Introduction to Biophysics

For 1st grad Faculty of physical therapy

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Table of content

Chapter 1	**Physical Quantities**	**4**
Quantitative and qualitative quantities		**5**
Scalars and Vectors quantities		**6**
The Role of Units		**6**
Divisions of units		**7**
Fundamental Units (Basic Units)		**7**
Derived Units		**7**
The international systems of units		**7**
Metric Prefixes		**8**
Dimensional Analysis		**9**
Accuracy and Precision:		**12**
Chapter 2	**Physical properties of materials**	**15**
Elasticity vs plasticity		**16**
Elasticity - Stress and Strain (Hooke's law)		**19**
Stress vs. Strain Curves		**20**
Elastic Modulus		**21**
Sideways Stress: Shear Modulus		**24**
Changes in Volume: Bulk Modulus		**26**
Elasticity of the human bone and tendon		**29**
Brittle Bones		**31**
Tendon		**32**
Strength of Human Bones		**35**
The Femur		**35**
Compression		**36**
Tension		**36**
Stress		**37**
Ultimate Strength of the Femur		**38**
Transverse Ultimate Strength		**38**
Body Levers		**39**
Lever Classes		**40**
Levers in the body		**44**
Pressure		**45**
Units, Equations and Representations		**46**
Pressure in Liquids and Gases: Fluids		**46**
Variation of Pressure with Depth		**47**
Gauge Pressure and Atmospheric Pressure		**47**
Atmospheric Pressure		**47**
Gauge Pressure		**48**

Hydrostatic Based Barometers	48
Aneroid Barometer	49
Pressure and Cardiovascular System	50
Circulation	51
The Role of Pressure in the Respiratory System	54
Pressure in the Eye	55
Surface tension	56
Cause of Surface tension	56
Effects of surface tension	57
Methods of measurement	58
Cohesion and Adhesion in Liquids	59
Adhesion and Capillary Action	59
Contact angle	60
Capillary action	61
Measuring Surface Tension	62
Chapter 3 Heat and temperature in the human body	**69**
Basic concepts of temperature and heat	70
Temperature scales:	70
Thermometers	72
Heat transfer modes	73
Conduction	73
Convection	73
Radiation	74
Specific Heat	74
Heat capacity	75
Latent heat	75
Temperature measurements in healthcare	76
Thermography	76
IRT in medical science	77
Infrared tympanic Ear Thermometer	79
Work, Energy, and Power in Humans	80
Energy Conversion in Humans	80
Power Consumed at Rest	80
How is energy stored in the body?	81
What are the human energy systems?	82
Human Energy Metabolism	85
Body energy consumption	86
How much energy do I need to consume daily?	88
Chapter 4 Sound waves in medicine	**90**

What is Sound?	**91**
Characteristics of Sound	**91**
Sound units	**93**
Speed of Sound	**94**
Human Hearing	**94**
How We Hear?	**95**
Range of Hearing	**96**
The Doppler effect	**97**
Ultrasound imaging	**98**
Ultrasound waves	**98**
From sound to image	**98**
Ultrasound Transducer	**101**
Types of Echo Display	**103**
Components of an Ultrasound Machine	**105**
Resolution	**106**
Doppler Ultrasound	**107**
Risks and side-effects	**109**
References	**111**

Chapter 1
Physical Quantities

Physical quantities

Physical Quantity refers to a characteristic of a matter or phenomenon that can be quantified. To quantify means to measure and give it a numerical value and a unit of measurement and it classified into two types:

- **Base Quantities**: are those quantities which are distinct in nature and cannot be defined by other quantities. Base quantities are those quantities based on which other quantities can be expressed. Like the brick – the basic building block of a house.
- **Derived quantities**: are those whose definitions are based on other physical quantities (base quantities). Like the house that was built from a collection of bricks (basic quantity).

Quantitative and qualitative quantities

Most observation in physics are quantitative for example What can be measured with the instruments on an airplane?

Descriptive observations (or qualitative) are usually imprecise, for example How do you measure artistic beauty?

Scalars and Vectors quantities

- **Scalar quantities** are quantities that have magnitude only, for example measuring mass and temperature.
- **Vector quantities** are quantities that have both magnitude and direction, for example measuring force.

Scalars	Vectors
Distance	Displacement
Speed	Velocity
Mass	Weight
Time	Acceleration
Pressure	Force
Energy	Momentum

The Role of Units

Physicists, like other scientists, make observations and ask basic questions. For example, how big is an object? How much mass does it have? How far did it travel? To answer these questions, they make measurements with various instruments (e.g., meter stick, balance, stopwatch, etc.).

The measurements of physical quantities are expressed in terms of units, which are standardized values. For example, the length of a race, which is a physical quantity, can be expressed in meters (for sprinters) or kilometers (for long distance runners).

Without standardized units, it would be extremely difficult for scientists to express and compare measured values in a meaningful way.

Divisions of units

- **Fundamental Units (Basic Units)**

Fundamental units are those units that can express themselves without the assistance of any other units. For example: Kilogram (kg) is a fundamental unit because it is independently expressed and cannot be broken down to multiple units.

- **Derived Units**

Derived units are those units which cannot be expressed in the absence of fundamental units. For example: Newton (N) is a derived unit because it cannot be expressed in the absence of fundamental unit (meter) and can be broken down to multiple units (Newton equals to **kg.m /s²**).

The international systems of units

In earlier time scientists of different countries were using different systems of units for measurement. Three such systems, the CGS, the FPS (or British) system and the MKS system were in use extensively till recently. The base units for length, mass and time in these systems were as follows:

- **In CGS system they were centimetre, gram and second respectively.**
- **In FPS system they were foot, pound and second respectively.**
- **In MKS system they were metre, kilogram and second respectively.**

	MKS system (SI system)	CGS system	FPS system
Length	m(meter)	cm(centimeter)	ft (foot)
Mass	kg(kilogram)	g(gram)	lb(pound)
Time	s(second)	s(second)	s(second)

Quantity	Name	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A

Temperature	Kelvin	k
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

Metric Prefixes

Physical objects or phenomena may vary widely. For example, the size of objects varies from something very small (like an atom) to something very large (like a star). Yet the standard metric unit of length is the meter. So, the metric system includes many prefixes that can be attached to a unit. Each prefix is based on factors of 10 (10, 100, 1,000, etc., as well as 0.1, 0.01, 0.001, etc.).

Prefix	Symbol	Value	Example Name	Example Symbol	Example Value	Example Description
exa	E	10^{18}	Exameter	Em	10^{18} m	Distance light travels in a century
peta	P	10^{15}	Petasecond	Ps	10^{15} s	30 million years
tera	T	10^{12}	Terawatt	TW	10^{12} W	Powerful laser output
giga	G	10^{9}	Gigahertz	GHz	10^{9} Hz	A microwave frequency
mega	M	10^{6}	Megacurie	MCi	10^{6} Ci	High radioactivity
kilo	k	10^{3}	Kilometer	Km	10^{3} m	About 6/10 mile
hector	h	10^{2}	Hectoliter	hL	10^{2} L	26 gallons
deka	da	10^{1}	Dekagram	Dag	10^{1} g	Teaspoon of butter
deci	d	10^{-1}	Deciliter	dL	10^{-1} L	Less than half a soda
centi	c	10^{-2}	Centimeter	Cm	10^{-2} m	Fingertip thickness
mili	m	10^{-3}	Millimeter	Mm	10^{-3} m	Flea at its shoulder
micro	µ	10^{-6}	Micrometer	µm	10^{-6} m	Detail in microscope
nano	n	10^{-9}	Nanogram	Ng	10^{-9} g	Small speck of dust

pico	p	10^{-12}	Picofarad	pF	10^{-12} F	Small capacitor in radio
femto	f	10^{-15}	Femtometer	Fm	10^{-15} m	Size of a proton
atto	a	10^{-18}	Attosecond	As	10^{-18} s	Time light takes to cross an atom

Dimensional Analysis

In engineering and science, dimensional analysis is the analysis of the relationships between different physical quantities by identifying their base quantities (such as length, mass, time, and electric charge) and units of measure (such as miles vs. kilometers, or pounds vs. kilograms) and tracking these dimensions as calculations or comparisons are performed.

The importance of dimensional analysis

1. To check the correctness of the form of the equation
2. To derive a relation between the physical quantities but it can't have the values of the constants.
3. To determine the proper units for some particular terms in an equation.

Dimension of basic and derived units

The Dimension of Length	$[L]$	Basic Units
The Dimension of time	$[T]$	
The Dimension of mass	$[M]$	
The Dimension of Temperature	$[°K]$	
The Dimension of angle	dimensionless	
The Dimension of velocity	$[L][T^{-1}]$	Derived Units
The Dimension of acceleration	$[L][T^{-2}]$	
The Dimension of force	$M][L][T^{-2}]$	
The Dimension of frequency	$[T^{-1}]$	
The Dimension of density	$[M][L^{-3}]$	
The Dimension of volume	$[L^3]$	
The Dimension of pressure	$[M][L^{-1}][T^{-2}]$	
The Dimension of work	$[M][L^2][T^{-2}]$	

Example (1):

Show that the following equation is dimensionally correct:

$$X = V_o t + \frac{1}{2} a t^2$$

where (V_o) is velocity and (a) is acceleration

Solution:

$$Dim[LHS] = [L]$$

$$Dim[RHS] = \left[\frac{L}{T}\right][T] + \frac{1}{2}\left[\frac{L}{T^2}\right][T]^2 = [L] + \frac{1}{2}[L]$$

$$Dim[LHS] = Dim[RHS] \Longrightarrow$$

$$\therefore \boxed{The\ equation\ is\ dimensionally\ correct\ (ignore\ constants)}$$

Example (2):

Show that the following equation is dimensionally correct:

$$V = V_o + at$$

where (V_o) is velocity and (a) is acceleration

Solution:

$$Dim[LHS] = \left[\frac{L}{T}\right]$$

$$Dim[RHS] = \left[\frac{L}{T}\right] + \left[\frac{L}{T^2}\right][T] = \left[\frac{L}{T}\right] + \left[\frac{L}{T}\right]$$

$$Dim[LHS] = Dim[RHS] \Longrightarrow$$

$$\therefore \boxed{The\ equation\ is\ dimensionally\ correct\ (ignore\ constants)}$$

Example (3):

The period $(p)$of a simple pendulum is the time for one complete swing. How does (p)depends on mass $(m)$of the bob, the length $(L)$of the string, and the acceleration due to gravity(g)?

Solution:

$$Let\ p \propto m^a L^b g^c$$
$$p = k\, m^a L^b g^c$$
$$Dim[LHS] = Dim[RHS]$$
$$[T] = [M]^a [L]^b \left[\frac{L}{T^2}\right]^c \Rightarrow [T] = [M]^a [L]^{b+c} [T]^{-2c}$$
$$\therefore -2c = 1 \Rightarrow c = -0.5$$
$$\therefore a = 0$$
$$\therefore b + c = 0 \Rightarrow b = 0.5$$
$$\therefore\ p = k\, L^{0.5} g^{-05}$$
$$\therefore \boxed{p = k\sqrt{\frac{L}{g}}}$$

Example (4):

The wave length λ of a wave depends on the speed (v) of the wave and its frequency (f) . Decide which of the following equations is correct: $\lambda = vf$ or $\lambda = v/f$.

Solution:

$$\lambda = v^a f^b$$
$$[L] = \left[\frac{L}{T}\right]^a \left[\frac{1}{T}\right]^b = [L]^a [T]^{-a-b}$$
$$\therefore a = 1, \qquad -a - b = 0 \Rightarrow \qquad \therefore b = -1$$
$$\therefore \boxed{The\ correct\ relation\ is: \lambda = v/f}$$

$$Dim[LHS] = [L]$$

From equation (1):

$$Dim[RHS] = \left[\frac{L}{T}\right]\left[\frac{1}{T}\right] = \left[\frac{L}{T^2}\right] \neq Dim[LHS] \Rightarrow Uncorrect$$

From equation (2):

$$Dim[RHS] = \left[\frac{L}{T}\right] / \left[\frac{1}{T}\right] = [L] = Dim[LHS] \Rightarrow Correct$$

$$\therefore \boxed{The\ correct\ relation\ is: \lambda = v/f}$$

Example (5):

Newton's second law states that acceleration is proportional to the force acting on an object and is inversely proportional to the object mass. What are the dimensions of force?

Solution:

$$The\ acceleration\ a \longrightarrow [a]=[L]/[T]^2, \quad The\ force\ F \longrightarrow [F]??$$

$$The\ mass\ m \longrightarrow [m]=[M]$$

$$a \propto Fm^{-1} \Rightarrow a=\frac{kF}{m}$$

$$\therefore F=\frac{ma}{k} \Rightarrow \boxed{[F]=[m][a]=[M][L][T^{-2}]}$$

Example (6):

Suppose a sphere of Radius (R) is pulled at constant speed (v) through a fluid viscosity η. The force (F) that is required to pull the sphere through the fluid depends on v, R and η, (F = ($const$)$vR\eta$). Find the dimensions of η.

