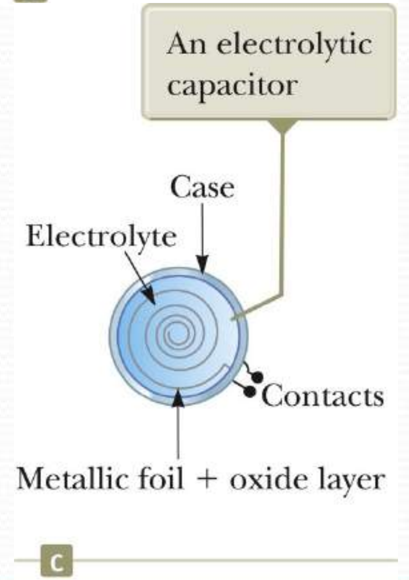
The electrolyte is a solution that conducts electricity by virtue of motion of ions contained in the solution.

When a voltage is applied between the foil and the electrolyte, a thin layer of metal oxide is formed on the foil.

This layer serves as a dielectric.







Electric Current

Most practical applications of electricity deal with electric currents.

- The electric charges move through some region of space.

The *resistor* is a new element added to circuits.

Electric current is the rate of flow of charge through some region of space.

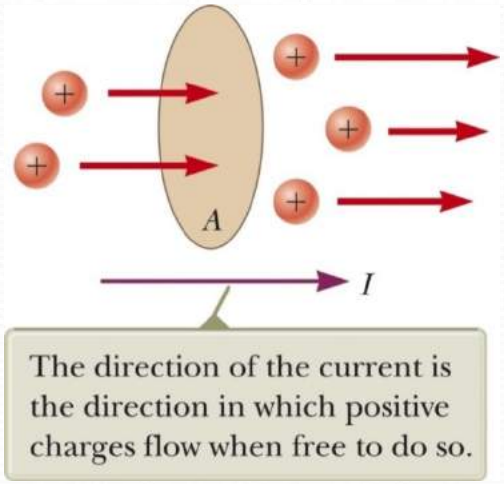
Assume charges are moving perpendicular to a surface of area *A*. If ΔQ is the amount of charge that passes through *A* in time Δt, then the average current is

$$I_{avg} = \frac{\Delta Q}{\Delta t}$$

The symbol for electric current is I.

In an ordinary conductor, the direction of current flow is opposite the direction of the flow of electrons. It is common to refer to any moving charge as a *charge carrier.*

The SI unit of current is the **ampere** (A). 1 A = 1 C / s



Current Density

J is the **current density** of a conductor. It is defined as the current per unit area.

- $J \equiv I / A$
- J is uniform and A is perpendicular to the direction of the current.

J has SI units of A/m^2

Conductivity

A current density and an electric field are established in a conductor whenever a potential difference is maintained across the conductor.

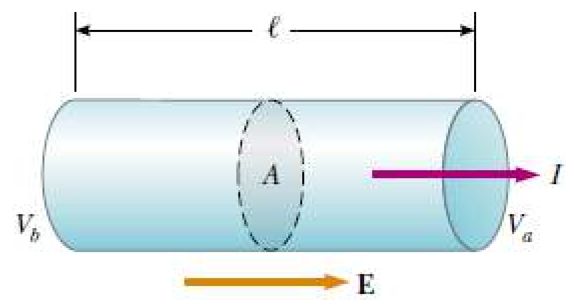
The constant of proportionality, σ, is called the **conductivity** of the conductor.

Ohm's Law

Ohm's law states that for many materials, the ratio of the current density to the electric field is a constant σ that is independent of the electric field producing the current.

- Mathematically, $J = \sigma E$ *or* $V=IR$
- Materials that obey Ohm's law are said to be *ohmic.* Most metals obey Ohm's law
- Materials that do not obey Ohm's law are said to be *nonohmic..*

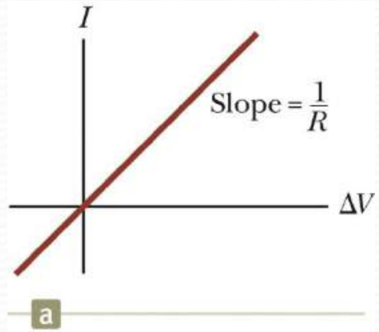
Resistance



potential difference $\Delta V = V_b - V_a$ is maintained across the wire, creating in the wire an electric field E and a current I. If the field is assumed to be uniform, the potential difference is $\Delta V = E\ell$

Therefore, the magnitude of the current density in the wire is

$$J = \sigma E = \sigma \frac{\Delta V}{\ell}$$



Because $J = I/A$, we can write the potential difference as

$$\Delta V = \frac{\ell}{\sigma} J = \left(\frac{\ell}{\sigma A}\right) I = RI$$

The quantity $R = \ell/\sigma A$ is called the **resistance** of the conductor. We can define the resistance as the ratio of the potential difference across a conductor to the current in the conductor:

SI units of resistance are *ohms* (Ω). 1 Ω = 1 V / A

Resistance in a circuit arises due to collisions between the electrons carrying the current with the fixed atoms inside the conductor.

Most electric circuits use circuit elements called **resistors** to control the current in the various parts of the circuit.

Resistivity

The inverse of the conductivity is the **resistivity**:

- $\rho = 1 / \sigma$

Resistivity has SI units of ohm-meters ($\Omega \cdot$ m)

Resistance is also related to resistivity: $R = \rho \dfrac{\ell}{A}$

Every ohmic material has a characteristic resistivity that depends on the properties of the material and on temperature.

The resistance of a material depends on its geometry and its resistivity.

TABLE 27.2 *Resistivities and Temperature Coefficients of Resistivity for Various Materials*

Material	Resistivity[a] ($\Omega \cdot$ m)	Temperature Coefficient[b] $\alpha[(°C)^{-1}]$
Silver	1.59×10^{-8}	3.8×10^{-3}
Copper	1.7×10^{-8}	3.9×10^{-3}
Gold	2.44×10^{-8}	3.4×10^{-3}
Aluminum	2.82×10^{-8}	3.9×10^{-3}
Tungsten	5.6×10^{-8}	4.5×10^{-3}
Iron	10×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[c]	1.00×10^{-6}	0.4×10^{-3}
Carbon	3.5×10^{-5}	-0.5×10^{-3}
Germanium	0.46	-48×10^{-3}
Silicon[d]	2.3×10^{3}	-75×10^{-3}
Glass	10^{10} to 10^{14}	
Hard rubber	$\sim 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

[a] All values at 20°C. All elements in this table are assumed to be free of impurities.
[b] See Section 27.4.
[c] A nickel–chromium alloy commonly used in heating elements. The resistivity of Nichrome varies with composition and ranges between 1.00×10^{-6} and $1.50 \times 10^{-6}\ \Omega \cdot$ m.
[d] The resistivity of silicon is very sensitive to purity. The value can be changed by several orders of magnitude when it is doped with other atoms.

Resistance and Temperature

Over a limited temperature range, the resistivity of a conductor varies approximately linearly with the temperature.

- ρ_o is the resistivity at some reference temperature T_o
  - T_o is usually taken to be 20° C
  - α is the **temperature coefficient of resistivity**
    - SI units of α are $^oC^{-1}$

The temperature coefficient of resistivity can be expressed as

$$\alpha = \frac{1}{\rho_o}\frac{\Delta\rho}{\Delta T}$$

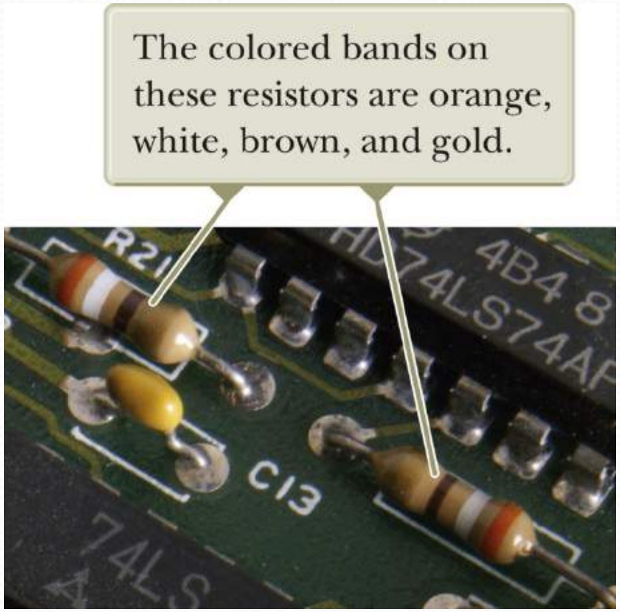
Since the resistance of a conductor with uniform cross sectional area is proportional to the resistivity, you can find the effect of temperature on resistance.

$$R = R_o\,[1 + \alpha(T - T_o)]$$

Use of this property enables precise temperature measurements through careful monitoring of the resistance of a probe made from a particular material.

Resistors

Most electric circuits use circuit elements called **resistors** to control the current in the various parts of the circuit.



- Resistors can be built into integrated circuit chips.

Values of resistors are normally indicated by colored bands.

- The first two bands give the first two digits in the resistance value.
- The third band represents the power of ten for the multiplier band.
- The last band is the tolerance.

Example: Resistor Color Code

Red (=2) and blue (=6) give the first two digits: 26

Green (=5) gives the power of ten in the multiplier: 10^5

The value of the resistor then is $26 \times 10^5\ \Omega$ (or 2.6 MΩ)

The tolerance is 10% (silver = 10%) or $2.6 \times 10^5\ \Omega$

Resistor Color Codes

TABLE 27.1 *Color Coding for Resistors*

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%
Colorless			20%

Example

Calculate the resistance of an aluminum cylinder that has a length of 10.0 cm and a cross-sectional area of 2.00 x 10^{-4}m^2. Repeat the calculation for a cylinder of the same dimensions and made of glass having a resistivity of

3.0 x 10^{10} Ω.m.

Solution : we can calculate the resistance of the aluminum cylinder as follows:

$$R = \rho \frac{\ell}{A} = (2.82 \times 10^{-8}\ \Omega \cdot \mathrm{m}) \left(\frac{0.100\ \mathrm{m}}{2.00 \times 10^{-4}\ \mathrm{m}^2} \right)$$

$$= \boxed{1.41 \times 10^{-5}\ \Omega}$$

Similarly, for glass we find that

$$R = \rho \frac{\ell}{A} = (3.0 \times 10^{10}\ \Omega \cdot \mathrm{m}) \left(\frac{0.100\ \mathrm{m}}{2.00 \times 10^{-4}\ \mathrm{m}^2} \right)$$

$$= \boxed{1.5 \times 10^{13}\ \Omega}$$

Example: The Resistance of Nichrome Wire

(A) Calculate the resistance per unit length of a 22-gauge Nichrome wire, which has a radius of 0.321 mm. The resistivity of Nichrome is 1.5 x 10^{-6} Ω.m

Solution: The cross-sectional area of this wire is

$$A = \pi r^2 = \pi(0.321 \times 10^{-3}\ \mathrm{m})^2 = 3.24 \times 10^{-7}\ \mathrm{m}^2$$

The resistance per unit length:

$$\frac{R}{\ell} = \frac{\rho}{A} = \frac{1.5 \times 10^{-6}\ \Omega\cdot\mathrm{m}}{3.24 \times 10^{-7}\ \mathrm{m}^2} = \boxed{4.6\ \Omega/\mathrm{m}}$$

(B) If a potential difference of 10 V is maintained across a 1.0-m length of the Nichrome wire, what is the current in the wire?

Solution: Because a 1.0-m length of this wire has a resistance of 4.6 Ω then

$$I = \frac{\Delta V}{R} = \frac{10\ \mathrm{V}}{4.6\ \Omega} = \boxed{2.2\ \mathrm{A}}$$

Resistors in Series

For a series combination of resistors, the currents are the same in all the resistors

$I = I_1 = I_2$

The potential difference will divide among the resistors

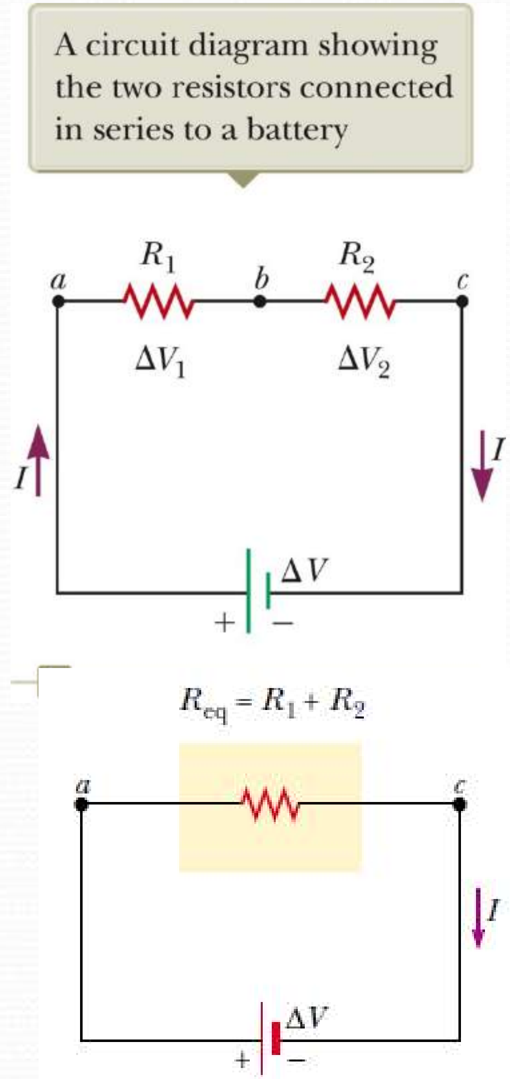
$$\Delta V = V_1 + V_2 = IR_1 + IR_2$$
$$= I(R_1 + R_2)$$

- Consequence of Conservation of Energy

The equivalent resistance has the same effect on the circuit as the original combination of resistors.

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

If one device in the series circuit creates an open circuit, all devices are inoperative.



Resistors in Parallel

The potential difference across each resistor is the same because each is connected directly across the battery terminals.

$$\Delta V = \Delta V_1 = \Delta V_2$$

A **junction** is a point where the current can split.

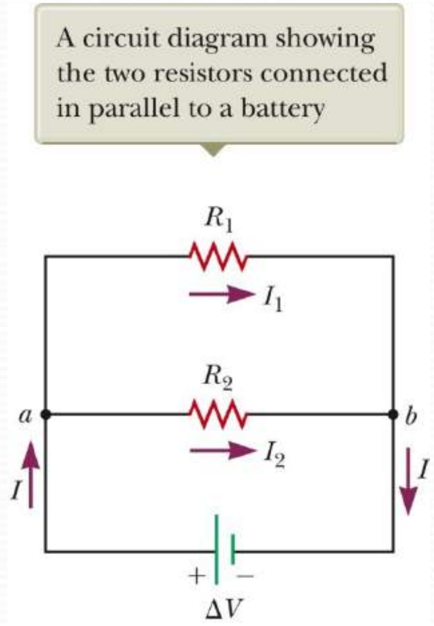
The current, I, that enters junction must be equal to the total current leaving that junction.

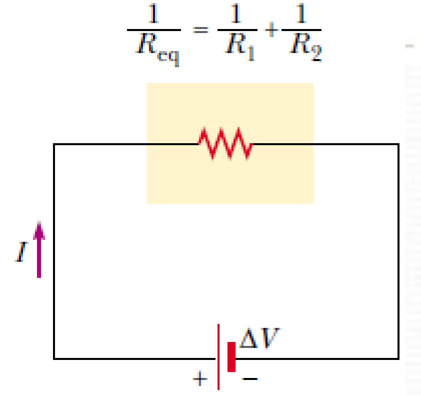
- $I = I_1 + I_2 = (\Delta V_1 / R_1) + (\Delta V_2 / R_2)$
- The currents are generally not the same.
- Consequence of conservation of electric charge

Equivalent Resistance

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

- The equivalent is always less than the smallest resistor in the group.