Solution:

$$[R]=[L], \quad [v]=\left[\frac{L}{T}\right], \quad [F]=\frac{[M][L]}{[T^2]}, \quad [\eta]=??$$

$$F=(const)vR\eta$$

$$\therefore \eta=\frac{F}{(const)vR} \Rightarrow [\eta]=\frac{[F]}{[v][R]}$$

$$\therefore [\eta]=\frac{[M][L]}{[T^2]}\frac{1}{\left[\frac{L}{T}\right][L]}$$

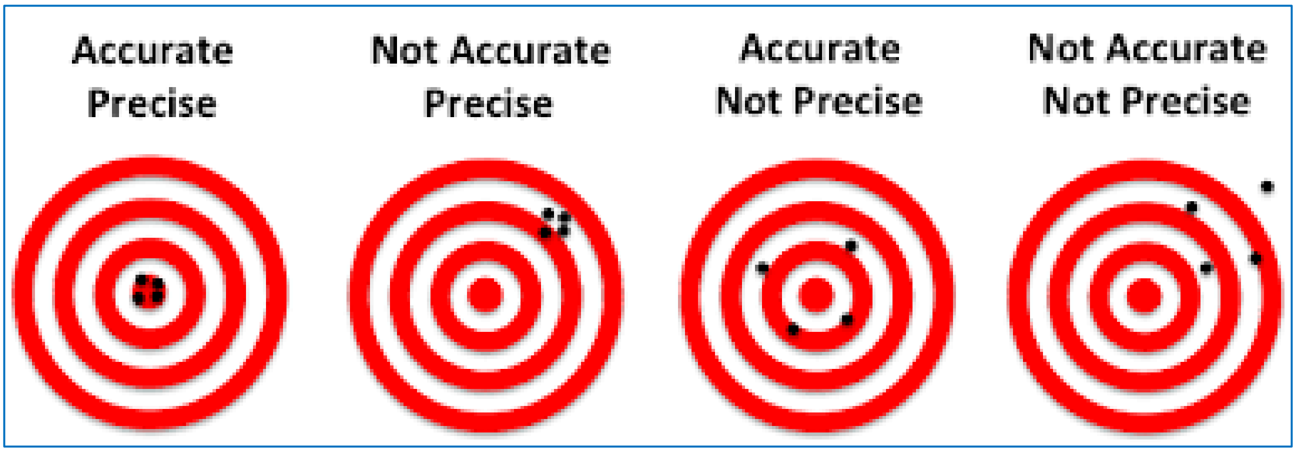
$$\therefore \boxed{[\eta]=\frac{[M]}{[L][T]}}$$

Accuracy and Precision:

Accuracy refers to the closeness of a measured value to a standard or known value. For example, if in lab you obtain a weight measurement of 3.2 kg for a given substance, but the actual or known weight is 10 kg, then your measurement is not accurate. In this case, your measurement is not close to the known value.

Precision refers to the closeness of two or more measurements to each other. Using the example above, if you weigh a given substance five times, and get 3.2 kg each time, then your measurement is very precise. Precision is independent of accuracy. You can be very precise but inaccurate, as described above. You can also be accurate but imprecise.

For example, if on average, your measurements for a given substance are close to the known value, but the measurements are far from each other, then you have accuracy without precision.



Quiz (1)

1- <u>Write the dimensions of:</u>

Velocity – acceleration – force – work – density – pressure

2- Using the dimension analysis check the correction of the following equations:

- $v^2 = v_0{}^2 + 2a$
- $F = m\,\frac{v^2}{r}$
- $T = 2\pi\sqrt{\frac{L}{g}}$

3- Using the given data in the table draw the following formula:

$$L = \frac{V}{4}\frac{1}{v} - 0\cdot 6\,r$$

v (Hz)	256	256	320	384	520
L (cm)	35	35	27	22	15

4- Using the dimension analysis, complete the following table:

Physical quantity	Dimension	unit
Density	……………………..	……………………..
……………………..	$[M^1\,L^2\,T^{-3}]$	……………………..
……………………..	……………………..	dyne g^{-1}

5- The density of material depends on mass and volume, using the dimension analysis drive the expression for the density?

6- For the equation F α $A^a\,v^b\,d^c$, where F is the force, A is the area, v is the velocity and d is the density, find the values of a, b and c?

Chapter 2

Physical properties of materials

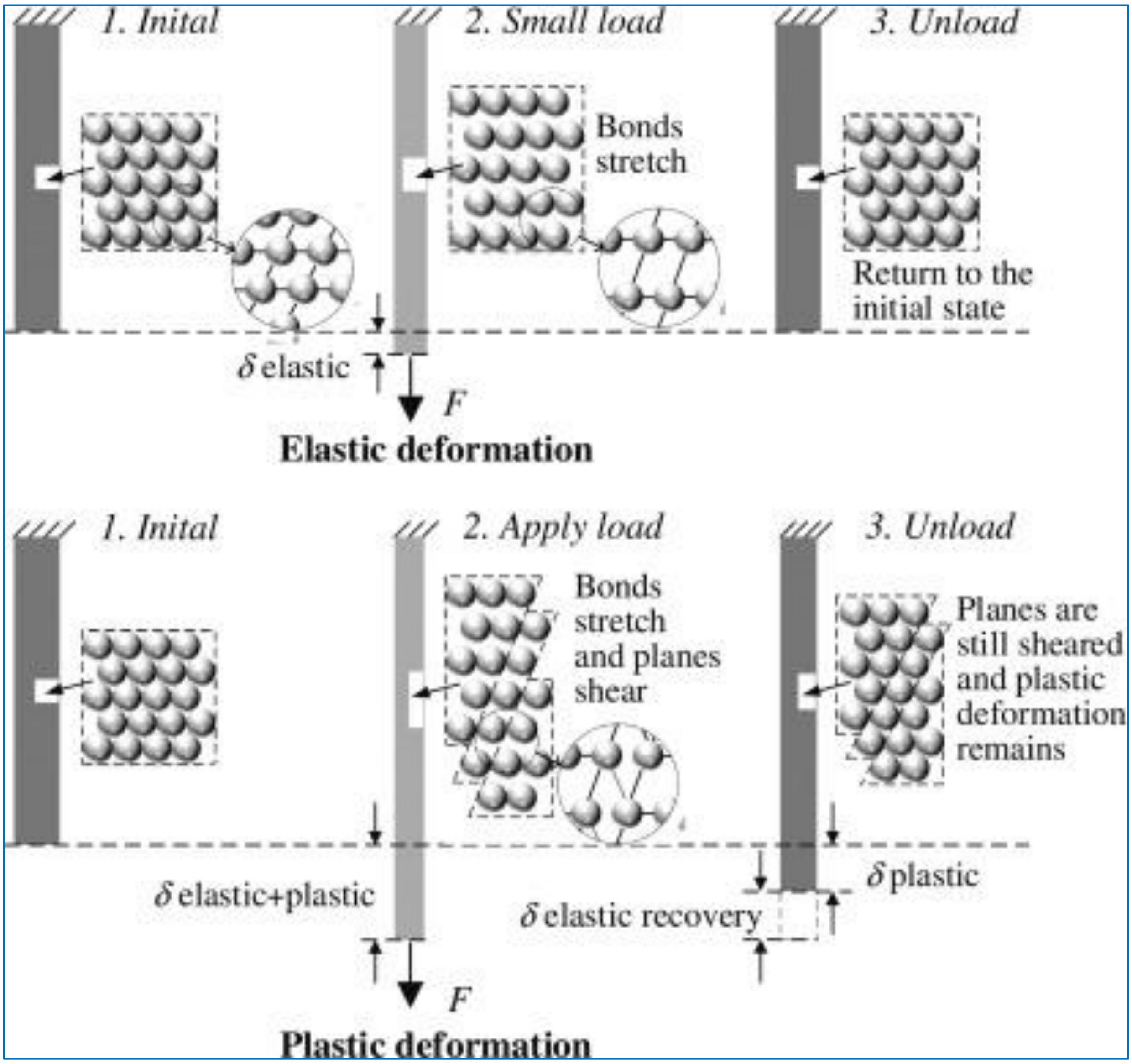
Elasticity vs plasticity

Objects deform when pushed, pulled, and twisted.

Elasticity is the measure of the amount that the object can return to its original shape after these external forces and pressures stop. This is what allows springs to store elastic potential energy.

Plasticity is the opposite of elasticity; when something is stretched, and it stays stretched, the material is said to be plastic.

- When energy goes into changing the shape of some material and it stays changed, that is said to be ***plastic deformation***.
- When the material goes back to its original form, that's ***elastic deformation***.


1. Inital
2. Small load
3. Unload
Bonds stretch
Return to the initial state
δ elastic
F
Elastic deformation
1. Inital
2. Apply load
3. Unload
Bonds stretch and planes shear
Planes are still sheared and plastic deformation remains
δ elastic+plastic
δ plastic
δ elastic recovery
F
Plastic deformation

ELASTIC DEFORMATION VERSUS PLASTIC DEFORMATION

ELASTIC DEFORMATION	PLASTIC DEFORMATION
Elastic deformation is the deformation that disappears upon the removal of the external forces, causing the alteration and the stress associated with it	Plastic deformation is the permanent deformation or change in shape of a solid body without fracture under the action of a sustained force
Reversible	Irreversible
Non-permanent; the substance can resume the initial state back	Permanent; the substance stays unchanged after removing the stress
Causes the chemical bonds of the substance to undergo stretching and bending	Cause some of the chemical bonds of the substance to undergo breakage
Atoms do not slip pass on each other	Atoms slip pass on each other

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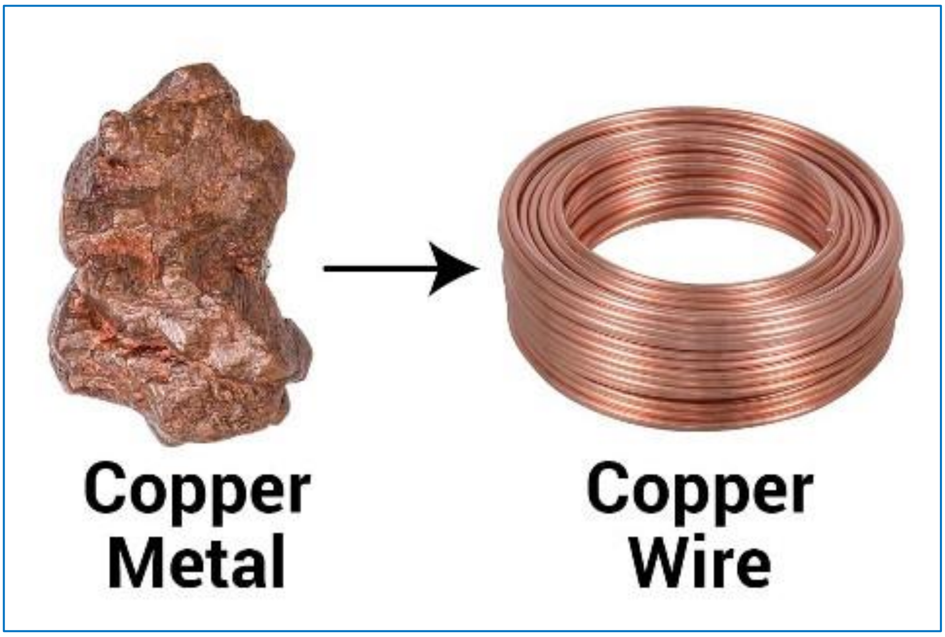
Most materials have an amount of force or pressure for which they deform elastically. If more force or pressure is applied, then they have plastic deformation. Materials that have a fair amount of plastic deformation before breaking are said to be **ductile**. Materials that can't stretch or bend much without breaking are said to be **brittle**.

Copper is quite ductile, which is part of why it is used for wires (most metals are ductile (but copper especially so).

Glass and ceramics are often brittle; they will break rather than bend!



Elasticity - Stress and Strain (Hooke's law)

A change in shape due to the application of a force is a **deformation**.

Even very small forces are known to cause some deformation. For small deformations, two important characteristics are observed.

- ⇐ **First**, the object returns to its original shape when the force is removed—that is, the deformation is elastic for small deformations.
- ⇐ **Second**, the size of the deformation is proportional to the force—that is, for small deformations, Hooke's law is obeyed. In equation form, Hooke's law is given by:

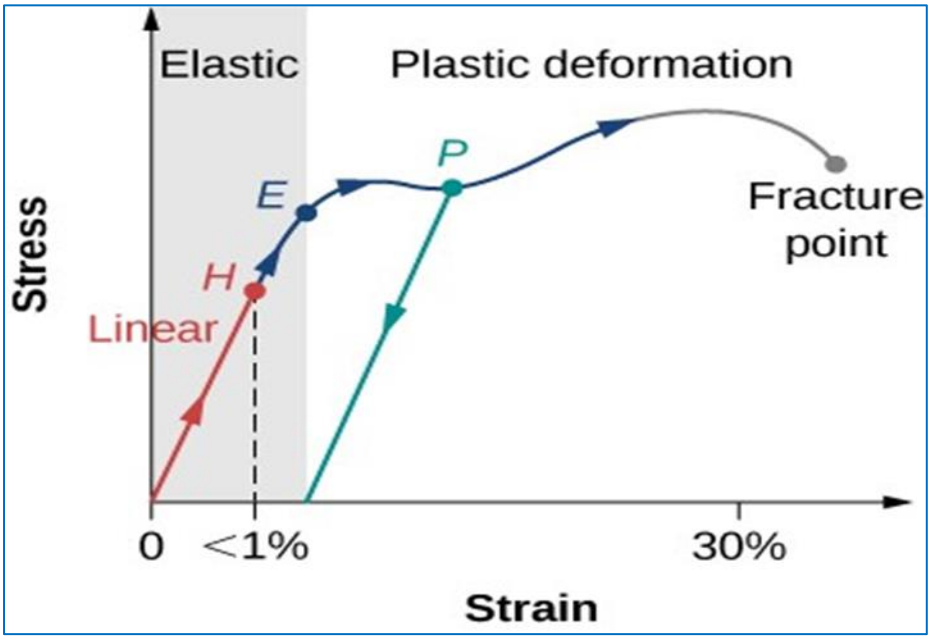
$$F = k\Delta L,$$

where ΔL is the amount of deformation (the change in length, for example) produced by the force F, and k is a proportionality constant that depends on the shape and composition of the object and the direction of the force. Note that this force is a function of the deformation ΔL it is not constant as a kinetic friction force is. Rearranging this to makes it clear that the deformation is proportional to the applied force.

$$\Delta \boldsymbol{l} = \frac{\boldsymbol{F}}{\boldsymbol{K}}$$

Stress vs. Strain Curves

If you apply stress to a material and measure the strain, or *vice versa*, you can create a stress vs. strain curve like the one shown below for a typical metal. Let's discuss the important parts of the graph:



1. The absolute highest point on the graph is the ultimate strength, indicating the onset of failure toward fracture or rupture.
2. Notice that after reaching the ultimate strength, but before full failure, the stress can actually decrease as strain increases, this is because the material is changing shape by breaking rather than stretching or compressing the distance between molecules in the material.
3. In the first part of the elastic region, the strain is proportional to the stress, this is known as the linear region.
4. After the stress reaches the linearity limit (*H*) the slope is no longer constant, but the material still behaves elastically.