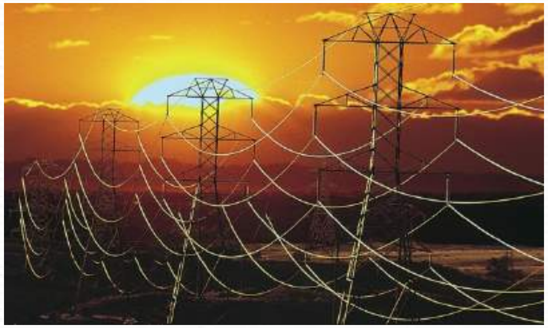


Electric Power

The **power** is the rate at which the energy is delivered to the resistor.

The power is given by the equation P = I ΔV.

Applying Ohm's Law, alternative expressions can be found:



$$P = I \Delta V = I^2 R = \frac{(\Delta V)^2}{R}$$

Units: I is in A, R is in Ω, ΔV is in V, and P is in W (Watt)

- It may take hours for an electron to move completely around a circuit.

The current is the same everywhere in the circuit.

The charges flow in the same rotational sense at all points in the circuit.

Real power lines have resistance.

Power companies transmit electricity at high voltages and low currents to minimize power losses.

Example **Power in an Electric Heater**

An electric heater is constructed by applying a potential difference of 120 V to a Nichrome wire that has a total resistance of 8.00 Ω. Find the current carried by the wire and the power rating of the heater.

Solution Because $\Delta V = IR$, we have

$$I = \frac{\Delta V}{R} = \frac{120\ \text{V}}{8.00\ \Omega} = \boxed{15.0\ \text{A}}$$

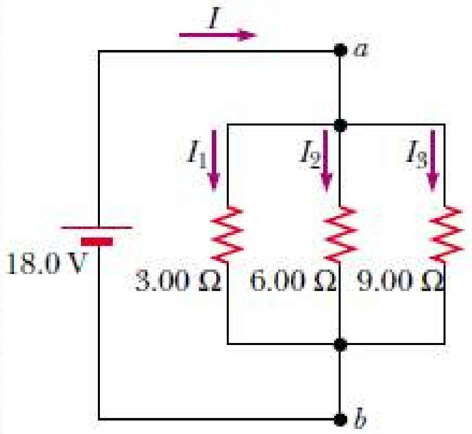
We can find the power rating as

$$\mathcal{P} = I^2R = (15.0\ \text{A})^2(8.00\ \Omega) = 1.80 \times 10^3\ \text{W}$$

$$\mathcal{P} = \boxed{1.80\ \text{kW}}$$

Example **Three Resistors in Parallel**

Three resistors are connected in parallel as shown in Figure. A potential difference of 18.0 V is maintained between points *a* and *b*.



(A) Find the current in each resistor.

$$I_1 = \frac{\Delta V}{R_1} = \frac{18.0\ \text{V}}{3.00\ \Omega} = \boxed{6.00\ \text{A}}$$

$$I_2 = \frac{\Delta V}{R_2} = \frac{18.0\ \text{V}}{6.00\ \Omega} = \boxed{3.00\ \text{A}}$$

$$I_3 = \frac{\Delta V}{R_3} = \frac{18.0\ \text{V}}{9.00\ \Omega} = \boxed{2.00\ \text{A}}$$

(B) Calculate the power delivered to each resistor and the total power delivered to the combination of resistors.

3.00-Ω: $\mathcal{P}_1 = I_1^2R_1 = (6.00\ \text{A})^2(3.00\ \Omega) = \boxed{108\ \text{W}}$

6.00-Ω: $\mathcal{P}_2 = I_2^2R_2 = (3.00\ \text{A})^2(6.00\ \Omega) = \boxed{54.0\ \text{W}}$

9.00-Ω: $\mathcal{P}_3 = I_3^2R_3 = (2.00\ \text{A})^2(9.00\ \Omega) = \boxed{36.0\ \text{W}}$

$$\frac{1}{R_{\text{eq}}} = \frac{1}{3.00\ \Omega} + \frac{1}{6.00\ \Omega} + \frac{1}{9.00\ \Omega}$$

$$R_{\text{eq}} = \frac{18.0\ \Omega}{11.0} = \boxed{1.64\ \Omega}$$

(C) Calculate the equivalent resistance of the circuit.

Direct Current

When the current in a circuit has a constant direction, the current is called ***direct current.***

- Most of the circuits analyzed will be assumed to be in *steady state*, with constant magnitude and direction.

Because the potential difference between the terminals of a battery is constant, the battery produces direct current.

The battery is known as a source of emf.

Electromotive Force

The electromotive force (emf), ε, of a battery is the maximum possible voltage that the battery can provide between its terminals.

- The emf supplies energy, it does not apply a force.

The battery will normally be the source of energy in the circuit.

The positive terminal of the battery is at a higher potential than the negative terminal.

We consider the wires to have no resistance.

Internal Battery Resistance

If the internal resistance is zero, the terminal voltage equals the emf.

In a real battery, there is internal resistance, *r.*

The terminal voltage, $\Delta V = \varepsilon - Ir$

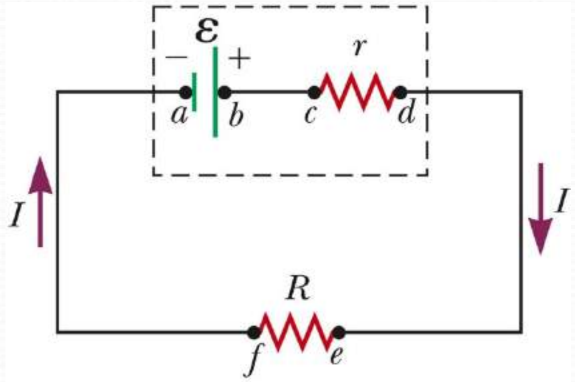
The emf is equivalent to the *open-circuit* voltage.

- This is the terminal voltage when no current is in the circuit.
- This is the voltage labeled on the battery.

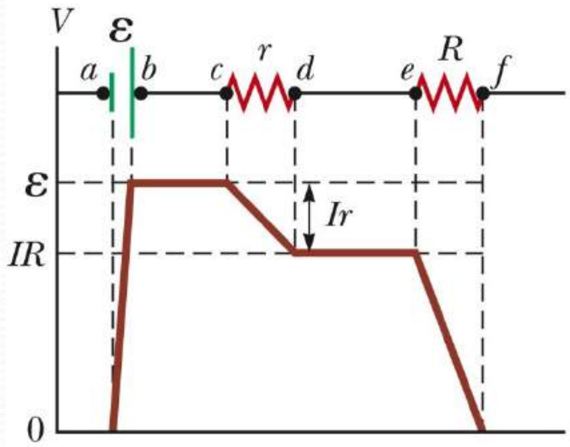
The actual potential difference between the terminals of the battery depends on the current in the circuit.

The terminal voltage also equals the voltage across the external resistance.

- This external resistor is called the ***load resistance***.
- In general, the load resistance could be any electrical device.



a



b

Power

The total power output of the battery is

$$P = I\,\Delta V = I\,\varepsilon$$

This power is delivered to the external resistor ($I^2 R$) and to the internal resistor ($I^2 r$).

$$P = I^2 R + I^2 r$$

The battery is a supply of constant emf.

- The battery does not supply a constant current since the current in the circuit depends on the resistance connected to the battery.
- The battery does not supply a constant terminal voltage.

Example: **Terminal Voltage of a Battery**

A battery has an emf of 12.0 V and an internal resistance of 0.05 Ω. Its terminals are connected to a load resistance of 3.0 Ω

(A) Find the current in the circuit and the terminal voltage of the battery.

$$I = \frac{\mathcal{E}}{R + r} = \frac{12.0\ \text{V}}{3.05\ \Omega} = \boxed{3.93\ \text{A}}$$

$$\Delta V = \mathcal{E} - Ir = 12.0\ \text{V} - (3.93\ \text{A})(0.05\ \Omega) = \boxed{11.8\ \text{V}}$$

To check this result, we can calculate the voltage across the load resistance *R*:

$$\Delta V = IR = (3.93\ \text{A})(3.00\ \Omega) = 11.8\ \text{V}$$

(B) Calculate the power delivered to the load resistor, the power delivered to the internal resistance of the battery, and the power delivered by the battery.

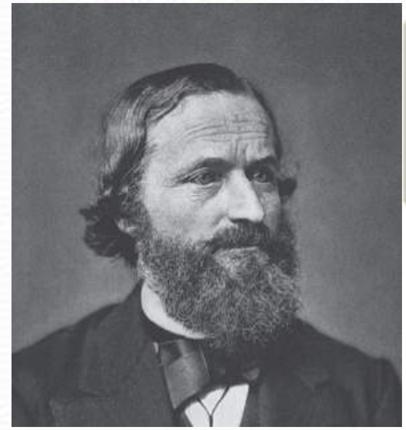
Solution The power delivered to the load resistor is

$$\mathcal{P}_R = I^2R = (3.93\ \text{A})^2\ (3.00\ \Omega) = \boxed{46.3\ \text{W}}$$

The power delivered to the internal resistance is

$$\mathcal{P}_r = I^2r = (3.93\ \text{A})^2\ (0.05\ \Omega) = \boxed{0.772\ \text{W}}$$

Gustav Kirchhoff (1824 – 1887)



German physicist

The procedure for analyzing more complex circuits is greatly simplified if we use two principles called, called **Kirchhoff's rules**,.

Kirchhoff's Junction Rule

The sum of the currents at any junction must equal zero.

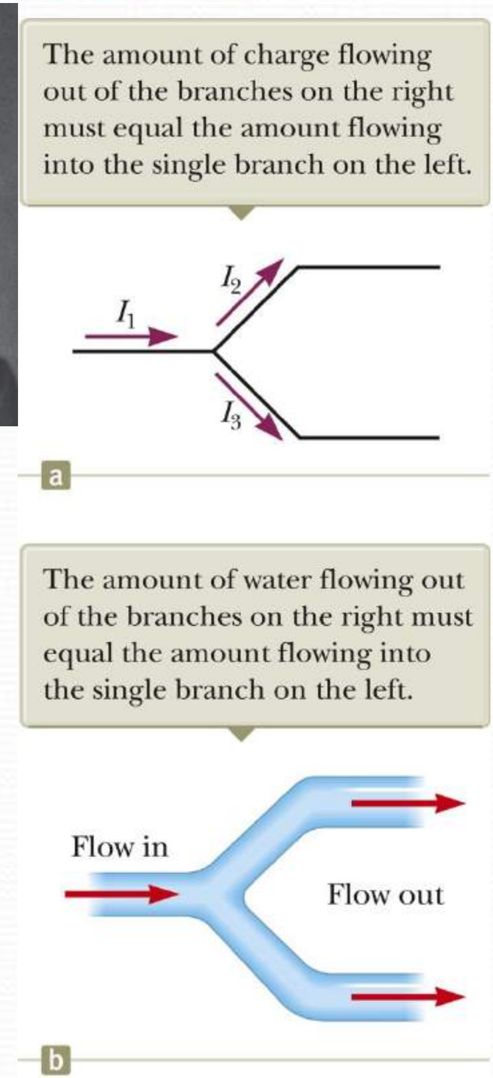
- Currents directed into the junction are entered into the equation as +I and those leaving as - I.

- Mathematically, $\sum_{junction} I = 0$

$I_1 - I_2 - I_3 = 0$

Required by Conservation of Charge

- In general, the number of times the junction rule can be used is one fewer than the number of junction points in the circuit.



Kirchhoff's Loop Rule

- The sum of the potential differences across all elements around any closed circuit loop must be zero.
  - A statement of Conservation of Energy

Mathematically, $$\sum_{\text{closed loop}} \Delta V = 0$$

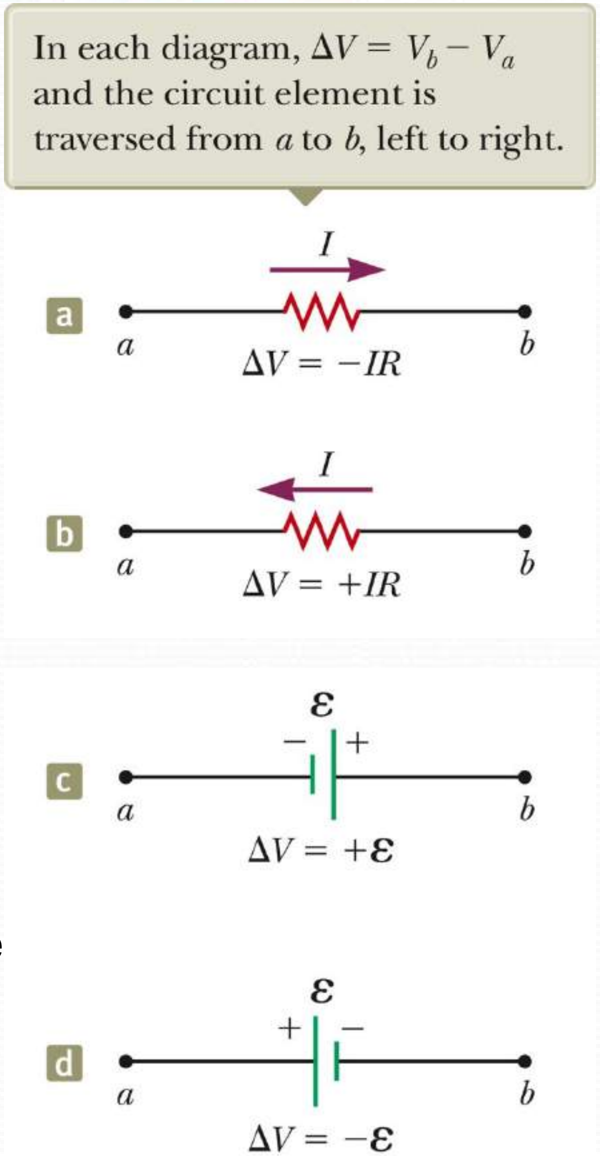
Traveling around the loop from *a* to *b*

In (a), the resistor is traversed in the direction of the current, the potential across the resistor is – IR.

In (b), the resistor is traversed in the direction opposite of the current, the potential across the resistor is is + IR.

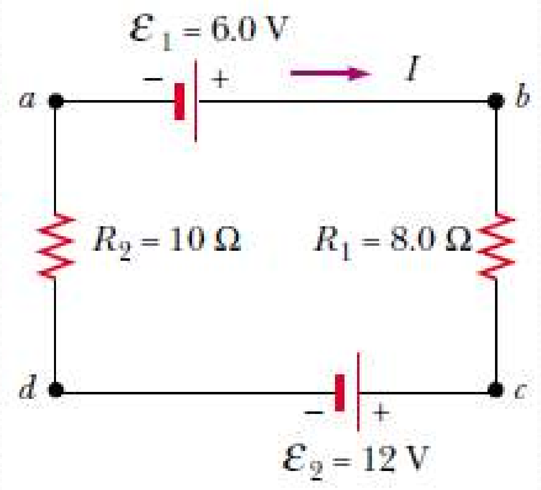
In (c), the source of emf is traversed in the direction of the emf (from – to +), and the change in the potential difference is $+\varepsilon$.

In (d), the source of emf is traversed in the direction opposite of the emf (from + to -), and the change in the potential difference is $-\varepsilon$.



Example **A Single-Loop Circuit**

A single-loop circuit contains two resistors and two batteries, as shown in Figure. (Neglect the internal resistances of the batteries.)



(A) Find the current in the circuit.

Solution:

$$\sum \Delta V = 0$$

$$\mathcal{E}_1 - IR_1 - \mathcal{E}_2 - IR_2 = 0$$

$$I = \frac{\mathcal{E}_1 - \mathcal{E}_2}{R_1 + R_2} = \frac{6.0\text{ V} - 12\text{ V}}{8.0\ \Omega + 10\ \Omega} = -0.33\text{ A}$$

(B) What power is delivered to each resistor? What power is delivered by the 12-V battery?

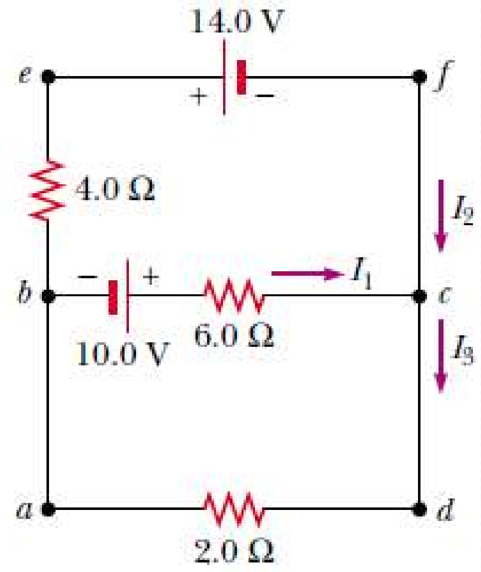
$$\mathcal{P}_1 = I^2R_1 = (0.33\text{ A})^2(8.0\ \Omega) = 0.87\text{ W}$$

$$\mathcal{P}_2 = I^2R_2 = (0.33\text{ A})^2(10\ \Omega) = 1.1\text{ W}$$

Hence, the total power delivered to the resistors is 2.0 W.

Example **Applying Kirchhoff's Rules**

Find the currents I_1, I_2, and I_3 in the circuit shown in Figure



$$(1) \qquad I_1 + I_2 = I_3$$

$$(2) \qquad abcda \quad 10.0\text{ V} - (6.0\ \Omega)I_1 - (2.0\ \Omega)I_3 = 0$$

$$(3) \quad befcb \quad -14.0\text{ V} + (6.0\ \Omega)I_1 - 10.0\text{ V} - (4.0\ \Omega)\ I_2 = 0$$

$$10.0\text{ V} - (6.0\ \Omega)I_1 - (2.0\ \Omega)\ (I_1 + I_2) = 0$$

$$(4) \qquad 10.0\text{ V} = (8.0\ \Omega)I_1 + (2.0\ \Omega)I_2$$

$$(5) \qquad -12.0\text{ V} = -(3.0\ \Omega)I_1 + (2.0\ \Omega)I_2$$

$$22.0\text{ V} = (11.0\ \Omega)I_1$$

$$I_1 = \boxed{2.0\text{ A}}$$

$$\begin{aligned}(2.0\ \Omega)I_2 &= (3.0\ \Omega)I_1 - 12.0\text{ V} \\ &= (3.0\ \Omega)(2.0\text{ A}) - 12.0\text{ V} = -6.0\text{ V}\end{aligned}$$

$$I_2 = \boxed{-3.0\text{ A}} \qquad I_3 = I_1 + I_2 = \boxed{-1.0\text{ A}}$$

RC Circuit

In direct current circuits containing capacitors, the current may vary with time.

- The current is still in the same direction.

An RC circuit will contain a series combination of a resistor and a capacitor.

Electrical Safety

Electric shock can result in fatal burns.

Electric shock can cause the muscles of vital organs (such as the heart) to malfunction.

The degree of damage depends on:

- The magnitude of the current
- The length of time it acts
- The part of the body touched by the live wire
- The part of the body in which the current exists

Effects of Various Currents

5 mA or less

- Can cause a sensation of shock
- Generally little or no damage

10 mA

- Muscles contract
- May be unable to let go of a live wire

100 mA

- If passing through the body for a few seconds, can be fatal
- Paralyzes the respiratory muscles and prevents breathing

In some cases, currents of 1 A can produce serious burns.

- Sometimes these can be fatal burns

No contact with live wires is considered safe if the voltage is greater than 24 V.

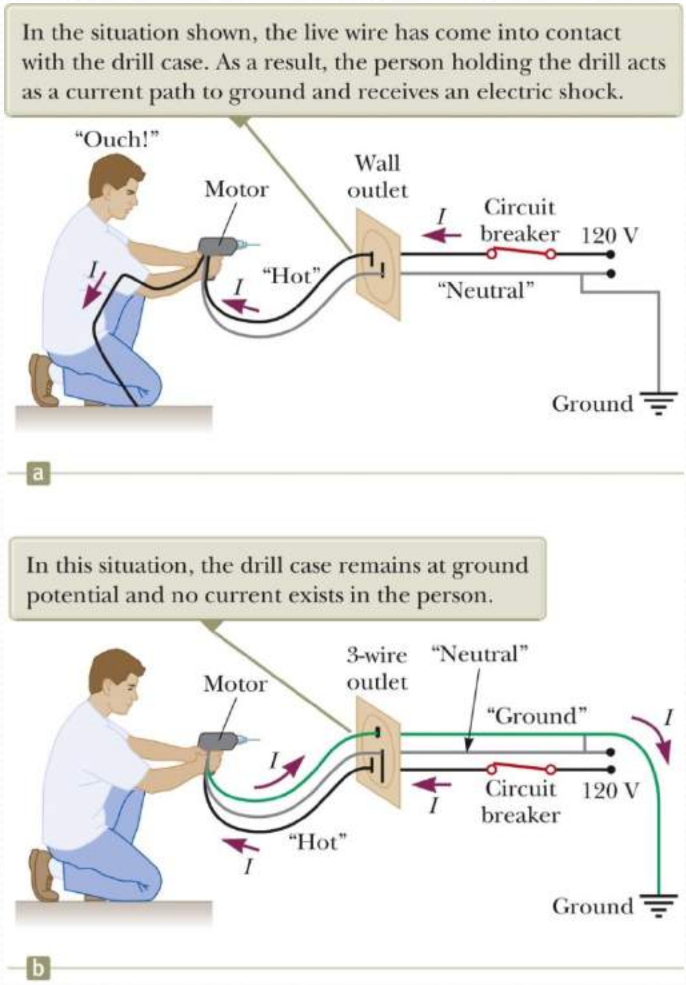
Ground Wire

Electrical equipment manufacturers use electrical cords that have a third wire, called a ground.

This safety ground normally carries no current and is both grounded and connected to the appliance.

If the live wire is accidentally shorted to the casing, most of the current takes the low-resistance path through the appliance to the ground.

If it was not properly grounded, anyone in contact with the appliance could be shocked because the body produces a low-resistance path to ground.



Ground-Fault Interrupters (GFI)

Special power outlets

Used in hazardous areas

Designed to protect people from electrical shock

Senses currents (< 5 mA) leaking to ground

Quickly shuts off the current when above this level

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Chapter 10 - Magnetism

Magnetic Poles

Every magnet, regardless of its shape, has two poles.

- The two poles called north and south poles and exert forces on one another similar to the way electric charges exert forces on each other
  - Like poles repel each other: N-N or S-S. Unlike poles attract each other: N-S.

The poles received their names due to the way a magnet behaves in the Earth's magnetic field.

If a bar magnet is suspended so that it can move freely, it will rotate.

- The magnetic north pole points toward the Earth's north geographic pole.
  - This means the Earth's north geographic pole is a magnetic south pole.
  - Similarly, the Earth's south geographic pole is a magnetic north pole.

The force between two poles varies as the inverse square of the distance between them.

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

- All attempts so far to detect an isolated magnetic pole has been unsuccessful.
  - No matter how many times a permanent magnetic is cut in two, each piece always has a north and south pole.

Magnetic Fields

Reminder: an electric field surrounds any electric charge

The region of space surrounding any *moving* electric charge also contains a magnetic field.

A magnetic field also surrounds a magnetic substance making up a permanent magnet.

The magnetic field is a vector quantity and symbolized by $\vec{B}$

Direction is given by the direction a north pole of a compass needle points in that location

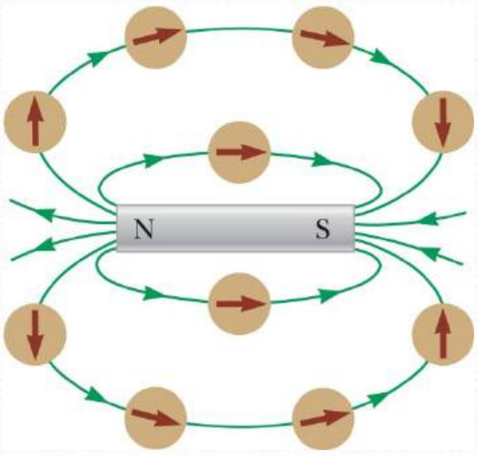
Magnetic field lines can be used to show how the field lines,

as traced out by a compass, would look.

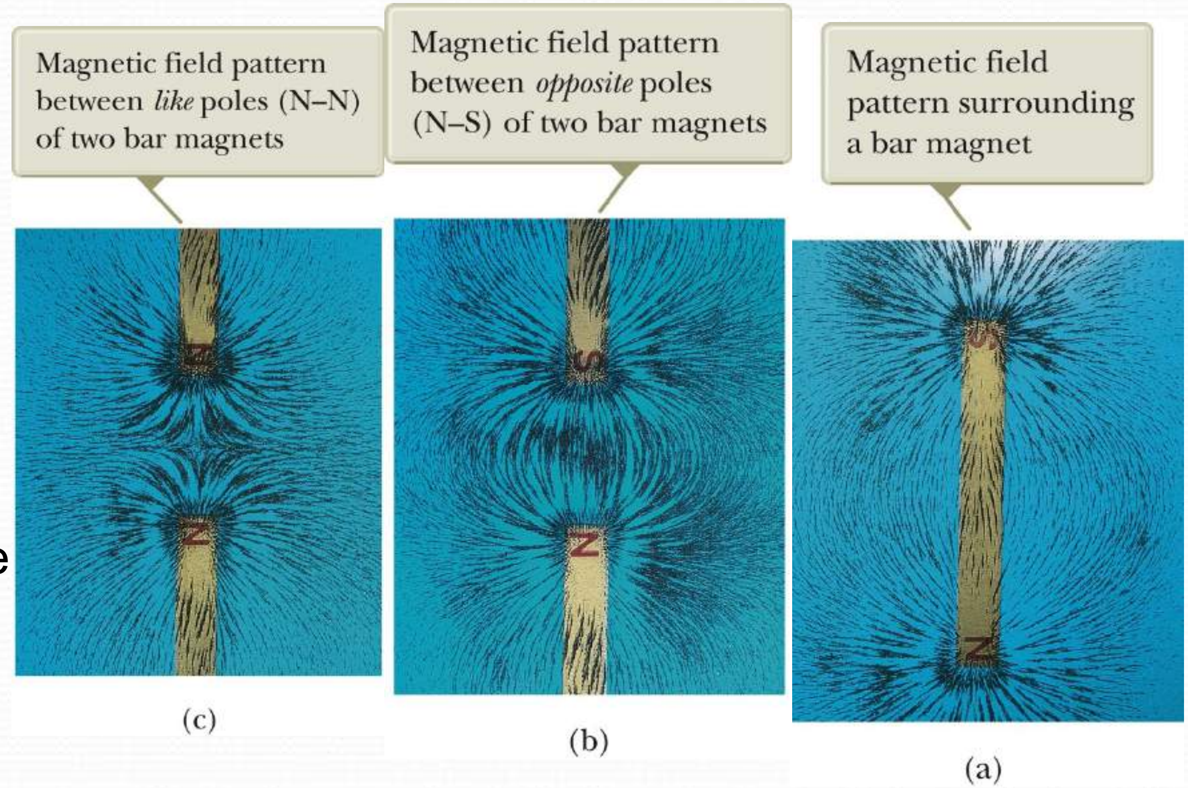
The compass can be used to trace the field lines.

The lines outside the magnet point from the North pole to

the South pole.



Magnetic Field Lines



Bar Magnet: Iron filings are used to show the pattern of the electric field lines.

The direction of the field is the direction a north pole would point.

Opposite Poles: Iron filings are used to show the pattern of the electric field lines.

The direction of the field is the direction a north pole would point.

Like Poles: Iron filings are used to show the pattern of the electric field lines.

The direction of the field is the direction a north pole would point.

- Compare to the electric field produced by like charges

Earth's Magnetic Poles

More proper terminology would be that a magnet has "north-seeking" and "south-seeking" poles.

The north-seeking pole points to the north geographic pole.

- This would correspond to the Earth's south magnetic pole.

The south-seeking pole points to the south geographic pole.

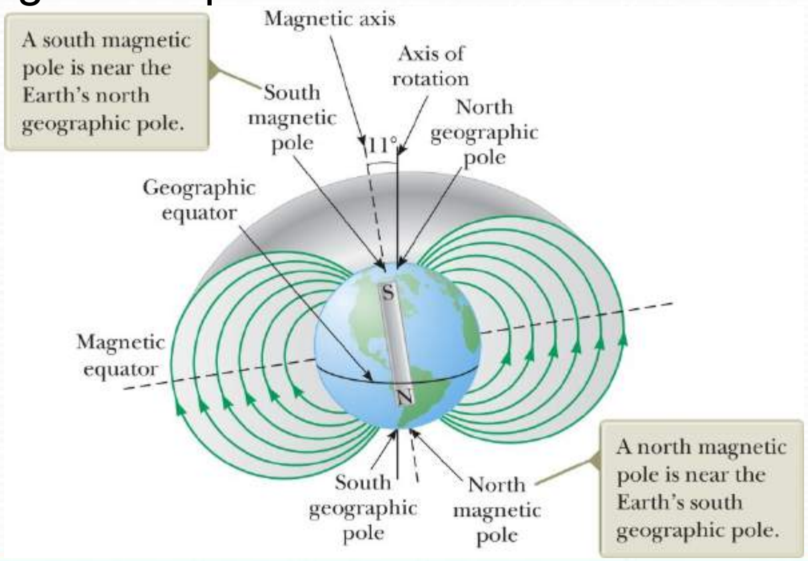
- This would correspond to the Earth's north magnetic pole.

The configuration of the Earth's magnetic field is very much like the one that would be achieved by burying a gigantic bar magnet deep in the Earth's interior.

The source of the Earth's magnetic field is likely convection currents in the Earth's core.

There is strong evidence that the magnitude of a planet's magnetic field is related to its rate of rotation.

The direction of the Earth's magnetic field reverses periodically.



Definition of Magnetic Field

The magnetic field at some point in space can be defined in terms of the magnetic force, $\vec{F}_B$.

The magnetic force will be exerted on a charged particle moving with a velocity, $\vec{v}$.

The magnitude F_B of the magnetic force exerted on the particle is proportional to the charge, q, and to the speed, v, of the particle.

When a charged particle moves parallel to the magnetic field vector, the magnetic force acting on the particle is zero.

When the particle's velocity vector makes any angle $\theta \neq 0$ with the field, the force acts in a direction perpendicular to the plane formed by the velocity and the field.

The magnetic force exerted on a positive charge is in the direction opposite the direction of the magnetic force exerted on a negative charge moving in the same direction.

The magnitude of the magnetic force is proportional to sin θ, where θ is the angle the particle's velocity makes with the direction of the magnetic field.