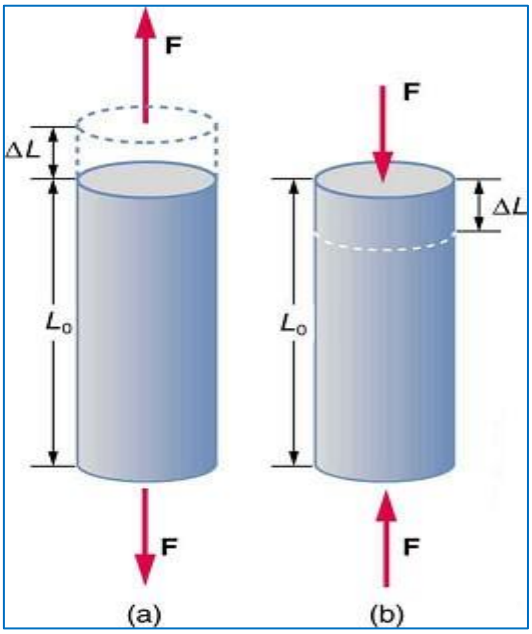
5. The elastic region ends, and the plastic region begins at the yield point (*E*). In the plastic region, a little more stress causes a lot more strain because the material is changing shape at the molecular level. In some cases, the stress can actually decrease as strain increases, because the material is changing shape by re-configuring molecules rather than just stretching or compressing the distance between molecules.
6. The green line originating at *P* illustrates the metal's return to non-zero strain value when the stress is removed after being stressed into the plastic region (permanent deformation).

Elastic Modulus

We now consider three specific types of deformations: changes in length (tension and compression), sideways shear (stress), and changes in volume. All deformations are assumed to be small unless otherwise stated.

A change in length ΔL is produced when a force is applied to a wire or rod parallel to its length L_0, either stretching it (a tension) or compressing it.

Experiments have shown that the change in length (ΔL) depends on only a few variables. As already noted, ΔL is proportional to the force F and depends on the substance from which the object is made. Additionally, the change in length is proportional to the original length L_0 and inversely proportional to the cross-sectional area of the wire or rod. For example, a long guitar string will stretch more than a short one, and a thick string will stretch less than a thin one. We can combine all these factors into one equation for ΔL:



$$\Delta L = \frac{1}{Y}\frac{F}{A}L_0$$

where ΔL is the change in length, F the applied force, Y is a factor, called **the elastic modulus or Young's modulus**, that depends on the substance, A is the cross-sectional area, and L_0 is the original length. Table lists values of Y for several materials—those with a large Y are said to have a large tensile stiffness because they deform less for a given tension or compression.

Material	Young's modulus (tension–compression) Y ($10^9 N/m^2$)	Sheer modulus S ($10^9 N/m^2$)	Bulk modulus B ($10^9 N/m^2$)
Aluminum	70	25	75
Bone – tension	16	80	8
Bone – compression	9		
Brass	90	35	75
Brick	15		
Concrete	20		
Glass	70	20	30
Granite	45	20	45
Hair (human)	10		
Hardwood	15	10	
Iron, cast	100	40	90
Lead	16	5	50
Marble	60	20	70
Nylon	5		
Polystyrene	3		
Silk	6		
Spider thread	3		
Steel	210	80	130
Tendon	1		
Acetone			0.7
Ethanol			0.9
Glycerin			4.5

Mercury			**25**
Water			**2.2**

Example: The Stretch of a Long Cable

Suspension cables are used to carry gondolas at ski resorts. Consider a suspension cable that includes an unsupported span of 3020 m. Calculate the amount of stretch in the steel cable. Assume that the cable has a diameter of 5.6 cm and the maximum tension it can withstand is $3x10^6$N.

Strategy

The force is equal to the maximum tension, or $F=3\times10^6$ N. The cross-sectional area is $\pi r^2=2.46\times10^{-3}m^2$. To find the change in length, we can use the equation:

$$\Delta L = \frac{1}{Y}\frac{F}{A}L_0$$

Solution

All quantities are known. Thus,

$$\Delta L = \left(\frac{1}{210x10^9 N/m^2}\right)\left(\frac{3x10^6 N}{2.46x10^{-3} m^2}\right)(3020m)$$

=18 m

The equation for change in length is traditionally rearranged and written in the following form:

$$\frac{F}{A} = Y\frac{\Delta L}{L_0}$$

The ratio of force to area, $\frac{F}{A}$ is defined as stress (measured in $N/m^2$and the ratio of the change in length to length, $\frac{\Delta L}{L_0}$ is defined as strain (a unitless quantity). In other words,

stress = Y ×strain.

In this form, the equation is analogous to Hooke’s law, with stress analogous to force and strain analogous to deformation. If we again rearrange this equation to the form

$$F = YA\frac{\Delta L}{L_0}$$

we see that it is the same as Hooke’s law with a proportionality constant

$$K = \frac{YA}{L_0}$$

This general idea—that force and the deformation it causes are proportional for small deformations—applies to changes in length, sideways bending, and changes in volume.

STRESS

The ratio of force to area, $\frac{F}{A}$ is defined as stress measured in N/m^2

STRAIN

The ratio of the change in length to length, $\frac{\Delta L}{L_0}$ is defined as strain (a unitless quantity). In other words,

stress=Y× strain

Sideways Stress: Shear Modulus

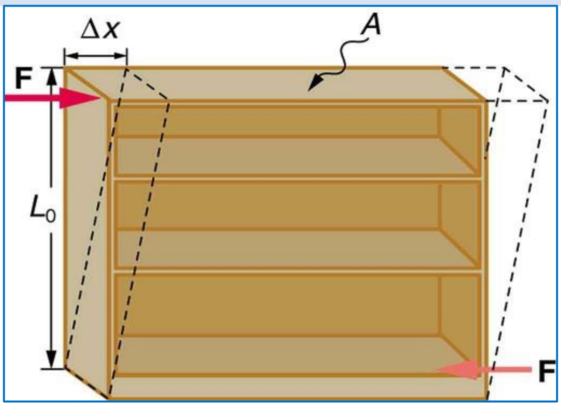
The following figure illustrates what is meant by a sideways stress or a *shearing force*. Here the deformation is called Δx and it is perpendicular to L_0, rather than parallel as with tension and compression. Shear deformation behaves similarly to tension and compression and can be described with similar equations. The expression for shear deformation is

$$\Delta x = \frac{1}{S}\frac{F}{A}L_0$$

where S is the shear modulus and F is the force applied perpendicular to L_0 and parallel to the cross-sectional area A. Again, to keep the object from accelerating, there are actually two equal and opposite forces F applied across opposite faces, as illustrated in the figure. The equation is logical—for example, it is easier to bend a long thin pencil (small A) than a short thick one, and both are more easily bent than similar steel rods (large S).

Shear deformation

$$\Delta x = \frac{1}{S}\frac{F}{A}L_0$$



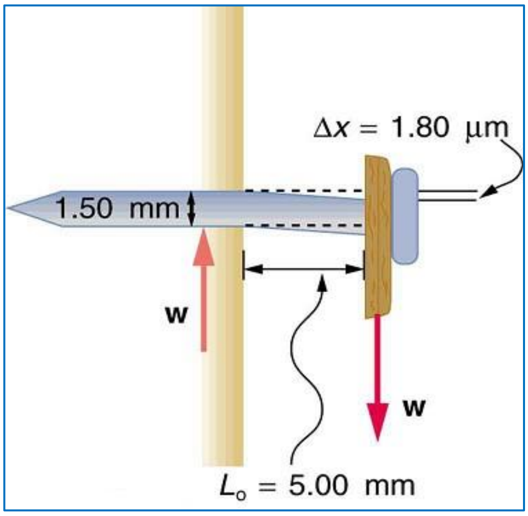
where S is the shear modulus (see Table) and F is the force applied perpendicular to L_0 and parallel to the cross-sectional area A .

Examination of the shear moduli in Table reveals some telling patterns. For example, shear moduli are less than Young's moduli for most materials.

Bone is a remarkable exception. Its shear modulus is not only greater than its Young's modulus, but it is as large as that of steel. This is why bones are so rigid.

Example: Calculating Force Required to Deform: That Nail Does Not Bend much Under a Load.

Find the mass of the picture hanging from a steel nail as shown in Figure, given that the nail bends only 1.80 µm . (Assume the shear modulus is known to two significant figures.)



Strategy

The force F on the nail (neglecting the nail's own weight) is the weight of the picture w. If we can find w, then the mass of the picture is just w/g . The equation $\Delta x = \frac{1}{S}\frac{F}{A}L_0$ can be solved for F

Solution

Solving the equation $\Delta x = \frac{1}{S}\frac{F}{A}L_0$ for F , we see that all other quantities can be found:

$$F = \frac{SA}{L_0}\Delta x$$

S is found in Table and is $S=80\times10^{9}N/m^{2}$. The radius r is 0.750 mm (as seen in the figure), so the cross-sectional area is $A=\pi r^{2}=1.77\times10^{-6}m^{2}$

The value for L_0 is also shown in the figure. Thus,

$$F = \left(\frac{(80x10^{9}N/m^{2})(1.77x10^{-6}m^{2})}{5x10^{-3}m}\right)(1.8x10^{-6}m) = 51$$

This 51 N force is the weight w of the picture, so the picture's mass is

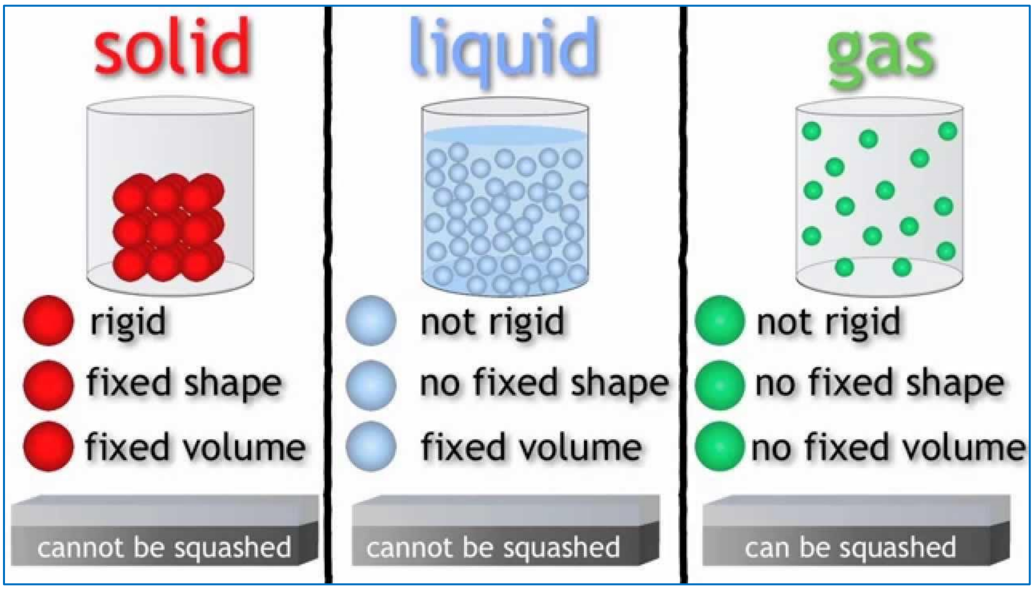
$$m = \frac{w}{g} = \frac{F}{g} = 5.2\ Kg$$

Discussion

This is a fairly massive picture, and it is impressive that the nail flexes only 1.80 µm an amount undetectable to the unaided eye.

Changes in Volume: Bulk Modulus

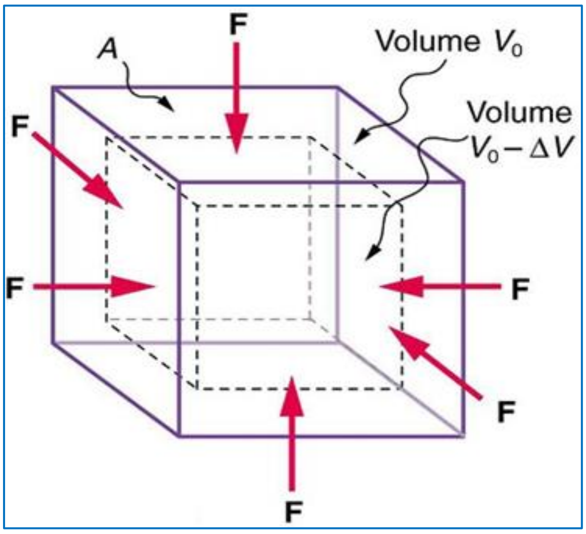
An object will be compressed in all directions if inward forces are applied evenly on all its surfaces as in the following figure. It is relatively easy to compress gases and extremely difficult to compress liquids and solids. For example, air in a wine bottle is compressed when it is corked. But if you try corking a brim-full bottle, you cannot compress the wine—some must be removed if the cork is to be inserted. The reason for these different compressibilities is that atoms and molecules are separated by large empty spaces in gases but packed close together in liquids and solids. To compress a gas, you must force its atoms and molecules closer together. To compress liquids and solids, you must actually compress their atoms and molecules, and very strong electromagnetic forces in them oppose this compression.



We can describe the compression or volume deformation of an object with an equation. First, we note that a force "applied evenly" is defined to have the same stress, or ratio of force to area $\frac{F}{A}$ on all surfaces. The deformation produced is a change in volume ΔV , which is found to behave very similarly to the shear, tension, and compression previously discussed. (This is not surprising, since a compression of the entire object is equivalent to compressing each of its three dimensions.) The relationship of the change in volume to other physical quantities is given by:

$$\Delta V = \frac{1}{B}\frac{F}{A}V_0$$

where B is the bulk modulus (see Table), V_0 is the original volume, and $\frac{F}{A}$ is the force per unit area applied uniformly inward on all surfaces. Note that no bulk moduli are given for gases.



Example: Calculating Change in Volume with Deformation: How much is Water Compressed at Great Ocean Depths?

Calculate the fractional decrease in volume $\frac{\Delta V}{V_0}$ for seawater at 5.00 km depth, where the force per unit area is $5\times10^7 N/m^2$.

Strategy

Equation $\Delta V = \frac{1}{B}\frac{F}{A}V_0$ is the correct physical relationship. All quantities in the equation except $\frac{\Delta V}{V_0}$ are known.

Solution

Solving for the unknown $\frac{\Delta V}{V_0}$ gives

$$\frac{\Delta V}{V_0} = \frac{1}{B}\frac{F}{A}$$

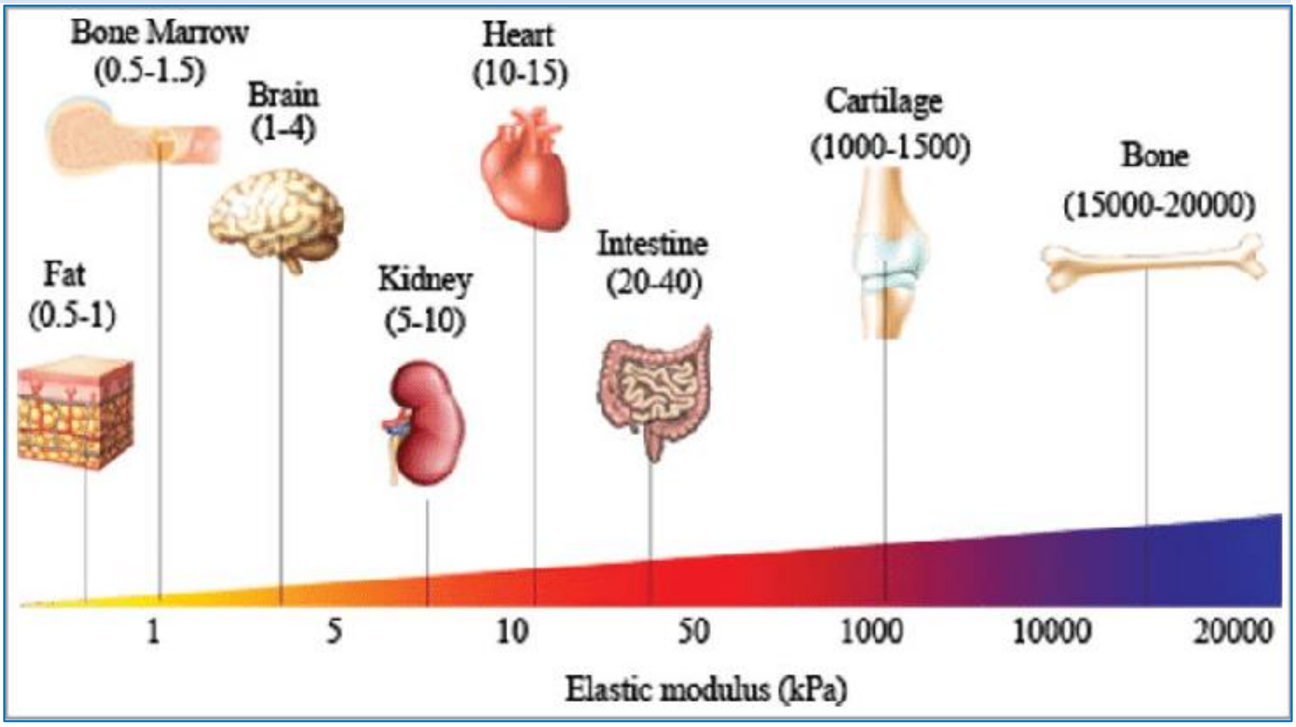
Substituting known values with the value for the bulk modulus B from Table,

$$\frac{\Delta V}{V_0} = \frac{5x10^7 N/m^2}{2.2x10^9 N/m^2} = 0.023$$

Discussion

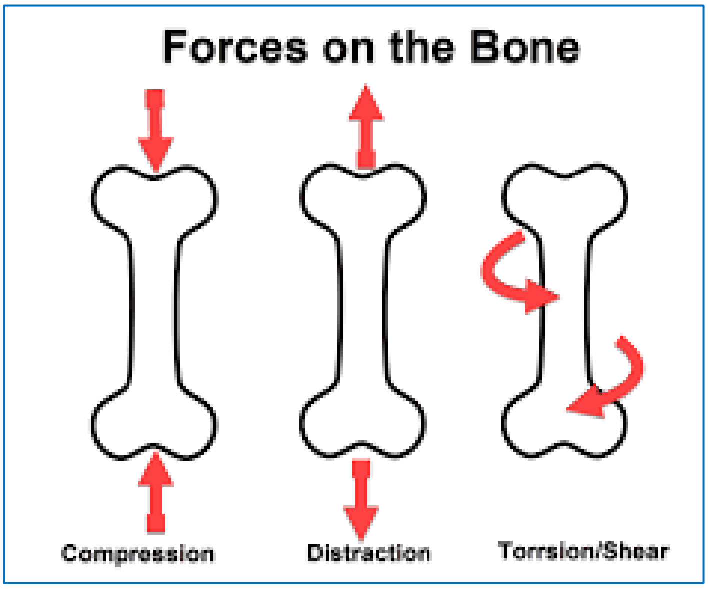
Although measurable, this is not a significant decrease in volume considering that the force per unit area is about 500 atmospheres (1 million pounds per square foot). Liquids and solids are extraordinarily difficult to compress.

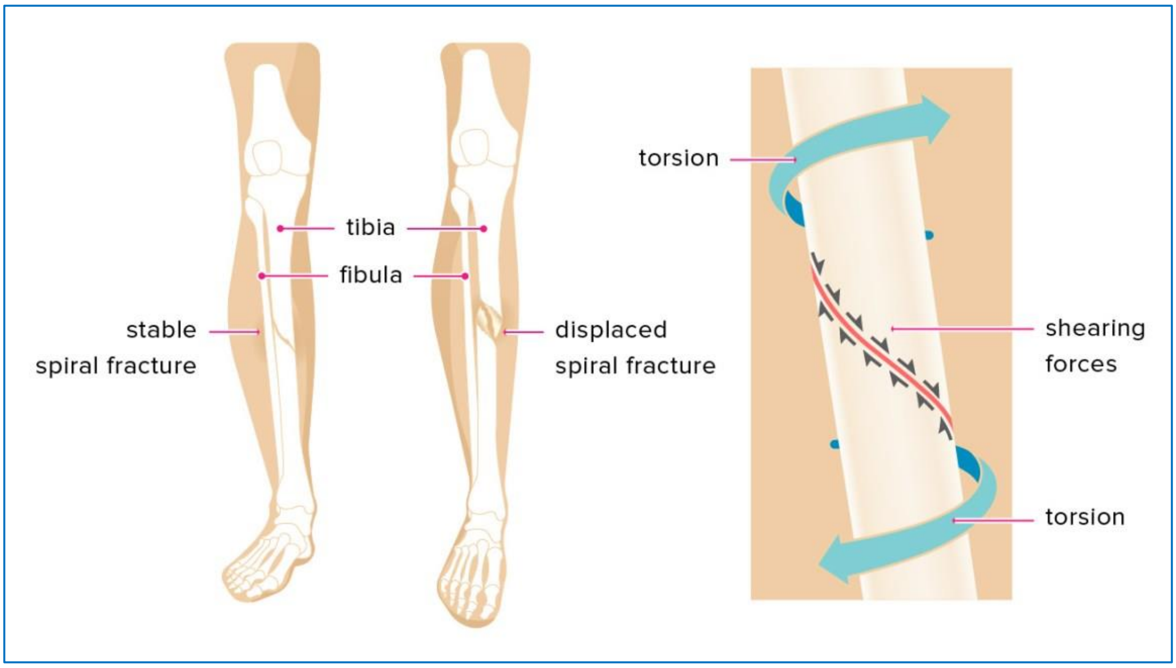
Elasticity of the human organs



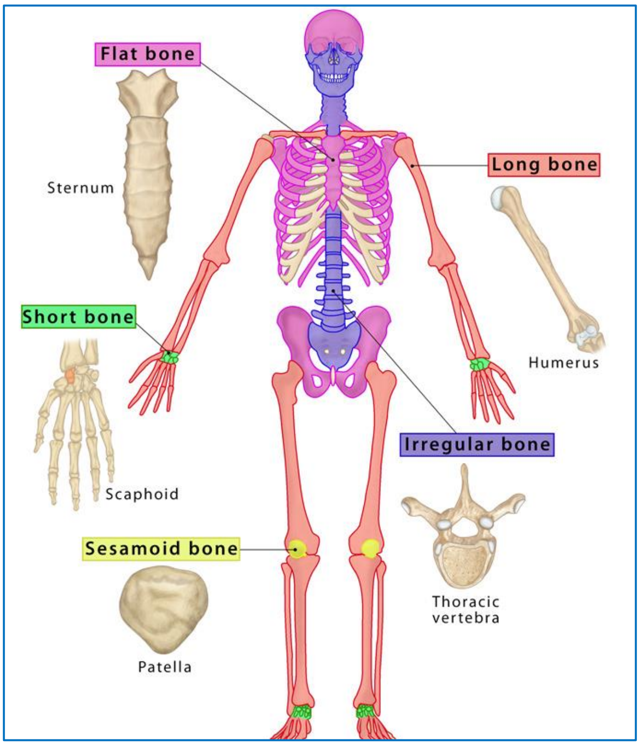
Elasticity of the human bone and tendon

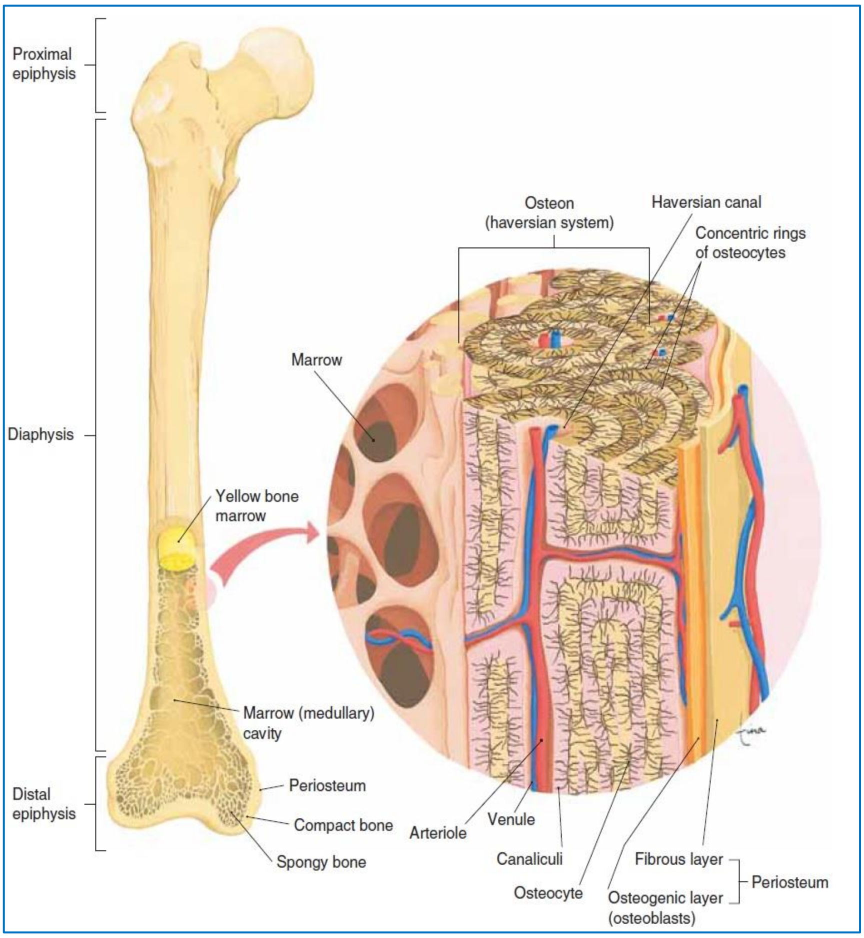
Bones, on the whole, do not fracture due to tension or compression. Rather they generally fracture due to sideways impact or bending, resulting in the bone shearing or snapping. The behavior of bones under tension and compression is important because it determines the load the bones can carry.





Bones are classified as weight-bearing structures such as columns in buildings and trees. Weight-bearing structures have special features; columns in building have steel-reinforcing rods while trees and bones are fibrous. The bones in different parts of the body serve different structural functions and are prone to different stresses. Thus, the bone in the top of the femur is arranged in thin sheets separated by marrow while in other places the bones can be cylindrical and filled with marrow or just solid. Overweight people have a tendency toward bone damage due to sustained compressions in bone joints and tendons.

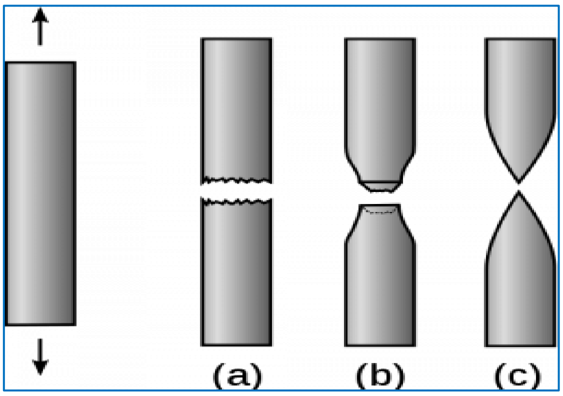


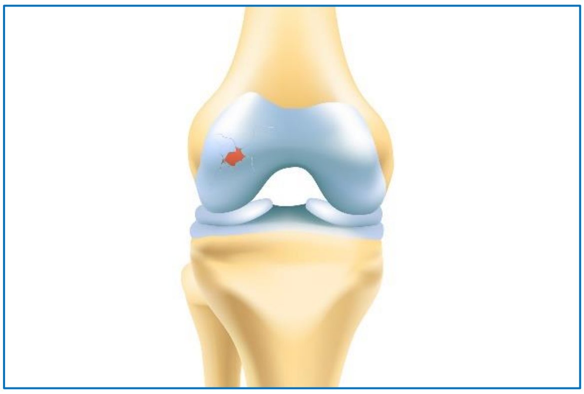


Brittle Bones

Brittle materials have a small plastic region and they begin to fail toward fracture or rupture almost immediately after being stressed beyond their elastic limit. Bone, cast iron, ceramic, and concrete are examples of brittle materials. Materials that have relatively large plastic regions under tensile stress are known as ductile. Examples of ductile materials include aluminum and copper.