Force on a Charge Moving in a Magnetic Field, Formula

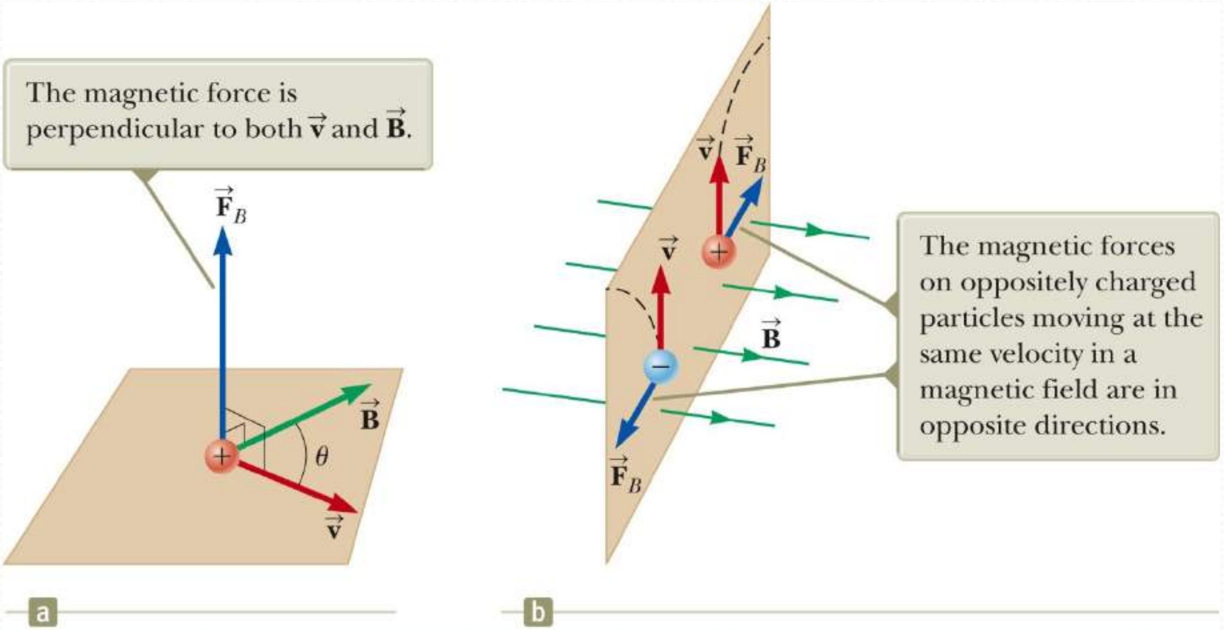
The properties can be summarized in a vector equation:

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

- $\vec{F}_B$ is the magnetic force
- q is the charge. $\vec{v}$ is the velocity of the moving charge. $\vec{B}$ is the magnetic field

The magnitude of the magnetic force on a charged particle is $F_B = |q|\, v\, B \sin \theta$.

- θ is the smaller angle between v and B

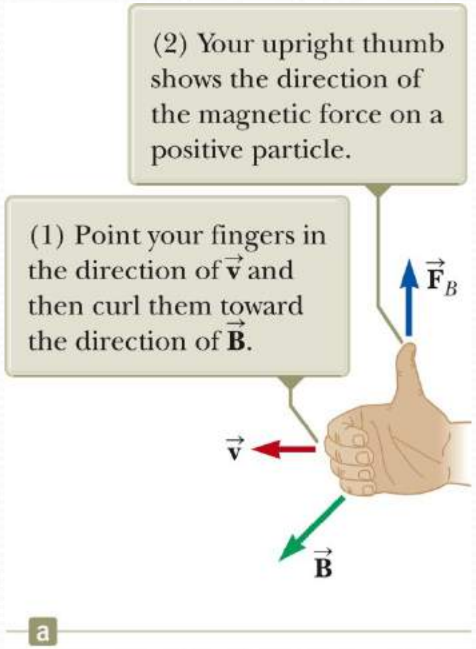


Direction: Right-Hand Rule

Rule 1: This rule is based on the right-hand rule for the cross product.

Your thumb is in the direction of the force if *q* is positive.

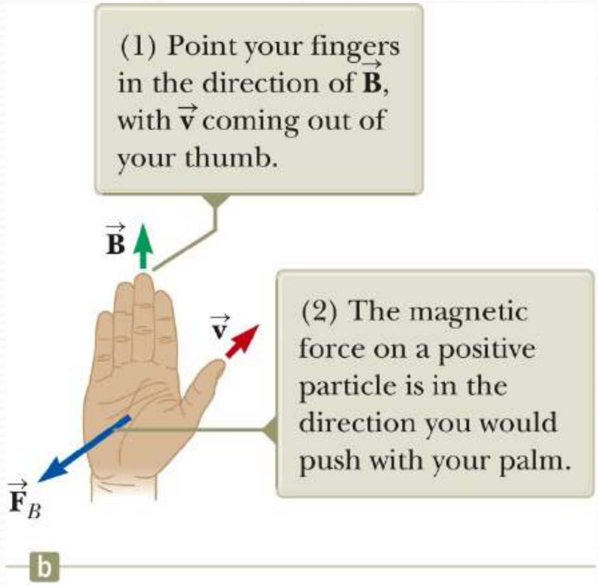
The force is in the opposite direction of your thumb if *q* is negative.



Rule 2: The force on a positive charge extends outward from the palm.

The advantage of this rule is that the force on the charge is in the direction you would push on something with your hand.

The force on a negative charge is in the opposite direction.



Differences Between Electric and Magnetic Fields

Direction of force

- The electric force acts along the direction of the electric field.
- The magnetic force acts perpendicular to the magnetic field.

Motion

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

Work

- The electric force does work in displacing a charged particle.
- The magnetic force associated with a steady magnetic field does no work when a particle is displaced.
- The kinetic energy of a charged particle moving through a magnetic field cannot be altered by the magnetic field alone.
- When a charged particle moves with a given velocity through a magnetic field, the field can alter the direction of the velocity, but not the speed or the kinetic energy.

Units of Magnetic Field

The SI unit of magnetic field is the tesla (T).

$$T = \frac{Wb}{m^2} = \frac{N}{C \cdot (m/s)} = \frac{N}{A \cdot m}$$

- Wb is a weber

A non-SI commonly used unit is a gauss (G).

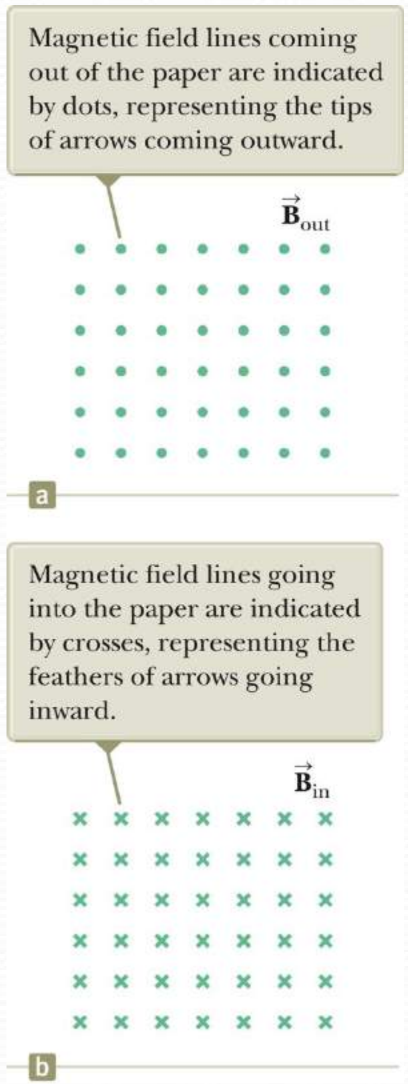
- $1\ T = 10^4\ G$

Notation Notes

When vectors are perpendicular to the page, dots and crosses are used.

- The dots represent the arrows coming out of the page.
- The crosses represent the arrows going into the page.

The same notation applies to other vectors.

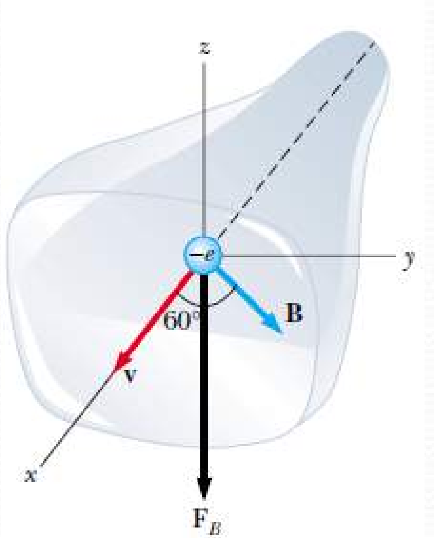


Example: An Electron Moving in a Magnetic Field

An electron in a television picture tube moves toward the front of the tube with a speed of 8.0 x 10^6 m/s along the *x* axis . Surrounding the neck of the tube are coils of wire that create a magnetic field of magnitude 0.025 T, directed at an angle of 60° to the *x* axis and lying in the *xy* plane.

(A) Calculate the magnetic force on the electron

$$\begin{aligned} F_B &= |q| vB \sin\theta \\ &= (1.6 \times 10^{-19}\ \text{C})(8.0 \times 10^6\ \text{m/s})(0.025\ \text{T})(\sin 60°) \\ &= 2.8 \times 10^{-14}\ \text{N} \end{aligned}$$



(B) Find a vector expression for the magnetic force on the electron

$$\mathbf{v} = (8.0 \times 10^6\ \hat{\mathbf{i}})\ \text{m/s}$$

$$\begin{aligned} \mathbf{B} &= (0.025 \cos 60°\ \hat{\mathbf{i}} + 0.025 \sin 60°\ \hat{\mathbf{j}})\text{T} \\ &= (0.013\ \hat{\mathbf{i}} + 0.022\ \hat{\mathbf{j}})\text{T} \end{aligned}$$

$$\begin{aligned} \mathbf{F}_B &= q\mathbf{v} \times \mathbf{B} \\ &= (-e)[(8.0 \times 10^6\ \hat{\mathbf{i}})\ \text{m/s}] \times [(0.013\ \hat{\mathbf{i}} + 0.022\ \hat{\mathbf{j}})\text{T}] \\ &= (-e)[(8.0 \times 10^6\ \hat{\mathbf{i}})\ \text{m/s}] \times [(0.013\ \hat{\mathbf{i}})\text{T}] \\ &\quad + (-e)[(8.0 \times 10^6\ \hat{\mathbf{i}})\ \text{m/s}] \times [(0.022\ \hat{\mathbf{j}})\text{T}] \\ &= (-e)(8.0 \times 10^6\ \text{m/s})(0.013\ \text{T})(\hat{\mathbf{i}} \times \hat{\mathbf{i}}) \\ &\quad + (-e)(8.0 \times 10^6\ \text{m/s})(0.022\ \text{T})(\hat{\mathbf{i}} \times \hat{\mathbf{j}}) \\ &= (-1.6 \times 10^{-19}\ \text{C})(8.0 \times 10^6\ \text{m/s})(0.022\ \text{T})\ \hat{\mathbf{k}} \end{aligned}$$

$$\mathbf{F}_B = (-2.8 \times 10^{-14}\ \text{N})\hat{\mathbf{k}}$$

Charged Particle move in a Magnetic Field

Consider a particle moving in an external magnetic field with its velocity perpendicular to the field.

The force is always directed toward the center of the circular path.

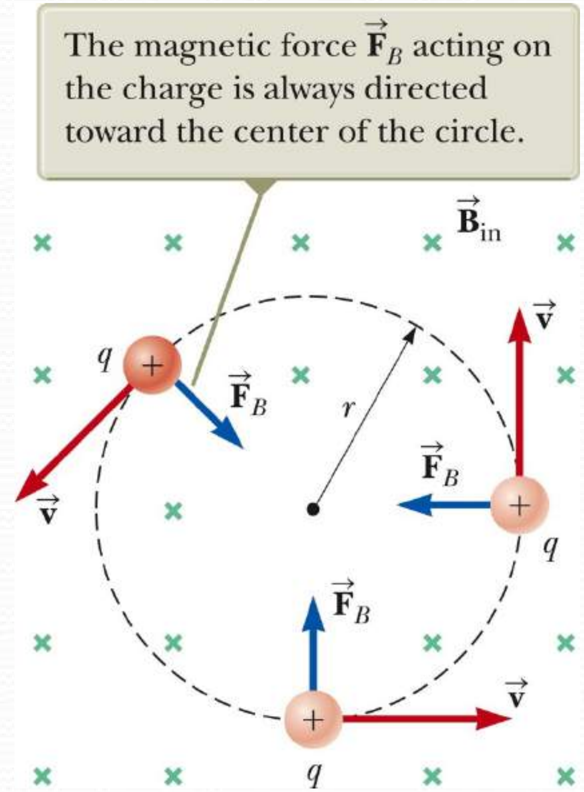
The magnetic force causes a centripetal acceleration, changing the direction of the velocity of the particle.

Use the particle under a net force and a particle in uniform circular motion models.

$$F_B = qvB = \frac{mv^2}{r}$$

Solving for r: $r = \frac{mv}{qB}$

r is proportional to the linear momentum of the particle and inversely proportional to the magnetic field.



The angular speed of the particle, ω, is referred to as the **cyclotron frequency,** is

$$\omega = \frac{v}{r} = \frac{qB}{m}$$

The period of the motion is $T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}$

A Proton Moving Perpendicular to a Uniform Magnetic Field

Example: A proton is moving in a circular orbit of radius 14 cm in a uniform 0.35-T magnetic field perpendicular to the velocity of the proton. Find the linear speed of the proton.

Solution:

$$v = \frac{qBr}{m_p} = \frac{(1.60 \times 10^{-19}\ \mathrm{C})(0.35\ \mathrm{T})(0.14\ \mathrm{m})}{1.67 \times 10^{-27}\ \mathrm{kg}}$$

$$= \boxed{4.7 \times 10^{6}\ \mathrm{m/s}}$$

Charged Particles Moving in Electric and Magnetic Fields

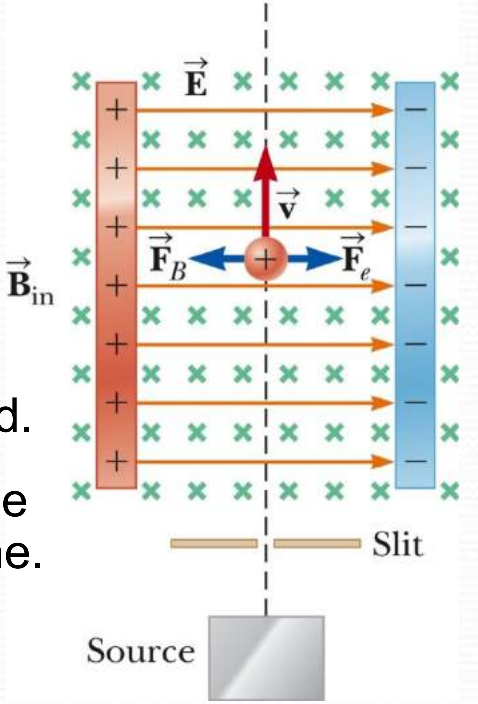
In many applications, charged particles will move in the presence of both magnetic and electric fields.

In that case, the total force is the sum of the forces due to the individual fields.

- The total force is called the Lorentz force.

In general: $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$

Velocity Selector



Used when all the particles need to move with the same velocity.

A uniform electric field is perpendicular to a uniform magnetic field.

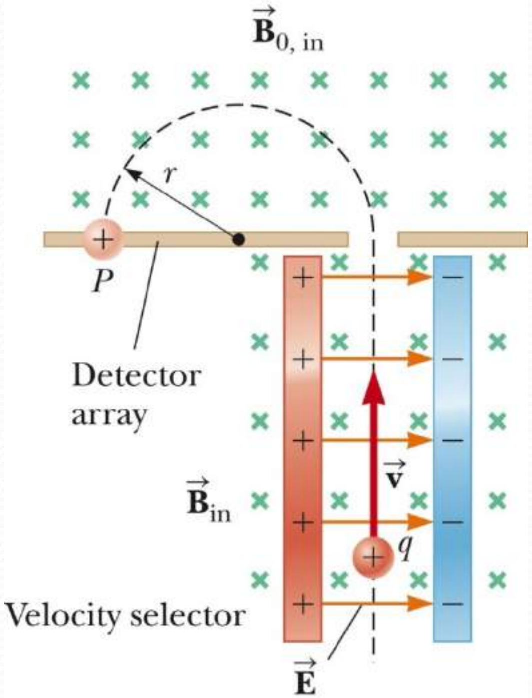
When the force due to the electric field is equal but opposite to the force due to the magnetic field, the particle moves in a straight line.

This occurs for velocities of value.

$$v = E / B$$

Only those particles with the given speed will pass through the two fields undeflected.

Mass Spectrometer



A mass spectrometer separates ions according to their mass-to-charge ratio.

In one design, a beam of ions passes through a velocity selector and enters a second magnetic field.

After entering the second magnetic field, the ions move in a semicircle of radius r before striking a detector at P.

If the ions are positively charged, they deflect to the left.

If the ions are negatively charged, they deflect to the right.

The mass to charge (m/q) ratio can be determined by measuring the radius of curvature and knowing the magnetic and electric field magnitudes.

$$\frac{m}{q} = \frac{rB_o}{v} = \frac{rB_oB}{E}$$

In practice, you can measure the masses of various isotopes of a given atom, with all the ions carrying the same charge.

- The mass ratios can be determined even if the charge is unknown.

Cyclotron

A **cyclotron** is a device that can accelerate charged particles to very high speeds.

The energetic particles produced are used to bombard a

tomic nuclei and thereby produce reactions.

These reactions can be analyzed by researchers D_1 and D_2 are called *dees* because of their shape

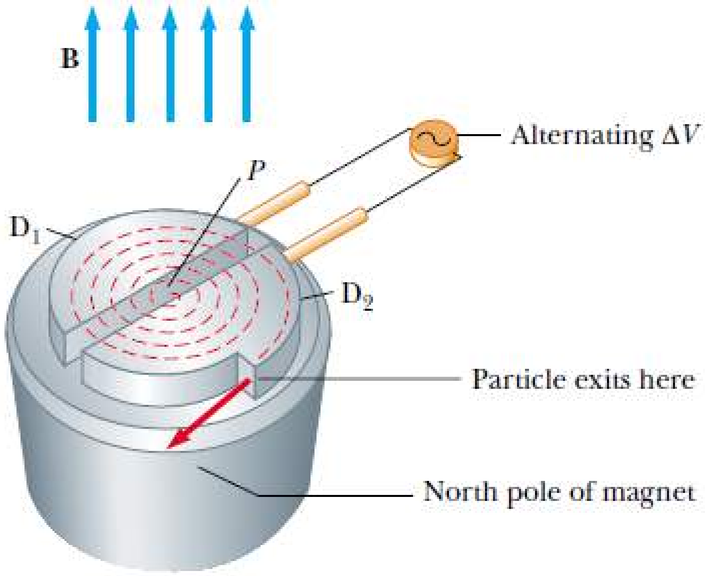
A high frequency alternating potential is applied to the dees.

A uniform magnetic field is perpendicular to them.

A positive ion is released near the center and moves in a semicircular path.

The potential difference is adjusted so that the polarity of the dees is reversed in the same time interval as the particle travels around one dee.

This ensures the kinetic energy of the particle increases each trip.



$$K = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$

Biot-Savart Law, Total Magnetic Field

Biot and Savart conducted experiments on the force exerted by an electric current on a nearby magnet. They arrived at a mathematical expression that gives the magnetic field at some point in space due a given current carrying conductor.

The observations are summarized in the mathematical equation called the **Biot-Savart law**:

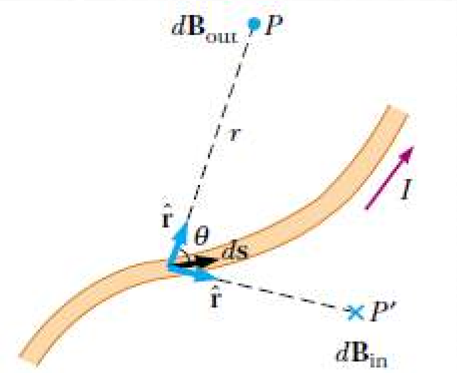
$$d\vec{B} = \frac{\mu_o}{4\pi}\frac{I\, d\vec{s} \times \hat{r}}{r^2}$$

The constant μ_o is called the **permeability of free space.** $\mu_o = 4\pi \times 10^{-7}$ T·m / A

$d\vec{B}$ is the field created by the current in the length segment ds.

To find the total field, sum up the contributions from all the current elements I $d\vec{s}$

$$\vec{B} = \frac{\mu_o I}{4\pi}\int \frac{d\vec{s} \times \hat{r}}{r^2}$$



- The integral is over the entire current distribution.

The law is also valid for a current consisting of charges flowing through space. For example, this could apply to the beam in an accelerator.

Magnetic Field Compared to Electric Field

Distance

- The magnitude of the magnetic field varies as the inverse square of the distance from the source.
- The electric field due to a point charge also varies as the inverse square of the distance from the charge.

Direction

- The electric field created by a point charge is radial in direction.
- The magnetic field created by a current element is perpendicular to both the length element $d\vec{\ell}$ and the unit vector. $\hat{\mathbf{r}}$

Source

- An electric field is established by an isolated electric charge.
- The current element that produces a magnetic field must be part of an extended current distribution.
  - Therefore you must integrate over the entire current distribution.

Example: Magnetic Field for a Long, Straight Conductor

Find the field contribution from a small element of current and then integrate over the current distribution.

The thin, straight wire is carrying a constant current

$$d\vec{s}\times\hat{\mathbf{r}} = (dx\ \sin\theta)\hat{\mathbf{k}}$$

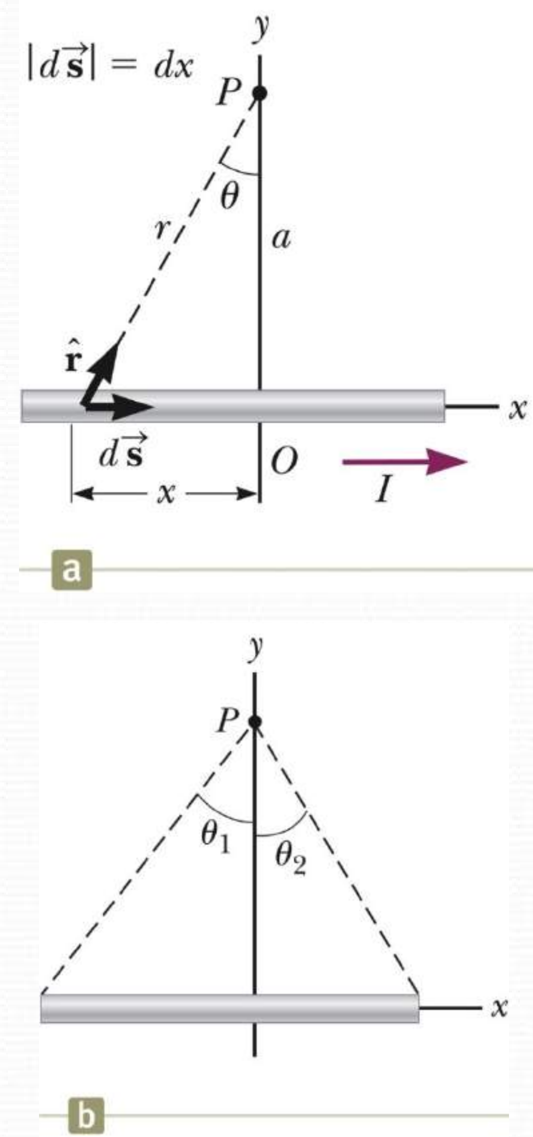
Integrating over all the current elements gives

$$B = -\frac{\mu_o I}{4\pi a}\int_{\theta_1}^{\theta_2} \cos\theta\ d\theta$$

$$= \frac{\mu_o I}{4\pi a}\left(\sin\theta_1 - \sin\theta_2\right)$$

If the conductor is an infinitely long, straight wire, $\theta_1 = \pi/2$ and $\theta_2 = -\pi/2$. The field becomes

$$B = \frac{\mu_o I}{2\pi a}$$

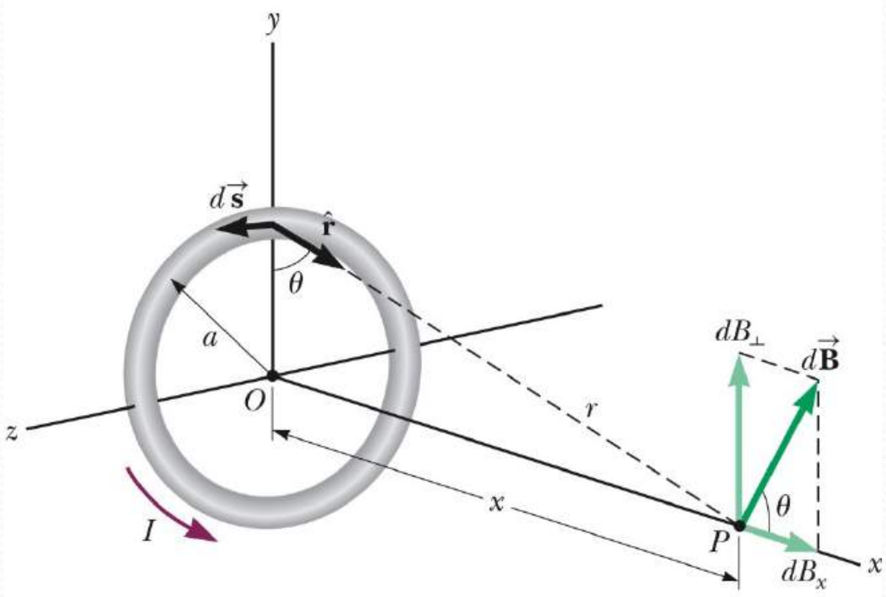


Magnetic Field for a Circular Current Loop

The loop has a radius of R and carries a steady current of I.

Find the field at point P:

$$B_x = \frac{\mu_o I a^2}{2\left(a^2 + x^2\right)^{3/2}}$$



Consider the field at the center of the current loop.

At this special point, $x = 0$

Then,

$$B_x = \frac{\mu_o I a^2}{2\left(a^2 + x^2\right)^{3/2}} = \frac{\mu_o I}{2a}$$

- This is exactly the same result as from the curved wire.

Definition of the Ampere

The force between two parallel wires can be used to define the ampere.

When the magnitude of the force per unit length between two long, parallel wires that carry identical currents and are separated by 1 m is 2×10^{-7} N/m, the current in each wire is defined to be 1 A.

Definition of the Coulomb

The SI unit of charge, the coulomb, is defined in terms of the ampere.

When a conductor carries a steady current of 1 A, the quantity of charge that flows through a cross section of the conductor in 1 s is 1 C.

Ferromagnetism

Some substances exhibit strong magnetic effects called ferromagnetism.

Some examples of ferromagnetic materials are:

- iron
- cobalt
- nickel
- gadolinium
- dysprosium

They contain permanent atomic magnetic moments that tend to align parallel to each other even in a weak external magnetic field.

Paramagnetism

Paramagnetic substances have small but positive magnetism.

It results from the presence of atoms that have permanent magnetic moments.

When placed in an external magnetic field, its atomic moments tend to line up with the field.

- The alignment process competes with thermal motion which randomizes the moment orientations.

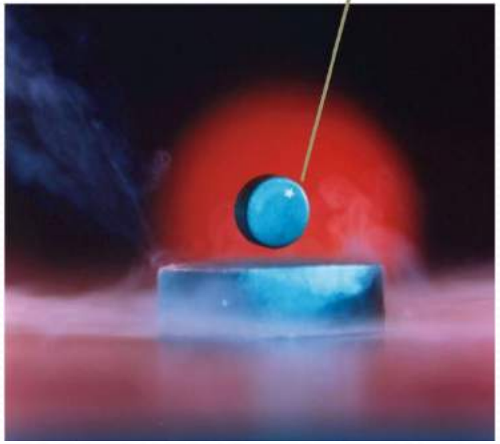
Diamagnetism

When an external magnetic field is applied to a diamagnetic substance, a weak magnetic moment is induced in the direction opposite the applied field.

Diamagnetic substances are weakly repelled by a magnet.

Certain types of superconductors also exhibit perfect diamagnetism in the superconducting state. This is called the **Meissner effect.** If a permanent magnet is brought near a superconductor, the two objects repel each other.

In the Meissner effect, the small magnet at the top induces currents in the superconducting disk below, which is cooled to 321°F (77 K). The currents create a repulsive magnetic force on the magnet causing it to levitate above the superconducting disk.



General Physics

for Science and Engineering Faculties

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Chapter 11 – Nuclear Physics and Radioactivity

Some Properties of Nuclei

All nuclei are composed of protons and neutrons except hydrogen with a single proton

The **atomic number** Z equals the number of protons in the nucleus.

- Sometimes called the charge number

The **neutron number** N is the number of neutrons in the nucleus.

The **mass number** A is the number of **nucleons** in the nucleus.

- $A = Z + N$
- Nucleon is a generic term used to refer to either a proton or a neutron
- The mass number is not the same as the mass.

A **nuclide** is a specific combination of atomic number and mass number that represents a nucleus. $^{A}_{Z}\mathrm{X}$

- X is the chemical symbol of the element.

Example:

$^{27}_{13}\mathrm{Al}$

- Mass number is 27
- Atomic number is 13
- Contains 13 protons. Contains 14 (27 – 13) neutrons

More Properties

The nuclei of all atoms of a particular element must contain the same number of protons.

They may contain varying numbers of neutrons.

- **Isotopes** of an element have the same Z but differing N and A values.
- The natural abundance of isotopes can vary.
- Isotope example:

$${}^{11}_{6}C,\ {}^{12}_{6}C,\ {}^{13}_{6}C,\ {}^{14}_{6}C$$

Charge

The proton has a single positive charge, *e.*

The electron has a single negative charge, - *e.*

- $e = 1.6 \times 10^{-19}$ C

The neutron has no charge.

Mass

It is convenient to use *atomic mass units*, u, to express masses.

- 1 u = 1.660 539 x 10^{-27} kg
- Based on definition that the mass of one atom of ^{12}C is exactly 12 u

Mass can also be expressed in MeV/c^2.

- From $E_R = mc^2$
- 1 u = 931.494 MeV/c^2
  - Includes conversion 1 eV = 1.602 176 x 10^{-19} J

Masses of Selected Particles in Various Units

	Mass		
Particle	**kg**	**u**	**MeV/c^2**
Proton	$1.672\,62 \times 10^{-27}$	1.007 276	938.28
Neutron	$1.674\,93 \times 10^{-27}$	1.008 665	939.57
Electron	$9.109\,39 \times 10^{-31}$	$5.485\,79 \times 10^{-4}$	0.510 999
$^1_1$H atom	$1.673\,53 \times 10^{-27}$	1.007 825	938.783
$^4_2$He nucleus	$6.644\,66 \times 10^{-27}$	4.001 506	3 727.38
$^{12}_6$C atom	$1.992\,65 \times 10^{-27}$	12.000 000	11 177.9

Size of Nucleus

Rutherford concluded that the positive charge of the atom was concentrated in a sphere whose radius was no larger than about 10^{-14} m.

- He called this sphere the nucleus.

These small lengths are often expressed in femtometers (fm) where 1 fm = 10^{-15} m. Also called a fermi

Since the time of Rutherford, many other experiments have concluded the following:

- Most nuclei are approximately spherical.
- Average radius is $r = a A^{1/3}$
  - a = 1.2 x 10^{-15} m
  - A is the mass number

There are very large repulsive electrostatic forces between protons.

- These forces should cause the nucleus to fly apart.