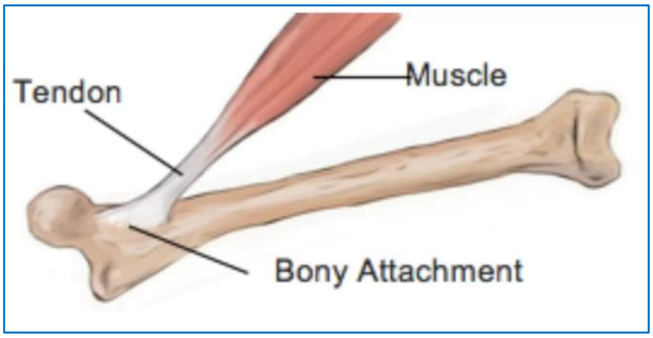
The following figure shows how brittle and ductile materials change shape under stress. Even the cartilage that makes up tendons and ligaments is relatively brittle because it behaves less like example (c) and more like examples (a) and (b). Luckily, those tissues have adapted to allow the deformation required for typical movement without the brittle nature of the materiel coming into play.



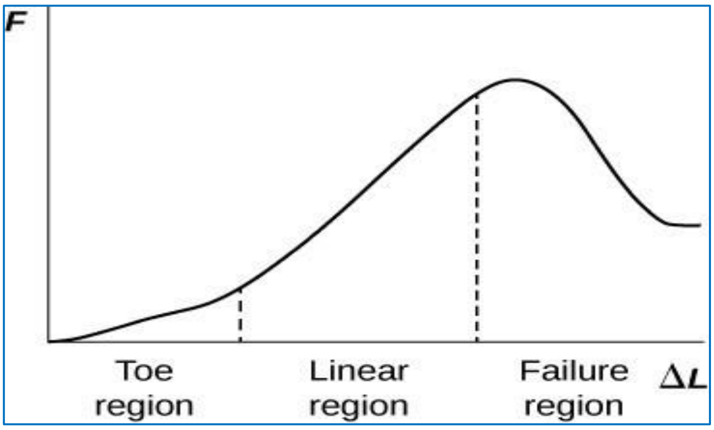


Tendon

Another biological example of Hooke's law occurs in tendons. Functionally, the tendon (the tissue connecting muscle to bone) must stretch easily at first when a force is applied but offer a much greater restoring force for a greater strain.

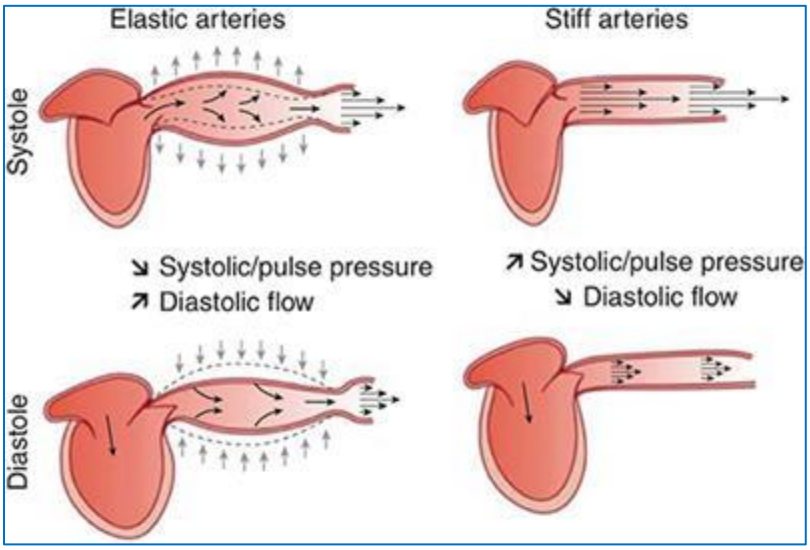


The following figure shows a stress-strain relationship for a human tendon. Some tendons have a high collagen content so there is relatively little strain, or length change; others, like support tendons (as in the leg) can change length up to 10%. Note that this stress-strain curve is nonlinear, since the slope of the line changes in different regions. In the first part of the stretch called the toe region, the fibers in the tendon begin to align in the direction of the stress—this is called *uncrimping*. In the linear region, the fibrils will be stretched, and in the failure region individual fibers begin to break. A simple model of this relationship can be illustrated by springs in parallel: different springs are activated at different lengths of stretch.

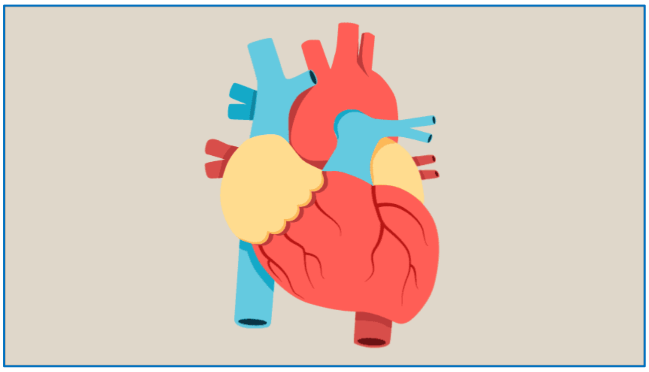


Typical stress-strain curve for mammalian tendon. Three regions are shown: (1) toe region (2) linear region, and (3) failure region.

- Unlike bones and tendons, which need to be strong as well as elastic, the arteries and lungs need to be very stretchable. The elastic properties of the arteries are essential for blood flow. The pressure in the arteries increases and arterial walls stretch when the blood is pumped out of the heart. When the aortic valve shuts, the pressure in the arteries drops and the arterial walls relax to maintain the blood flow. When you feel your pulse, you are feeling exactly this—the elastic behavior of the arteries as the blood gushes through with each pump of the heart. If the arteries were rigid, you would not feel a pulse.



- The heart is also an organ with special elastic properties.



- The lungs expand with muscular effort when we breathe in but relax freely and elastically when we breathe out.

- Our skins are particularly elastic, especially for the young. A young person can go from 100 kg to 60 kg with no visible sag in their skins. The elasticity of all organs reduces with age. Gradual physiological aging through reduction in elasticity starts in the early 20s.

Example : Calculating Deformation: How Much Does Your Leg Shorten When You Stand on It?

Calculate the change in length of the upper leg bone (the femur) when a 70.0 kg man supports 62.0 kg of his mass on it, assuming the bone to be equivalent to a uniform rod that is 40.0 cm long and 2.00 cm in radius.

Strategy

The force is equal to the weight supported, or

$F=mg=(62.0kg)(9.80m/s^2)=607.6N$,

and the cross-sectional area is $\pi r^2=1.257\times10^{-3}m^2$. To find the change in length, we can use the equation:

$$\Delta L = \frac{1}{Y}\frac{F}{A}L_0$$

Solution

All quantities except ΔL are known. Note that the compression value for Young's modulus for bone must be used here. Thus,

$$\Delta L = \left(\frac{1}{9x10^9 N/m^2}\right)\left(\frac{607.6\ N}{1.257x10^{-3}}\right)(0.4m)$$

= $2x10^{-5}$ m

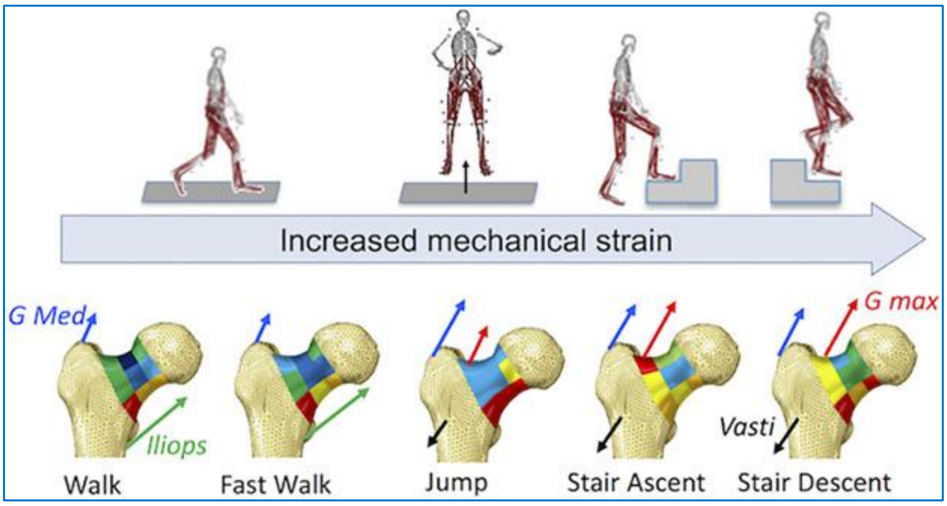
Discussion

This small change in length seems reasonable, consistent with our experience that bones are rigid. In fact, even the rather large forces encountered during strenuous physical activity do not compress or bend bones by large amounts. Although bone is rigid compared with fat or muscle, several of the substances listed in Table have larger values of Young's modulus YY. In other words, they are more rigid.

Strength of Human Bones

The Femur

"In human anatomy, the femur (thigh bone) is the longest and largest bone. Along with the temporal bone of the skull, it is one of the two strongest bones in the body. The average adult male femur is 48 cm (18.9 in) in length and 2.34 cm (0.92 in) in diameter and can support up to 30 times the weight of an adult."

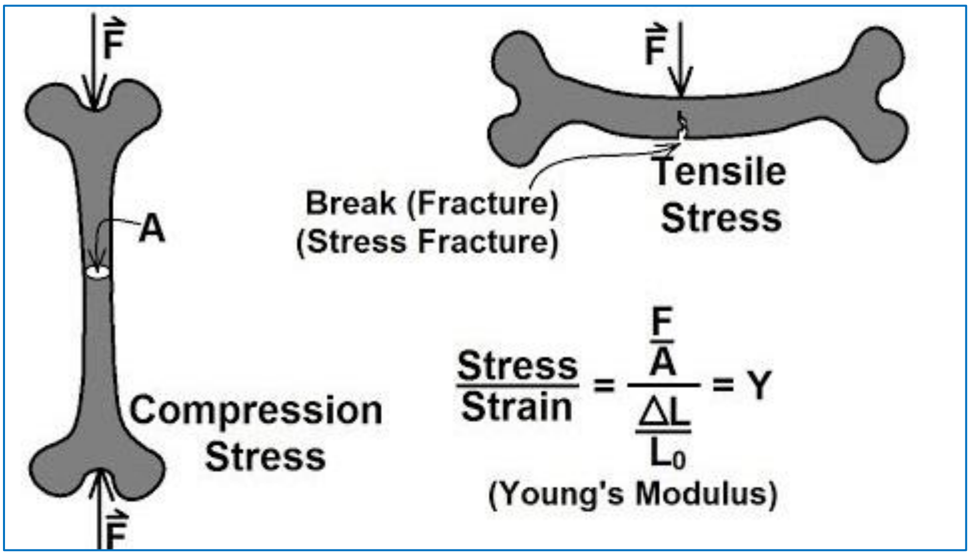


<u>Compression</u>

When you place an object on top of a structure, the object's weight tends to compress the structure. Any push that tends to compress a structure is called a compressive force. The average weight among adult males in the United States is 196 lbs (872 N). According to the statement that the femur can support 30x body weight, the adult male femur can support roughly 6,000 lbs of compressive force! Such high forces are rarely generated by the body under its own power; thus motor vehicle collisions are the number one cause of femur fractures.

<u>Tension</u>

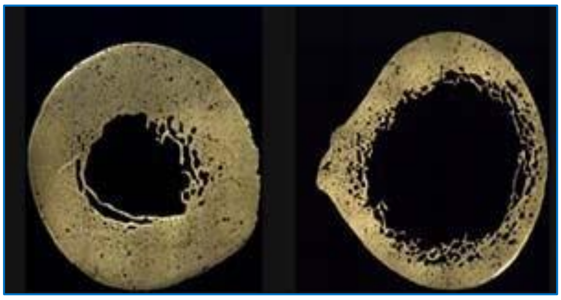
When you hang an object from a structure the object's weight will tend to stretch the structure. The structure responds by providing a tension force to hold up the object. Tension forces are restoring forces produced in response to materials being stretched. Non-rigid objects like ropes, cables, chains, muscles, tendons, can effectively provide tension forces *only*, while rigid object can supply compression and tension forces. For example, the biceps muscle is providing a tension (*T*) force on the thumb-side forearm bone (radius bone).



Stress

The maximum compression or tension forces that a bone can support depends on the size of the bone. More specifically, the more area available for the force to be spread out over, the more force the bone can support. That means the maximum forces bones, (and other objects) can handle are proportional to the cross-sectional area of the bone that is perpendicular (90°) to the direction of the force. For example, the force that the femur can support vertically along its length depends on the area of its horizontal cross-section which is roughly circular and somewhat hollow (bone marrow fills the center space).

These cross sections show the midshaft of the femur of an 84-year-old female with advanced osteoporosis (right), compared to a healthy femur of a 17-year-old female (left).