The nuclei are stable because of the presence of another, short-range force, called the **nuclear force.**

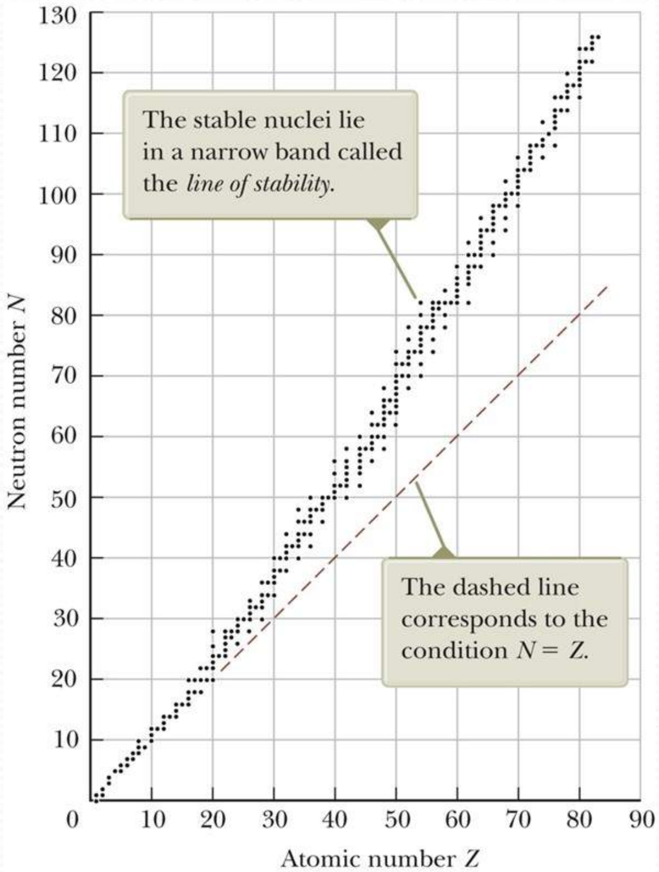
Nuclear Stability

There are very large repulsive electrostatic forces between protons.

- These forces should cause the nucleus to fly apart.

The nuclei are stable because of the presence of another, short-range force, called the **nuclear force.**

- This is an attractive force that acts between all nuclear particles.
- The nuclear attractive force is stronger than the Coulomb repulsive force at the short ranges within the nucleus.



Features of the Nuclear Force

Attractive force that acts between all nuclear particles

Very short range. Independent of charge

- The nuclear force on p-p, p-n, n-n are all the same
- Does not affect electrons

Binding Energy

The total energy of the bound system (the nucleus) is less than the combined energy of the separated nucleons.

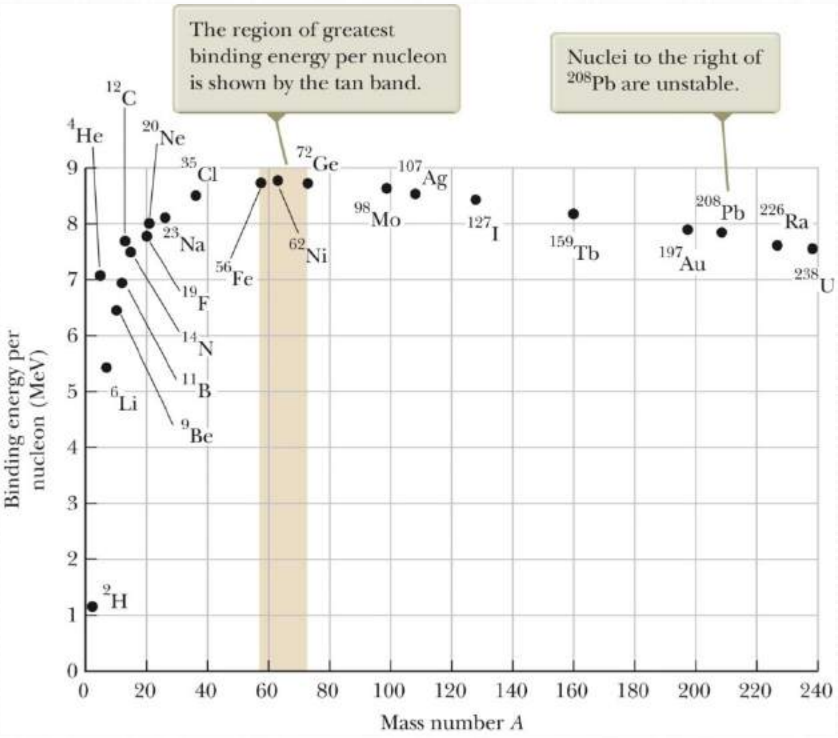
- This difference in energy is called the **binding energy** of the nucleus.
  - It can be thought of as the amount of energy you need to add to the nucleus to break it apart into its components.

The binding energy can be calculated from conservation of energy and the Einstein mass-energy equivalence principle:

$E_b = [Z m_p + N M_n – M(^A_Z X)] \times 931.494$ MeV/u

  - M_p is the mass of the proton
  - M (^A_ZX) represents the atomic mass of an atom of the isotope (^A_ZX)
  - M_n is the mass of the neutron

- The masses are expressed in atomic mass units and E_b will be in MeV.



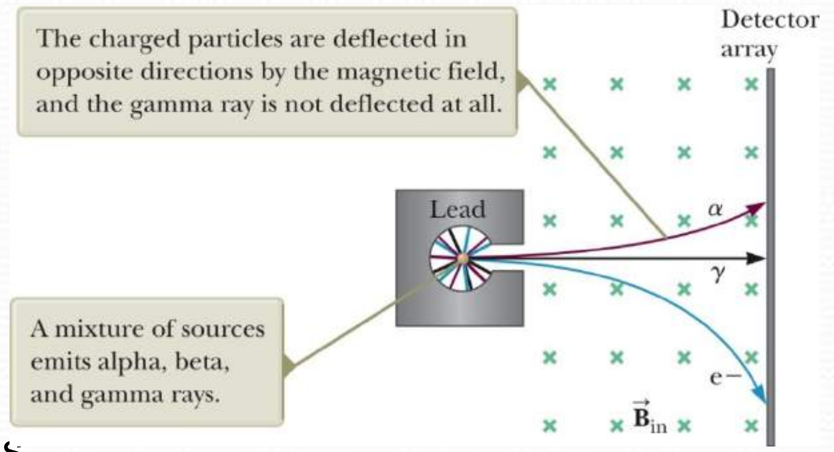
Radioactivity

Radioactivity is the spontaneous emission of radiation.

- Discovered by Becquerel in 1896

Experiments suggested that radioactivity was the result of the decay, or disintegration, of unstable nuclei.

Three types of radiation can be emitted.



- Alpha particles
  - The particles are ^{4}He nuclei.
  - Barely penetrate a piece of paper
- Beta particles
  - The particles are either electrons or positrons.
    - A **positron** is the antiparticle of the electron.
    - It is similar to the electron except its charge is +e.
    - Can penetrate a few mm of aluminum
- Gamma rays
  - The “rays” are high energy photons.
  - Can penetrate several cm of lead

The Decay Constant

The number of particles that decay in a given time is proportional to the total number of particles in a radioactive sample.

$$\frac{dN}{dt} = -\lambda N \text{ gives } N = N_o e^{-\lambda t}$$

- λ is called the **decay constant** and determines the probability of decay per nucleus per second.
- N is the number of undecayed radioactive nuclei present.
- N_o is the number of undecayed nuclei at time t = 0.

The **decay rate** R of a sample is defined as the number of decays per second.

$$R = \left|\frac{dN}{dt}\right| = \lambda N = R_o e^{-\lambda t}$$

- $R_o = N_o\lambda$ is the decay rate at t = 0.
- The decay rate is often referred to as the activity of the sample.

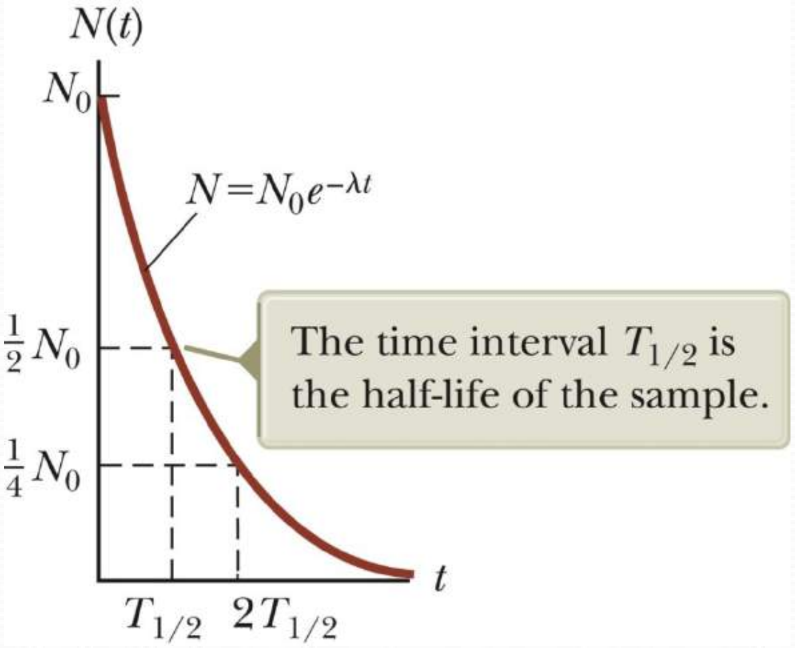
Decay Curve and Half-Life

The decay curve follows the equation $N = N_o e^{-\lambda t}$

The **half-life** is also a useful parameter.

- The half-life is defined as the time interval during which half of a given number of radioactive nuclei decay.

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$



During the first half-life, ½ of the original material will decay.

During the second half-life, ½ of the remaining material will decay, leaving ¼ of the original material remaining.

Summarizing, the number of undecayed radioactive nuclei remaining after *n* half-lives is $N = N_o (½)^n$

- *n* can be an integer or a noninteger.

Units

The unit of activity, R, is the **curie** (Ci)

- 1 Ci ≡ 3.7 x 10^{10} decays/s

The SI unit of activity is the **becquerel** (Bq)

- 1 Bq ≡ 1 decay/s
  - Therefore, 1 Ci = 3.7 x 10^{10} Bq

The most commonly used units of activity are the millicurie and the microcurie.

Marie Curie [1867 – 1934] Polish scientist

Shared Nobel Prize in Physics in 1903 for studies in radioactive substances

- Shared with Pierre Curie and Becquerel

Won Nobel Prize in Chemistry in 1911 for discovery of radium and polonium

Natural Radioactivity

Unstable nuclei found in nature. They give rise to ***natural radioactivity.*** Three series of natural radioactivity exist.

- Uranium, Actinium, Thorium

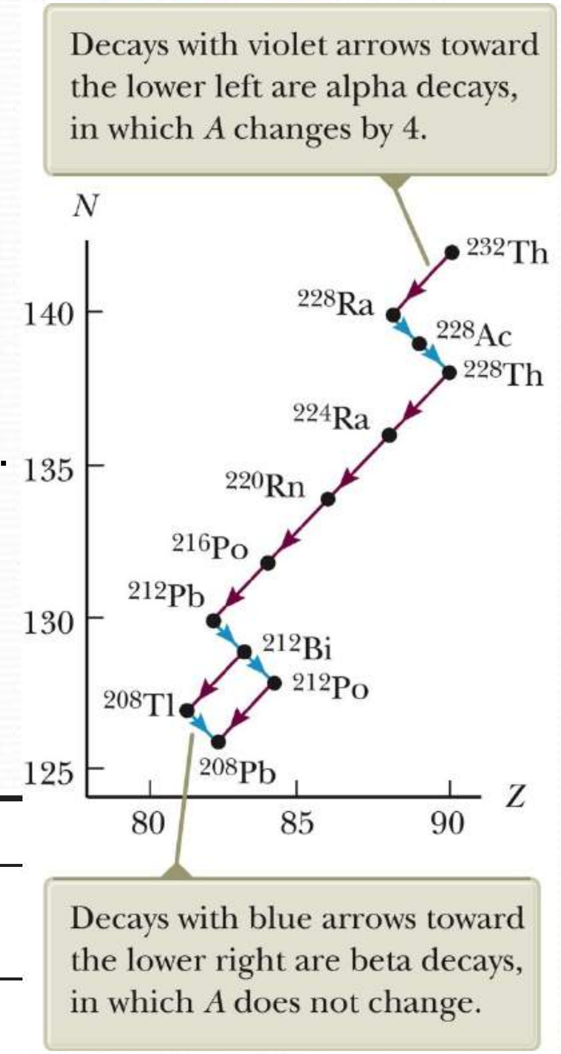
Nuclei produced in the laboratory through nuclear reactions. They exhibit ***artificial radioactivity***

Some radioactive isotopes are not part of any decay series.

Decay Series of ^{232}Th:

Processes through a series of alpha and beta decays

Series starts with ^{232}Th, branches at ^{212}Bi, Ends with a stable isotope of lead, ^{208}Pb



The Four Radioactive Series

Series		Starting Isotope	Half-life (years)	Stable End Product
Uranium	Natural	$^{238}_{92}U$	4.47×10^9	$^{206}_{82}Pb$
Actinium	Natural	$^{235}_{92}U$	7.04×10^8	$^{207}_{82}Pb$
Thorium	Natural	$^{232}_{90}Th$	1.41×10^{10}	$^{208}_{82}Pb$
Neptunium		$^{237}_{93}Np$	2.14×10^6	$^{209}_{83}Bi$

Example: The Activity of Carbon

At time t =0, a radioactive sample contains 3.50 mg of pure $^{11}_{6}C$, which has a half-life of 20.4 min.

(A) Determine the number N_0 of nuclei in the sample at t =0.

The molar mass of $^{11}_{6}C$ is approximately 11.0 g/mol.

$$n = \frac{3.50 \times 10^{-6}\text{ g}}{11.0\text{ g/mol}} = 3.18 \times 10^{-7}\text{ mol}$$

$$N_0 = 3.18 \times 10^{-7}\text{ mol}(6.02 \times 10^{23}\text{ nuclei/mol}) = 1.92 \times 10^{17}\text{ nuclei}$$

(B) What is the activity of the sample initially and after 8.00 h?

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{20.4\text{ min}}\left(\frac{1\text{ min}}{60\text{ s}}\right) = 5.66 \times 10^{-4}\text{ s}^{-1}$$

$$R_0 = \lambda N_0 = (5.66 \times 10^{-4}\text{ s}^{-1})(1.92 \times 10^{17}) = 1.08 \times 10^{14}\text{ Bq}$$

$$R = R_0 e^{-\lambda t} = (1.08 \times 10^{14}\text{ Bq})e^{-(5.66\times10^{-4}\text{ s}^{-1})(2.88\times10^{4}\text{ s})} = 8.96 \times 10^{6}\text{ Bq}$$

Example: Radioactive Dating

A piece of charcoal containing 25.0 g of carbon is found in some ruins of an ancient city. The sample shows a ^{14}C activity *R* of 250 decays/min. How long has the tree from which this charcoal came been dead? the ratio of ^{14}C to ^{12}C in the live sample was 1.3×10^{12}

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{(5\,730\text{ yr})(3.16 \times 10^{7}\text{ s/yr})}$$

$$= 3.83 \times 10^{-12}\text{ s}^{-1}$$

1- Calculate the number of moles

in 25.0 g of carbon:

$$n = \frac{25.0\text{ g}}{12.0\text{ g/mol}} = 2.083\text{ mol}$$

2- Find the number of ^{12}C nuclei and

find the number of 14C nuclei *before* decay

$$N(^{12}\text{C}) = 2.083\text{ mol}(6.02 \times 10^{23}\text{ nuclei/mol}) = 1.25 \times 10^{24}\text{ nuclei}$$

$$N_0(^{14}\text{C}) = (1.3 \times 10^{-12})(1.25 \times 10^{24}) = 1.63 \times 10^{12}\text{ nuclei}$$

3-Find the initial activity of the sample:

$$R_0 = \lambda N_0 = (3.83 \times 10^{-12}\text{ s}^{-1})(1.63 \times 10^{12}\text{ nuclei})$$

$$= 6.24\text{ decays/s} = 374\text{ decays/min}$$

4- Evaluate *t*

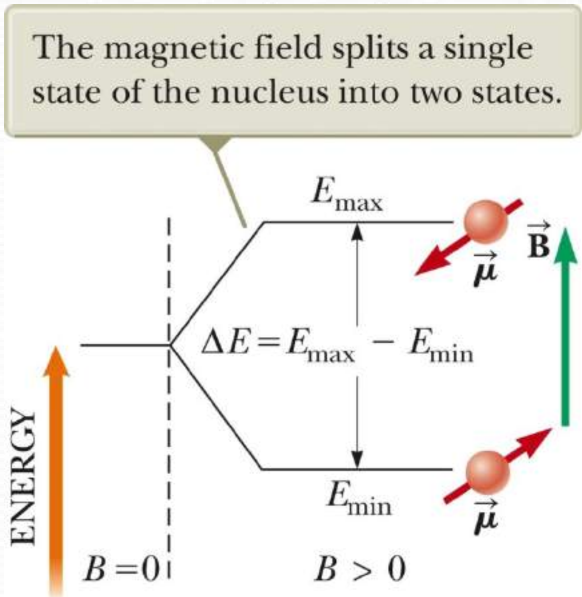
$$e^{-\lambda t} = \frac{R}{R_0} \quad \rightarrow \quad -\lambda t = \ln\left(\frac{R}{R_0}\right) \quad \rightarrow \quad t = -\frac{1}{\lambda}\ln\left(\frac{R}{R_0}\right)$$

$$t = -\frac{1}{3.83 \times 10^{-12}\text{ s}^{-1}} \ln\left(\frac{250\text{ min}^{-1}}{374\text{ min}^{-1}}\right)$$

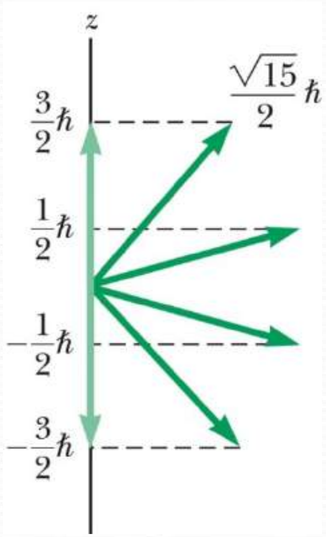
$$= 1.06 \times 10^{11}\text{ s} = \boxed{3.3 \times 10^{3}\text{ yr}}$$

Nuclear Magnetic Resonance (NMR)

A nucleus has spin angular momentum.



Shown is a vector model giving possible orientations of the spin and its projection on the *z* axis.



The magnitude of the spin angular momentum is

$$\sqrt{I(I+1)}\hbar$$

I is the nuclear spin quantum number.

For a nucleus with spin ½, there are only two allowed states E_{max} and E_{min}

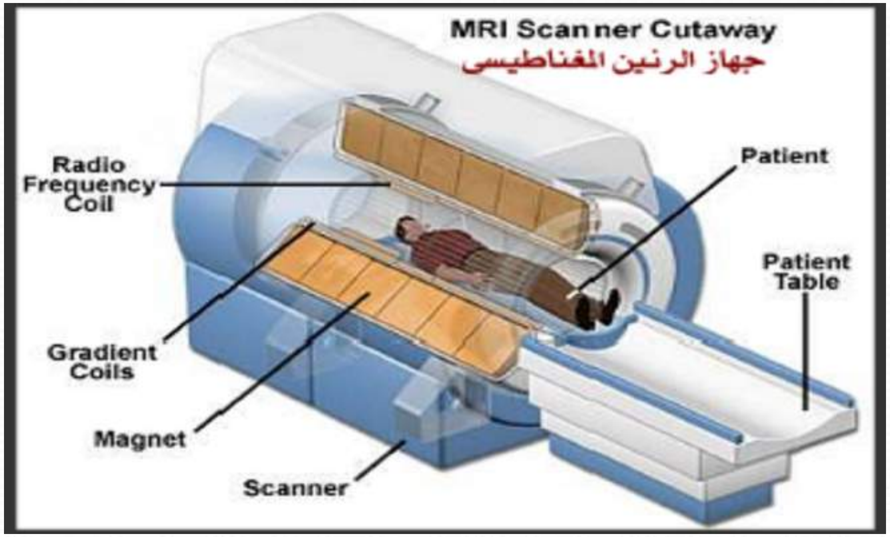
It is possible to observe transitions between two spin states using NMR.

MRI

An MRI (Magnetic Resonance Imaging) is based on NMR.

Because of variations in an external field, hydrogen atoms in different parts of the body have different energy splittings between spin states. The resonance signal can provide information about the positions of the protons.

Magnetic Resonance Imaging (MRI)



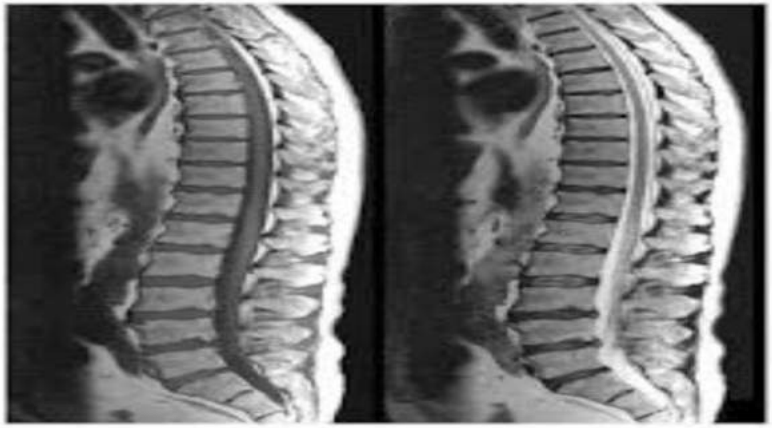
MRI scanning uses magnetism, radio waves, and a computer to produce images of body structures.

MRI scanning is painless and does not involve x-ray radiation.

Patients with heart pacemakers, metal implants, or metal chips or clips in or around the eyes cannot be scanned with MRI because of the effect of the magnet.

Claustrophobic sensation can occur with MRI scanning.

Example: As in figure, pictures of an MRI of the spine. This patient had a herniated disc between vertebrae L4 and L5. The resulting surgery was a discectomy.



Nuclear Reactions

The structure of nuclei can be changed by bombarding them with energetic particles. The changes are called **nuclear reactions.**

The following must be conserved in any nuclear reaction or decay:

- Energy, Momentum, Total charge, Total number of nucleons (also the atomic numbers and mass numbers)

A target nucleus, X, is bombarded by a particle a, resulting in a daughter nucleus Y and an outgoing particle b.

- $a + X \rightarrow Y + b$

The **reaction energy** Q is defined as the *total change in mass-energy resulting from the reaction.*

- $Q = (M_a + M_X - M_Y - M_b)c^2$

If a and b are identical, so that X and Y are also necessarily identical, the reaction is called a **scattering event.**

- If the kinetic energy before the event is the same as after, it is classified as ***elastic scattering***.
- If the kinetic energies before and after are not the same, it is an ***inelastic scattering***.

Nuclear Magnetic Resonance (NMR)

A nucleus has spin angular momentum.

Shown is a vector model giving possible orientations of the spin and its projection on the *z* axis.

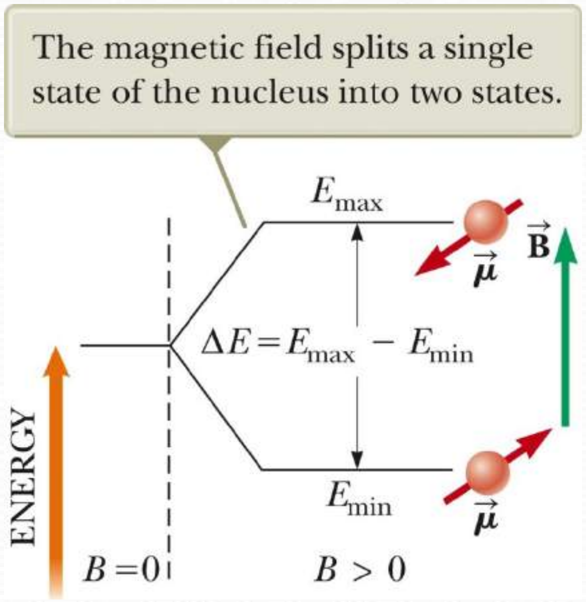
The magnitude of the spin angular momentum is

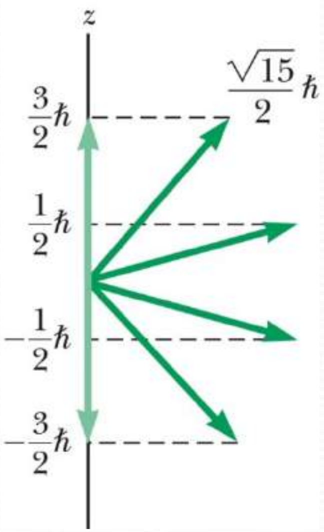
$$\sqrt{I(I+1)}\hbar$$

I is the nuclear spin quantum number.

For a nucleus with spin ½, there are only two allowed states E_{max} and E_{min}

It is possible to observe transitions between two spin states using NMR.





MRI

An MRI (Magnetic Resonance Imaging) is based on NMR.

Because of variations in an external field, hydrogen atoms in different parts of the body have different energy splittings between spin states. The resonance signal can provide information about the positions of the protons.

Nuclear Fission

A heavy nucleus splits into two smaller nuclei.

Fission is initiated when a heavy nucleus captures a thermal neutron.

The total mass of the daughter nuclei is less than the original mass of the parent nucleus. This difference in mass is called the **mass defect.**

- Multiplying the mass defect by c^2 gives the numerical value of the released energy.

First observed in 1938 by Otto Hahn and Fritz Strassman following basic studies by Fermi. Lise Meitner and Otto Frisch soon explained what had happened.

- After absorbing a neutron, the uranium nucleus had split into two nearly equal fragments. About 200 MeV of energy was released.

Fission Equation: ^{235}U

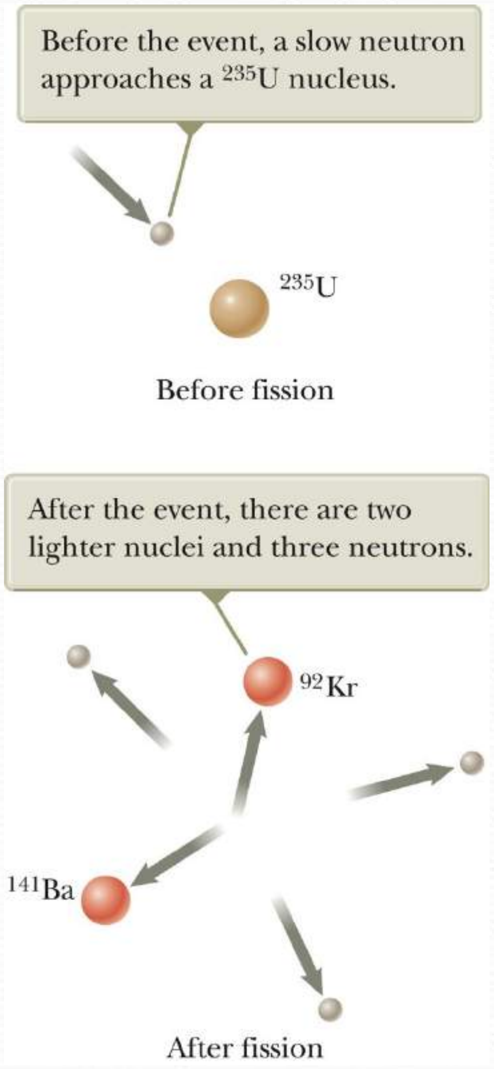
Fission of ^{235}U by a thermal neutron

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{92}^{236}U^{*} \rightarrow X + Y + \text{neutrons} $$

- $^{236}U^{*}$ is an intermediate, excited state that exists for about 10^{-12} s before splitting.
- X and Y are called **fission fragments.**
  - Many combinations of X and Y satisfy the requirements of conservation of energy and charge.

A typical fission reaction for uranium is

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3\left({}_{0}^{1}n\right) $$



Neutrons are emitted when ^{235}U undergoes fission. An average of 2.5 neutrons. These neutrons are then available to trigger fission in other nuclei.

This process is called a **chain reaction.**

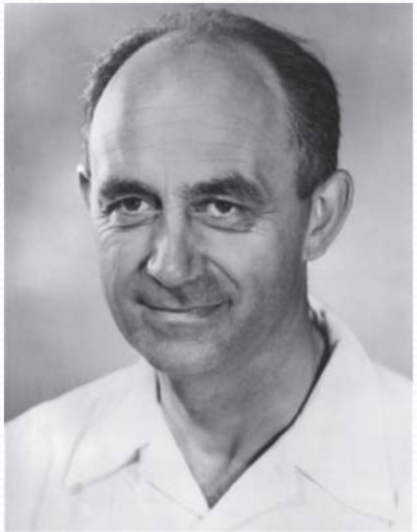
- If uncontrolled, a violent explosion can occur.
- When controlled, the energy can be put to constructive use.

Nuclear Reactor

A *nuclear reactor* is a system designed to maintain a **self-sustained chain reaction.**

The **reproduction constant** K is defined as the average number of neutrons from each fission event that will cause another fission event.

- The average value of K from uranium fission is 2.5.
  - In practice, K is less than this



Moderator

The moderator slows the neutrons.

The slower neutrons are more likely to react with ^{235}U than ^{238}U.

The probability of neutron capture by ^{238}U is high when the neutrons have high kinetic energies.

The slowing of the neutrons by the moderator makes them available for reactions with ^{235}U while decreasing their chances of being captured by ^{238}U

Enrico Fermi [1901 – 1954] Italian physicist

Nobel Prize in 1938 for producing transuranic elements by neutron irradiation and for his discovery of nuclear reactions brought about by thermal neutrons.

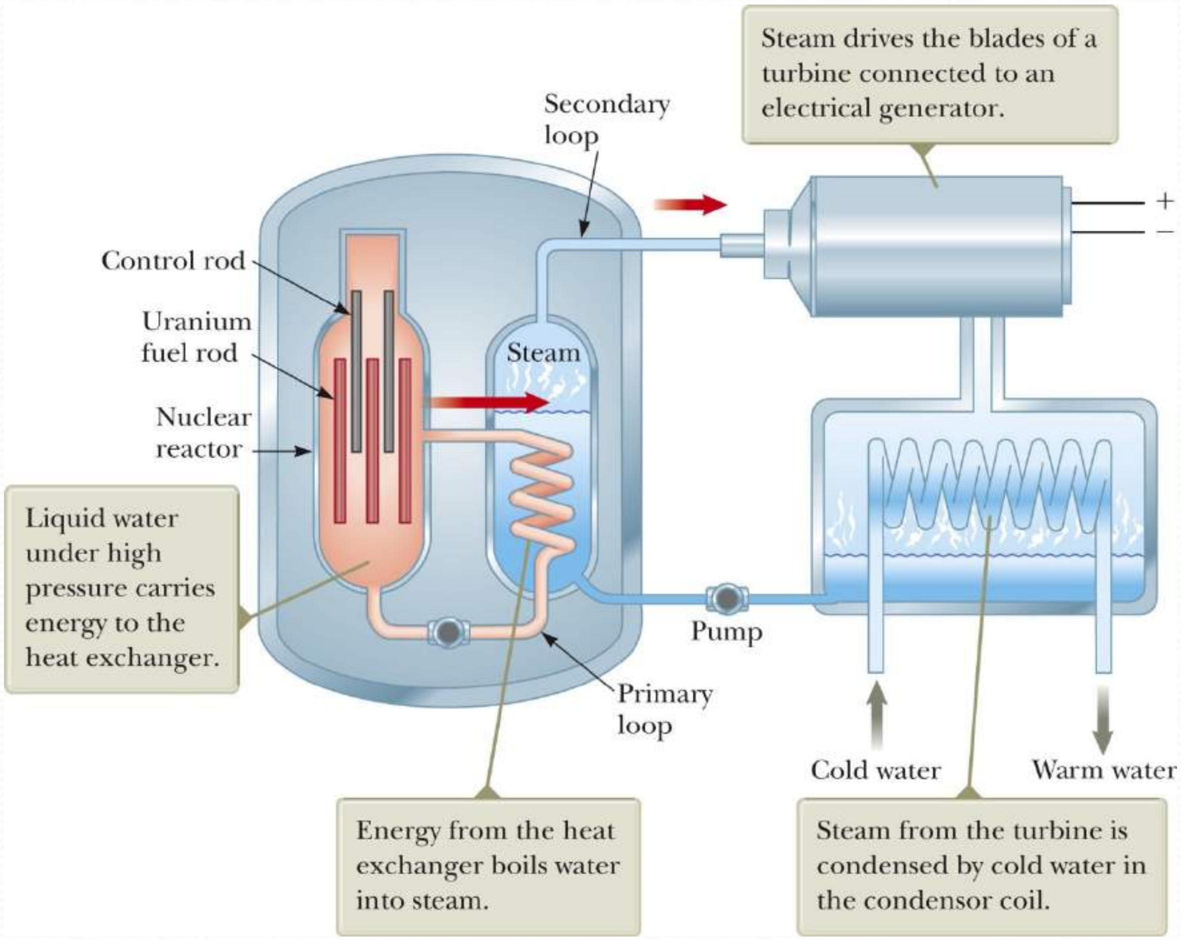
He develops of world’s first fission reactor (1942)

Pressurized Water Reactor – Diagram

Reactor Fuel

Most reactors today use uranium as fuel.