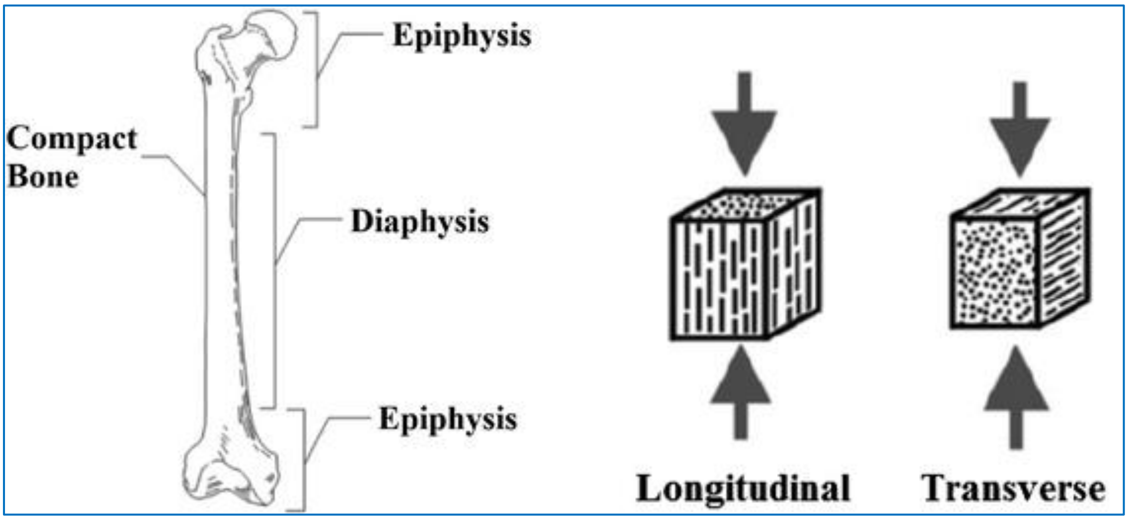


Larger bones can support more force, so in order to analyze the behavior of the bone material itself we need to divide the force applied to the bone by the minimum cross-sectional area (A). This quantity is known as the stress on the material. Stress has units of force per area, so the SI units are (N/m^2) which are also known as Pascals. Units of pounds per square inch (PSI, lbs/in^2) are common in the U.S.

$$stress = \frac{F}{A}$$

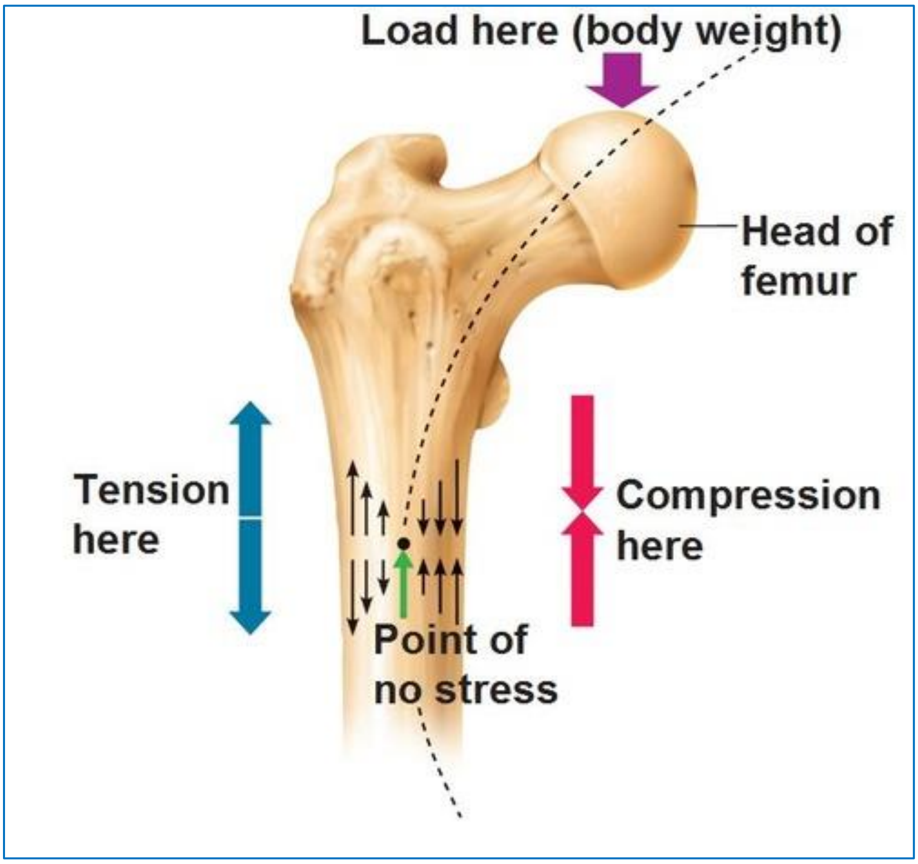
Ultimate Strength of the Femur

The maximum stress that bone, or any other material, can experience before the material begins fracture or rupture is called the ultimate strength. Notice that material strength is defined in terms of stress, not force, so that we are analyzing the material itself, without including the effect of *how much* material is present. For some materials the ultimate strength is different when the stress is acting to crush the material (compression) versus when the forces are acting to stretch the material under tension, so we often refer to ultimate tensile strength or ultimate compressive strength. For example, the ultimate compressive strength for human femur bone is measured to be 205 MPa (205 million Pascals) under compression along its length. The ultimate tensile strength of femur bone under tension along its length is 135 MPa. Along with bone, concrete and chalk are other examples of materials with different compressive and tensile ultimate strengths.



Transverse Ultimate Strength

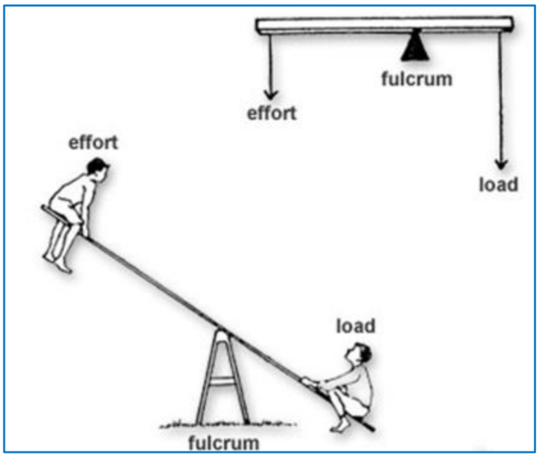
So far, we have discussed ultimate strengths along the long axis of the femur, known as the longitudinal direction. Some materials, such as bone and wood, have different ultimate strengths along different axes. The ultimate compressive strength for bone along the short axis (transverse direction) is 131 MPa, or about 36% less than the 205 MPa longitudinal value. Materials that have different properties along different axes are known as anisotropic. Materials that behave the same in all directions are called isotropic.



An interesting fact to finish up this section: when a person stands the femur actually experiences compressive and tensile stresses on different sides of the bone. This occurs because the structure of the hip socket applies the load of the body weight off to the side rather than directly along the long axis of the bone. Both tension and compressive stresses are applied to the Femur while standing.

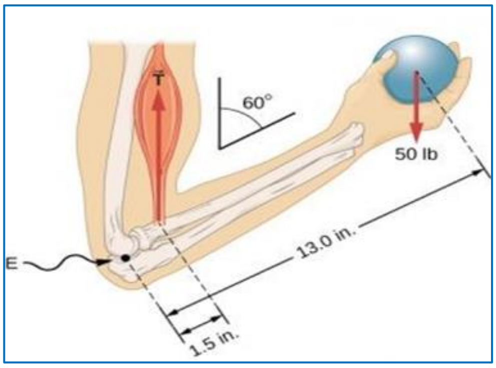
Body Levers

A lever is a rigid object used to make it easier to move a large load a short distance or a small load a large distance. There are three classes of levers, and all three classes are present in the body.



For example, the forearm is a 3rd class lever because the biceps pull on the forearm between the joint (fulcrum) and the ball (load).

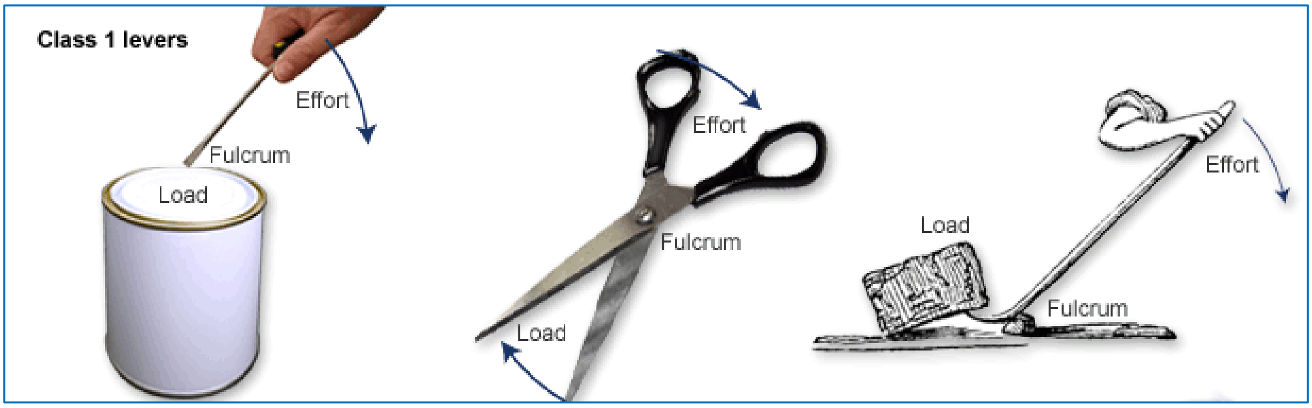
The elbow joint flexed to form a 60° angle between the upper arm and forearm while the hand holds a 50 lb ball.



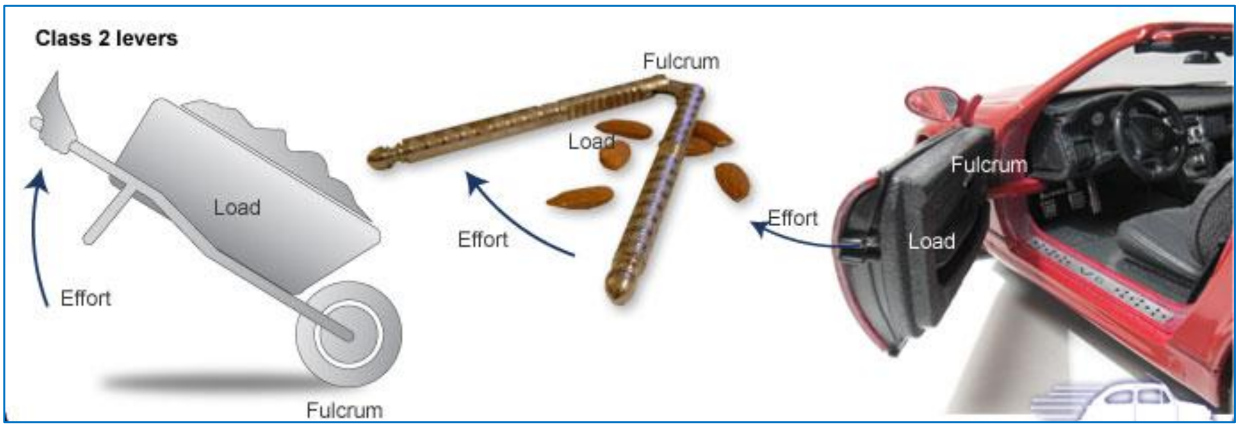
Lever Classes

Using the standard terminology of levers, the forearm is the lever, the biceps tension is the effort, the elbow joint is the fulcrum, and the ball weight is the resistance. When the resistance is caused by the weight of an object, we call it the load. The lever classes are identified by the relative location of the resistance, fulcrum and effort.

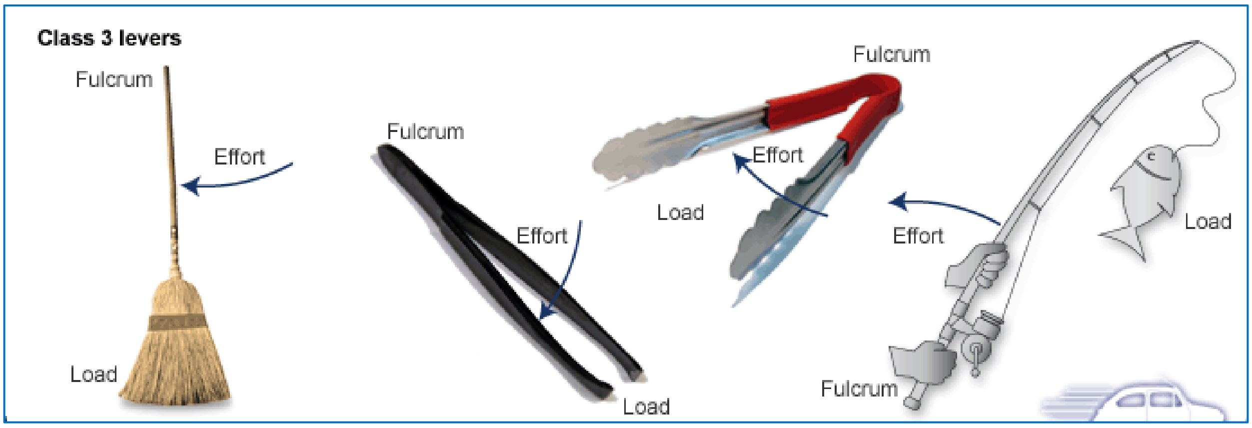
- First class levers have the fulcrum in the middle, between the load and resistance.



- Second class levers have resistance in the middle.



- Third class levers have the effort in the middle.



For all levers the effort and resistance (load) are actually just forces that are creating torques because they are trying to rotate the lever. In order to move or hold a load the torque created by the effort must be large enough to balance the torque caused by the load. Remembering that torque increases as the force is applied farther from the pivot, the effort needed to balance the resistance must depend on the distances of the effort and resistance from the pivot. These distances are known as the effort arm and resistance arm (load arm).

One way to remember the classes of lever is to think "FRE" or "free," as in: "I want to be free of confusion about levers."

- The F stands for fulcrum, in the middle of a class 1 lever (e.g., seesaw).
- The R stands for resistance (which is the same thing as the load), and it is in the middle of a class 2 lever (e.g., wheelbarrow).
- The E stands for effort, which is in the middle of a class 3 lever (e.g., broom).