- Naturally occurring uranium is 99.3% ^{238}U and 0.7% ^{235}U
  - ^{238}U almost never fissions
  - It tends to absorb neutrons producing neptunium and plutonium.
- Fuels are generally enriched to at least a few percent ^{235}U.



Pressurized Water Reactor – Notes

This type of reactor is the most common in use in electric power plants in the US.

Fission events in the uranium In the fuel rods raise the temperature of the water contained in the primary loop. The primary system is a closed system.

This water is maintained at a high pressure to keep it from boiling.

This water is also used as the moderator to slow down the neutrons.

The hot water is pumped through a heat exchanger.

The heat is transferred by conduction to the water contained in a secondary system. This water is converted into steam.

The steam is used to drive a turbine-generator to create electric power.

The water in the secondary system is isolated from the water in the primary system. This prevents contamination of the secondary water and steam by the radioactive nuclei in the core.

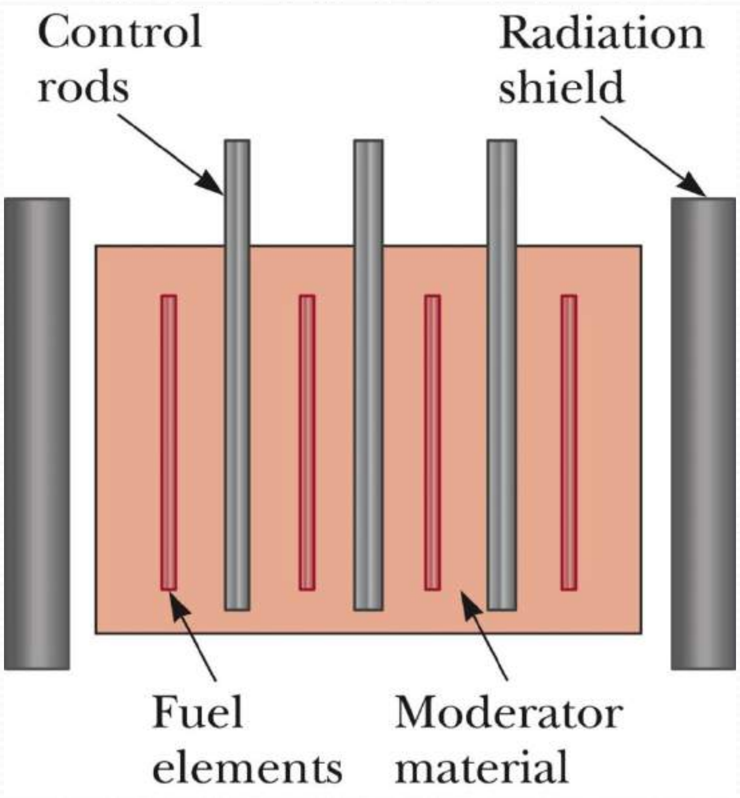
Basic Design of a Reactor Core

Fuel elements consist of enriched uranium.

The *moderator material* helps to slow down the neutrons.

The *control rods* absorb neutrons.

All of these are surrounded by a radiation shield.



Control Rods

To control the power level, control rods are inserted into the reactor core.

These rods are made of materials that are very efficient in absorbing neutrons as Cadmium.

By adjusting the number and position of the control rods in the reactor core, the K value can be varied and any power level can be achieved.

- The power level must be within the design of the reactor.

Reactor Safety

Radiation exposure, and its potential health risks, are controlled by three levels of containment:

Reactor vessel: Contains the fuel and radioactive fission products

Reactor building:

- Acts as a second containment structure should the reactor vessel rupture
- Prevents radioactive material from contaminating the environment

Location: Reactor facilities are in remote locations

Disposal and transportation of waste material

- Waste material contains long-lived, highly radioactive isotopes.
- Must be stored over long periods in ways that protect the environment
- At present, the most promising solution seems to be sealing the waste in waterproof containers and burying them in deep geological repositories.
- Accidents during transportation could expose the public to harmful levels of radiation.

Nuclear Fusion

Nuclear **fusion** occurs when two light nuclei combine to form a heavier nucleus.

The mass of the final nucleus is less than the masses of the original nuclei.

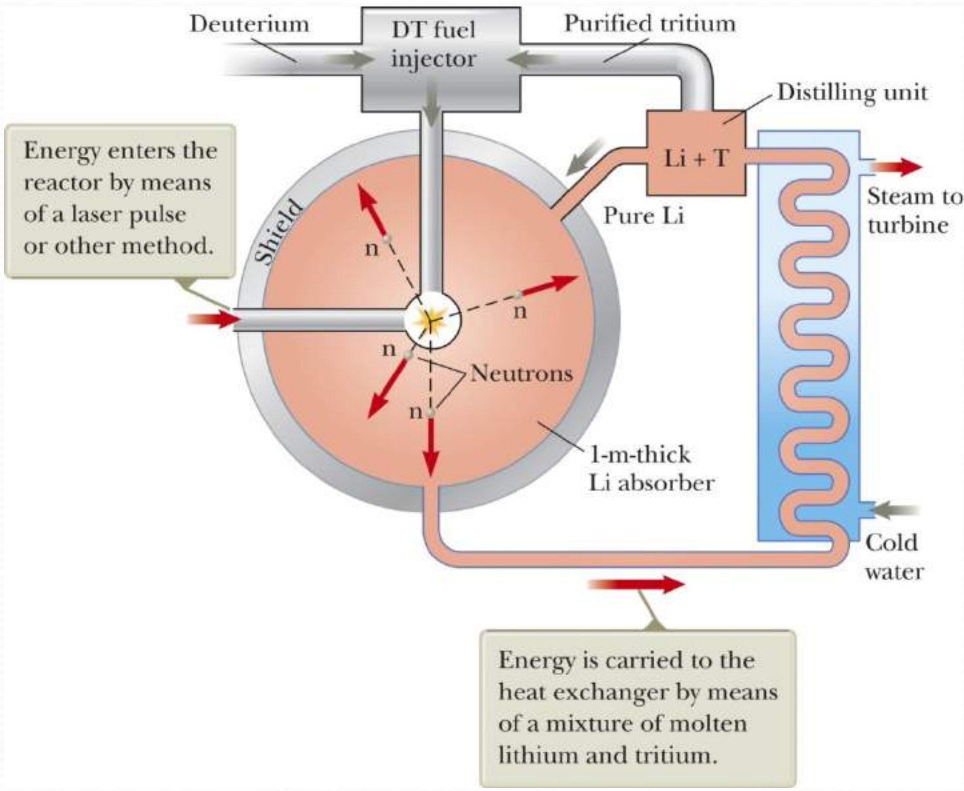
- This loss of mass is accompanied by a release of energy.

The **proton-proton cycle** is a series of three nuclear reactions believed to operate in the Sun. Energy liberated is primarily in the form of gamma rays, positrons and neutrinos.

Fusion Reactor Design.

One scheme is to use molten lithium to capture the neutrons.

The lithium goes to a heat-exchange loop and eventually produces steam to drive turbines.



Radiation Damage

Radiation absorbed by matter can cause damage.

The degree and type of damage depend on many factors.

- Type and energy of the radiation
- Properties of the matter

Radiation damage in the metals used in the reactors comes from neutron bombardment.

- They can be weakened by high fluxes of energetic neutrons producing metal fatigue.
- The damage is in the form of atomic displacements, often resulting in major changes in the properties of the material.

Radiation damage in biological organisms is primarily due to ionization effects in cells.

- Ionization disrupts the normal functioning of the cell.

Types of Damage in Cells

Somatic damage is radiation damage to any cells except reproductive ones.

- Can lead to cancer at high radiation levels
- Can seriously alter the characteristics of specific organisms

Genetic damage affects only reproductive cells.

- Can lead to defective offspring

Damage Dependence on Penetration

Damage caused by radiation also depends on the radiation’s penetrating power.

- Alpha particles cause extensive damage, but penetrate only to a shallow depth.
  - Due to their charge, they will have a strong interaction with other charged particles.
- Neutrons do not interact with material and so penetrate deeper, causing significant damage.
- Gamma rays can cause severe damage, but often pass through the material without interaction.

Units of Radiation Exposure

The **roentgen** (R) is defined as

- That amount of ionizing radiation that produces an electric charge of 3.33×10^{-10} C in 1 cm^3 of air under standard conditions.
- Equivalently, that amount of radiation that increases the energy of 1 kg of air by 8.76×10^{-3} J .

One **rad** (radiation absorbed dose)

- That amount of radiation that increases the energy of 1 kg of absorbing material by 1×10^{-2} J.

The **RBE** (relative biological effectiveness)

- The number of rads of x-radiation or gamma radiation that produces the same biological damage as 1 rad of the radiation being used.
- Accounts for type of particle which the rad itself does not

The **rem** (radiation equivalent in man)

- Defined as the product of the dose in rad and the RBE factor
  - Dose in rem = dose in rad x RBE

Radiation Levels

Natural sources – rocks and soil, cosmic rays

- Called *background radiation.* It is about 0.13 rem/yr

Upper limit suggested by US government is 0.50 rem/yr

Occupational:

- 5 rem/yr for whole-body radiation
- Certain body parts can withstand higher levels
- Ingestion or inhalation is most dangerous
- About 50% of the people exposed to a dose of 400 to 500 rem will die.

New SI units of radiation dosages: the *gray* (Gy) and the *sievert* (Sv).

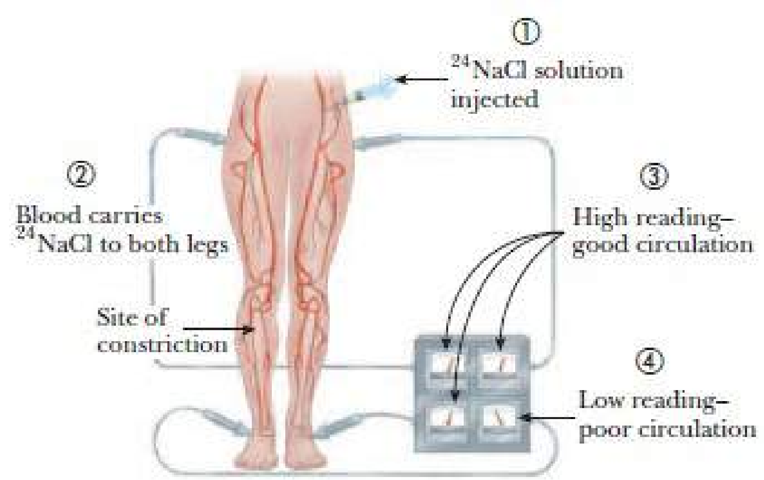
TABLE 45.2 *Units for Radiation Dosage*

Quantity	SI Unit	Symbol	Relations to Other SI Units	Older Unit	Conversion
Absorbed dose	gray	Gy	= 1 J/kg	rad	1 Gy = 100 rad
Dose equivalent	sievert	Sv	= 1 J/kg	rem	1 Sv = 100 rem

Applications of Radiation

Tracing

- Radioactive particles can be used to trace chemicals participating in various reactions.
  - Example, ^{131}I to test thyroid action
  - Also to analyze circulatory system
  - Also useful in agriculture and other applications



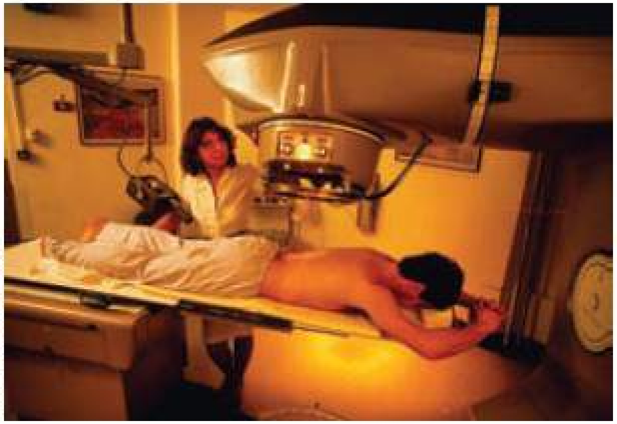
Materials analysis

- *Neutron activation analysis* uses the fact that when a material is irradiated with neutrons, nuclei in the material absorb the neutrons and are changed to different isotopes.

Applications of Radiation

Radiation therapy

- Radiation causes the most damage to rapidly dividing cells.
- Therefore, it is useful in cancer treatments.



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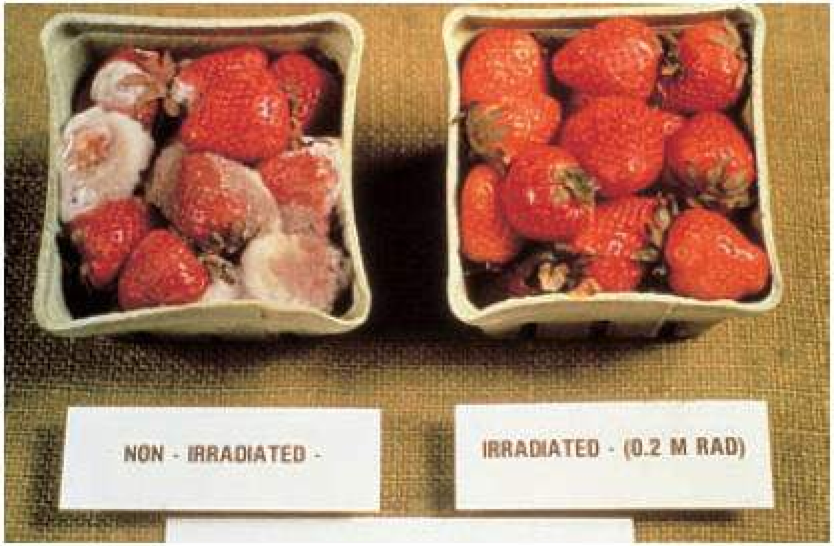
Food preservation

- High levels of radiation can destroy or incapacitate bacteria or mold spores.



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2- Power point slides of Serway book (Physics for Scientists and Engineers) from Cengage Learning Company (http://www.cengage.com).