Mechanical advantage

Mechanical advantage is a measure of the force amplification attained by the machine. Translation, how much easier does the machine make the work?

$$MA = \frac{F_B}{F_A}$$

MA = the ratio of the effort arm to the resistance arm

MA = effort arm /resistance arm

MA is used to measure the efficiency of the lever

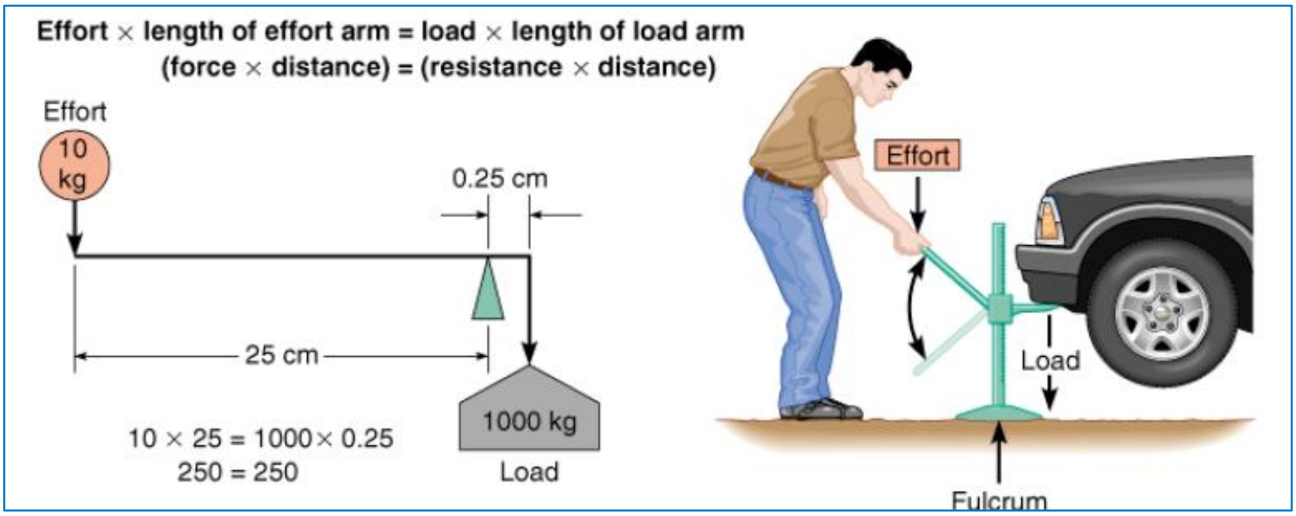
- A lever operates at a ***mechanical advantage*** when the effort is farther from the fulcrum than the load
- A lever operates at a ***mechanical disadvantage*** when the effort is nearer to the fulcrum than the load

Characteristics of class 1 levers

First-class levers always change the direction of the force. In other words, if the effort is “down,” the load moves “up.”

First-class levers can be used to affect the force on the load, the distance through which the load moves, and the speed with which it moves.

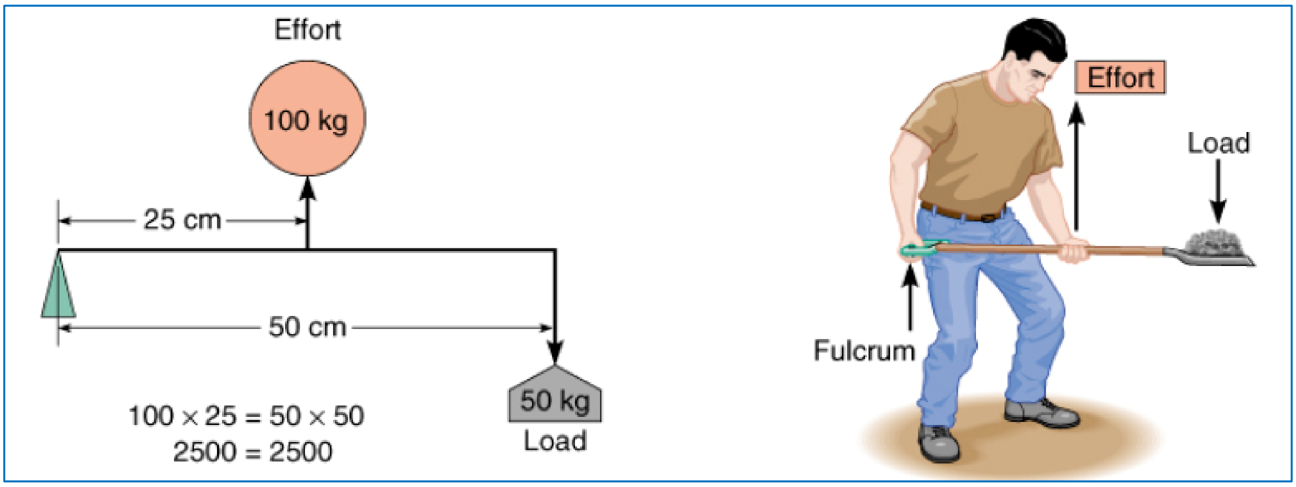
- If the fulcrum is close to the load and far from the effort, the force is increased but the effort must move through a greater distance or with a greater speed to move the load.
- If, on the other hand, the fulcrum is close to the effort, the force is not as much increased, but the load moves through a greater distance or with a greater speed.
- The mechanical advantage of a first-class lever can be greater than 1 or less than 1, depending on the location of the fulcrum relative to the load and effort.



Characteristics of class 2 levers

A second-class lever does not change the direction of the force (if the effort force points "up," the load moves "up").

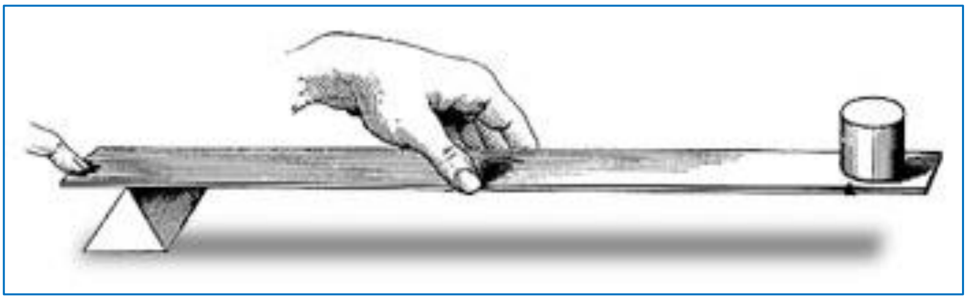
The second-class lever always confers a mechanical advantage because the "effort arm" or distance from the fulcrum to the effort is greater than the "load arm" or distance from the fulcrum to the load.



Characteristics of class 3 levers

Like a second-class lever, a third-class lever does not change the direction of the force. The interesting thing about third-class levers is that they do not confer a mechanical advantage. The mechanical advantage of a third-class lever is less than 1!

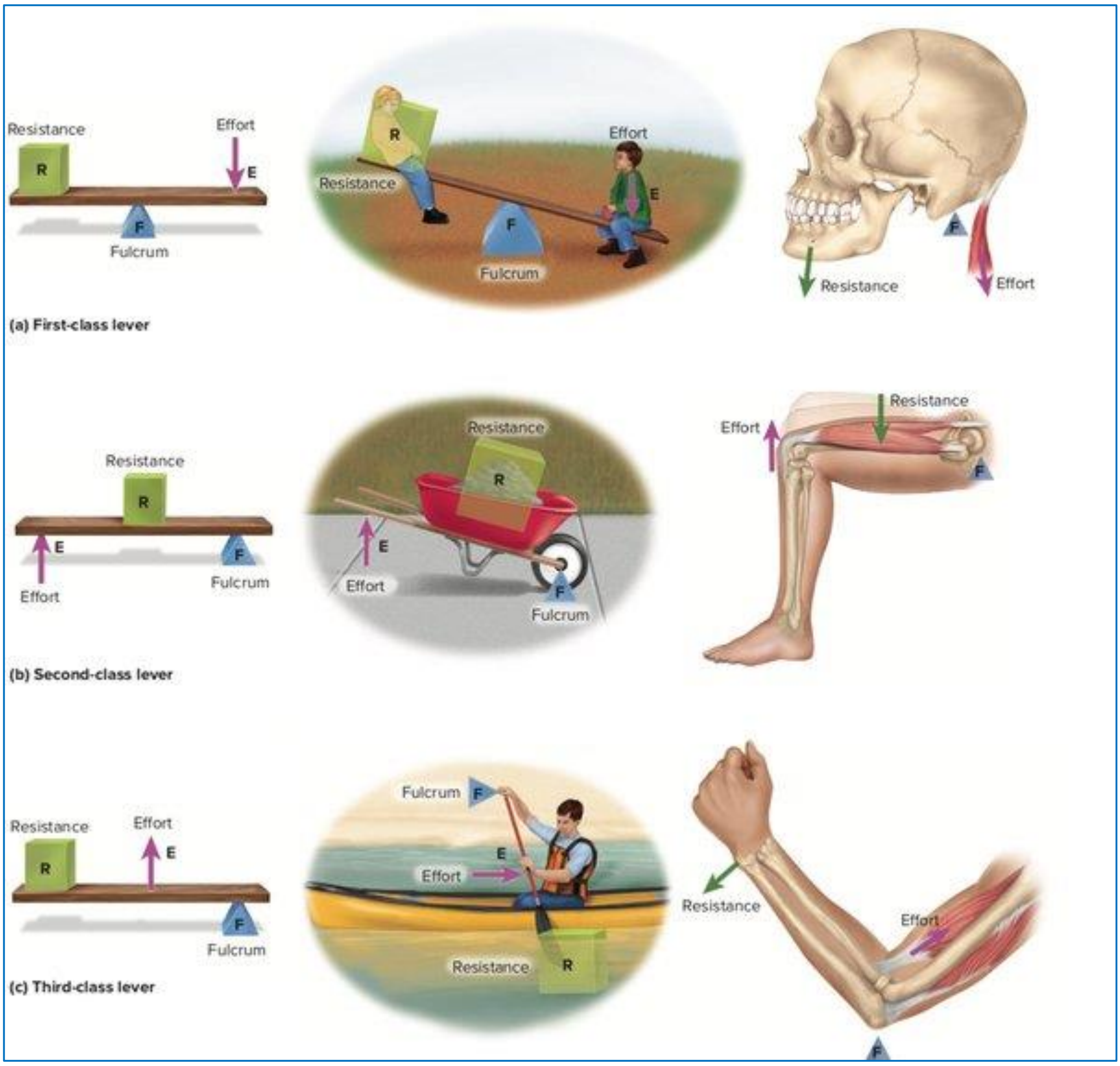
What, then, is the use of third-class levers? They always produce a gain in the speed (or distance covered per unit time) of the load. Sometimes the gain in speed of the load is useful in itself.



Levers in the body

The bones in the human body act as levers, with the joints fulfilling the role of pivot points. The muscles provide the effort, and the weights of segments of the body — or external weights — provide the load.

The human body provides examples of first, second, and third-class levers. First and third-class levers are the most common in the body.



As we saw in the last section, a characteristic of third-class levers is that they confer no mechanical advantage. And the first-class levers in the body often operate with a mechanical advantage less than 1. The human body is built for speed, rather than mechanical advantage!

First-class levers in the human body

An example of a first-class lever is provided by the head, top of the spine, and neck muscles. The fulcrum of this system is the joint between the occipital bone at the base of the skull and the atlas, the first vertebra of the neck. The weight of the head is like the load, tending to rotate the head forward and down (as one might move if looking through a microscope or writing at a desk). The neck extensor muscles exert the effort to hold the head up.

Second-class levers in the human body

When you do a press-up from the floor, your head, neck, trunk, and legs form a lever that has the balls of the feet as fulcrum. The action of the arms raises the load. This is an example of a second-class lever, with the effort at one end, the load in the middle, and the fulcrum at the other end.

Third-class levers in the human body

A biceps curl is an example of a third-class lever. The load is the weight held in the hand, the fulcrum is the elbow joint and the effort is provided by the bicep muscles of the arm.

The contraction of the muscles in the upper arm pulls the lower arm up. The muscles move a short distance compared to the end of the lever (the lower arm). The speed of movement in the lower arm is helpful for throwing a ball or swinging a tennis racket.

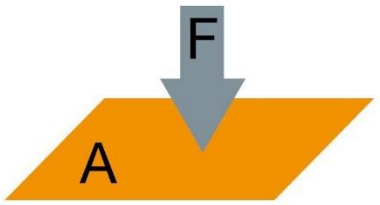
Pressure

Pressure is an important physical quantity—it plays an essential role in topics ranging from thermodynamics to solid and fluid mechanics. As a scalar physical quantity (having magnitude but no direction), pressure is defined as the force per unit area applied perpendicular to the surface to which it is applied. Pressure can be expressed in a number of units depending on the context of use.

Units, Equations and Representations

In SI units, the unit of pressure is the Pascal (Pa), which is equal to a Newton / meter^2 (N/m^2). Other important units of pressure include the pound per square inch (psi) and the standard atmosphere (atm). The elementary mathematical expression for pressure is given by:

$$Pressure\ (p) = \frac{Force\ (F_n)}{Area(A)}$$



where p is pressure, F is the force acting perpendicular to the surface to which this force is applied, and A is the area of the surface. Any object that possesses weight, whether at rest or not, exerts a pressure upon the surface with which it is in contact.

Pressure in Liquids and Gases: Fluids

Just as a solid exerts a pressure on a surface upon which it is in contact, liquids and gases likewise exert pressures on surfaces and objects upon which they are in contact with. The pressure exerted by an ideal gas on a closed container in which it is confined is best analyzed on a molecular level. Gas molecules in a gas container move in a random manner throughout the volume of the container, exerting a force on the container walls upon collision. Taking the overall average force of all the collisions of the gas molecules confined within the container over a unit time allows for a proper measurement of the effective force of the gas molecules on the container walls. Given that the container acts as a confining surface for this net force, the gas molecules exert a pressure on the container. For such an ideal gas confined within a rigid container, the pressure exerted by the gas molecules can be calculated using the ideal gas law:

$$\boldsymbol{P = \frac{nRT}{V}}$$

where n is the number of gas molecules, R is the ideal gas constant (R = 8.314 J mol^{-1} K^{-1}), T is the temperature of the gas, and V is the volume of the container.

$$p = \frac{nRT}{V}$$

n	n_0	$2n_0$	n_0	n_0
T	T_0	T_0	T_0	T_0
V	V_0	V_0	V_0	$2V_0$
p	p_0	$2p_0$	$2p_0$	$\frac{1}{2}p_0$

Variation of Pressure with Depth

Pressure within static fluids depends on the properties of the fluid, the acceleration due to gravity, and the depth within the fluid.

$$P = h\rho g$$

The pressure exerted by a static liquid depends only on the depth, density of the liquid, and the acceleration due to gravity.

Pressure within a gas: The force contributing to the pressure of a gas within the medium is not a continuous distribution as for liquids.

$$p = p_0 e^{-\frac{Mgh}{kT}}$$

Where p_0 is the pressure at h = 0, M is the mass of a single molecule of gas, g is the acceleration due to gravity, k is the Boltzmann constant, T is the temperature of the gas, and h is the height or depth within the gas.

Gauge Pressure and Atmospheric Pressure

Pressure is often measured as gauge pressure, which is defined as the absolute pressure minus the atmospheric pressure.

Atmospheric Pressure

An important distinction must be made as to the type of pressure quantity being used when dealing with pressure measurements and calculations. **Atmospheric pressure** is the magnitude of pressure in a system due to the atmosphere, such as the pressure exerted by air molecules (a static fluid) on the surface of the earth at a given elevation.

In most measurements and calculations, the atmospheric pressure is considered to be constant at 1 atm or 101,325 Pa, which is the atmospheric pressure under standard conditions at sea level.

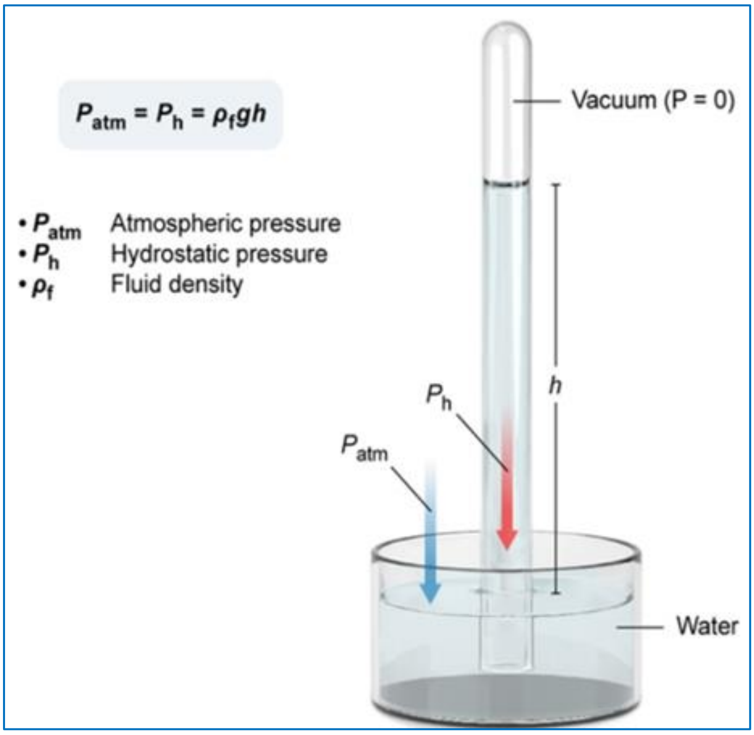
Gauge Pressure

For most applications, particularly those involving pressure measurements, it is more practical to use gauge pressure than absolute pressure as a unit of measurement. Gauge pressure is a relative pressure measurement which measures pressure relative to atmospheric pressure and is defined as the absolute pressure minus the atmospheric pressure. Most pressure measuring equipment give the pressure of a system in terms of gauge pressure as opposed to absolute pressure. For example, tire pressure and blood pressure are gauge pressures by convention, while atmospheric pressures, deep vacuum pressures, and altimeter pressures must be absolute.

Hydrostatic Based Barometers

Early barometers were used to measure atmospheric pressure through the use of hydrostatic fluids. Hydrostatic based barometers consist of columnar devices usually made from glass and filled with a static liquid of consistent density. The columnar section is sealed, holds a vacuum, and is partially filled with the liquid while the base section is open to the atmosphere and makes an interface with the surrounding environment. As the atmospheric pressure changes, the pressure exerted by the atmosphere on the fluid reservoir exposed to the atmosphere at the base changes, increasing as the atmospheric pressure increases and decreasing as the atmospheric pressure decreases. This change in pressure causes the height of the fluid in the columnar structure to change, increasing in height as the atmosphere exerts greater pressure on the liquid in the reservoir base and decreasing as the atmosphere exerts lower pressure on the liquid in the reservoir base.

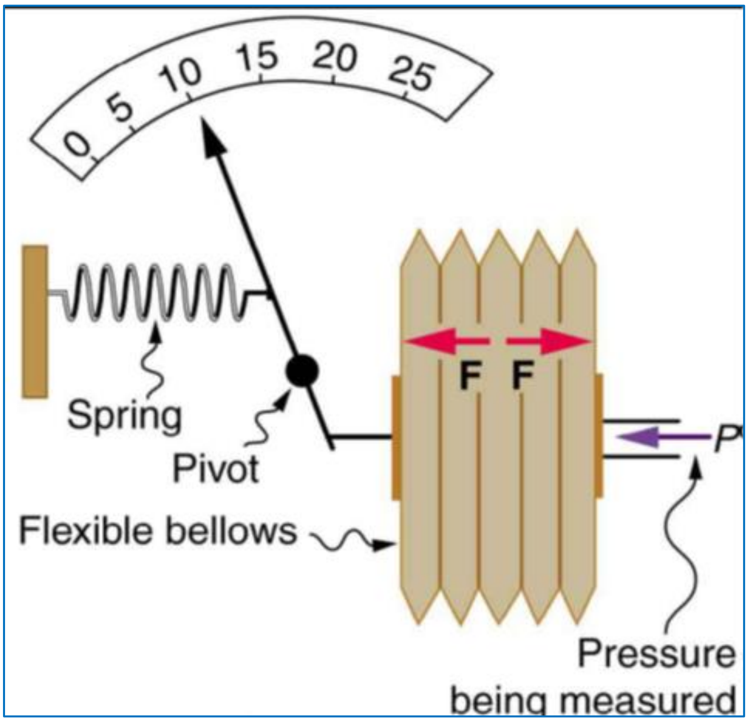
The height of the liquid within the glass column then gives a measure of the atmospheric pressure. Pressure, as determined by hydrostatic barometers, is often measured by determining the height of the liquid in the barometer column, thus the torr as a unit of pressure, but can be used to determine pressure in SI units. Hydrostatic based barometers most commonly use water or mercury as the static liquid. While the use of water is much less hazardous than mercury, mercury is often a better choice for fabricating accurate hydrostatic barometers. The density of mercury is much higher than that of water, thus allowing for higher accuracy of measurements and the ability to fabricate more compact hydrostatic barometers.



Aneroid Barometer

Another type of barometer is the aneroid barometer, which consists of a small, flexible sealed metal box called an aneroid cell. The aneroid cell is made from beryllium-copper alloy and is partially evacuated. A stiff spring prevents the aneroid cell from collapsing. Small changes in external air pressure cause the cell to expand or contract. This expansion and contraction are amplified by mechanical mechanisms to give a pressure reading. Such pressure measuring devices are more practical than hydrostatic barometers for measuring system pressures. Many modern pressure measuring devices are pre-engineered to output gauge pressure measurements.

While the aneroid barometer is the underlying mechanism behind many modern pressure measuring devices, pressure can also be measured using more advanced measuring mechanisms.



Pressure and Cardiovascular System

The cells of the body act like individual engines. In order for them to function they must have:

- Fuel from our food to supply energy.
- O_2 from the air we breathe to combine with the food to release energy.
- A way to dispose of the by-products of the combustion (mostly CO_2, H_2O, and heat).

Since the body has many billions of cells an elaborate transportation system is needed to deliver the fuel and O_2 to the cells and remove the by-products. The blood performs this important body function. Blood represents about **7%** of the body mass or about 4.5 kg (~ 4.4 liters) in a 64 kg person. The blood, blood vessels, and heart make up the cardiovascular system (CVS).

Major components of the cardiovascular system

The heart is basically a double pump; it provides the force needed to circulate the blood through the two major circulatory systems: -

1. The pulmonary circulation in the lungs.

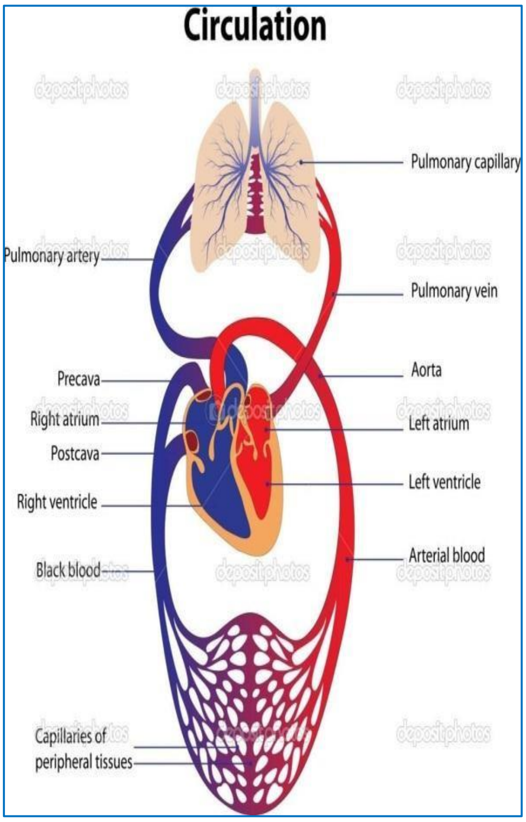
2. The systemic circulation in the rest of the body.

The blood in a normal individual circulates through one system before being pumped by the other section of the heart to the second system.

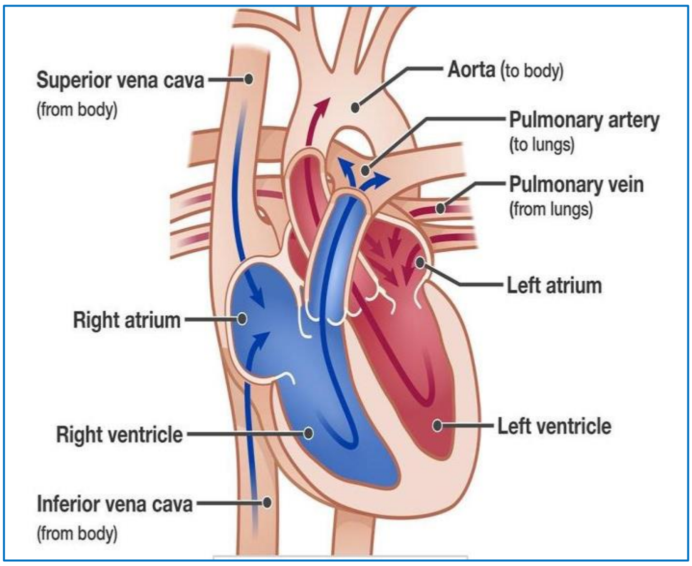
Circulation

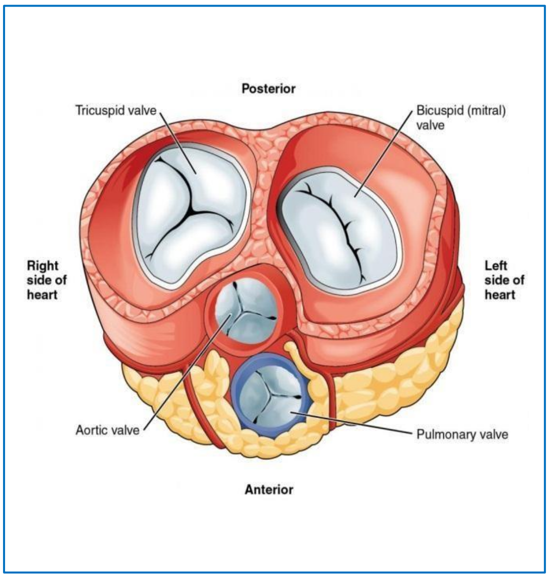
Let us start with the blood in the left side of the heart and follow its circulation through one** complete **loop.

- The blood is pumped by the contraction of the heart muscles from the left ventricle at a pressure of about 125 mm Hg into a system of arteries that subdivided into smaller and smaller arteries (arterioles) and finally into a very fine meshwork of vessels called the capillary bed.
- During the few seconds it is in the capillary bed the blood supplies O_2 to the cells and picks up CO_2 from the cells.
- After passing through the capillary bed the blood collects in small veins (venules) that gradually combine into larger and larger veins before it enters the right side of the heart via two main veins-the superior vena cava and the inferior vena cava.
- The returning blood is momentarily stored in the reservoir (the right atrium). And during a weak contraction (5-6 mm Hg) the blood flows into the right ventricular.
- On the next ventricular contraction this blood is pumped at a pressure of about 25 mm Hg via the pulmonary arteries to the capillary system in the lungs, where it receives more O_2 and where some of the CO_2 diffuses into the air in the lungs to be exhaled.
- The freshly oxygenated blood then travels via the main veins from the lungs into the left reservoir of the heart (left atrium); during the weak atrial contraction (7-8 mmHg) the blood flows into the left ventricle.
- On the next ventricular contraction this blood is again pumped from the left side of the heart into the general circulation.



The heart has a system of valves that, if functioning properly, permit the blood to flow only in the correct direction. If these valves become diseased and do not open or close properly the pumping of the blood becomes inefficient.





The blood volume is not uniformly divided between the pulmonary and systemic circulation, but it is: -

Blood Circulation 100/100					
Systemic Circulation 80/100			Pulmonary Circulation 20/100		
Arteries 15/100	Capillaries 10/100	Veins 75/100	Arteries 46.5/100	Capillaries 7/100	Veins 46.5/100

Q) Calculate the mass of blood in all circulation of a person his body mass is 80kg.

Mass of Blood (**80 × 7/100 = 5.6 kg**)

Mass of Blood in Systemic Circulation 5.6 × 80/100 = 4.48 kg			Mass of Blood in Pulmonary Circulation 5.6 × 20/100 = 1.12 kg		
Arteries	Capillaries	Veins	Arteries	Capillaries	Veins
4.48 × 15/100 = 0.672 kg	4.48 × 10/100 = 0.448 kg	4.48 × 75/100 = 3.360 kg	1.12 × 46.5/100 = 0.521 kg	1.12 × 7/100 = 0.078 kg	1.12 × 46.5/100 = 0.521 kg

Q) The mass of the pulmonary blood of a person is 1.5 kg, find: -

1) The mass of this person.

2) The mass of his systemic blood.

Pulmonary Mass = Blood Mass x 20/100

1.5 = Blood Mass x 20/100

Blood Mass = 7.5 kg

1)The mass of this person: -

Blood Mass = Body Mass x 7/100

7.5 = Body Mass x 7/100

Body Mass = 107 kg

2)The mass of his systemic blood: -

Systemic Mass = Blood Mass x 80/100

Systemic Mass = 7.5 x 80/100 ======== Systemic Mass = 6 kg

To the eye blood appears to be a red liquid slightly thicker than water. When examined by various physical techniques it is found to consist of several different components.

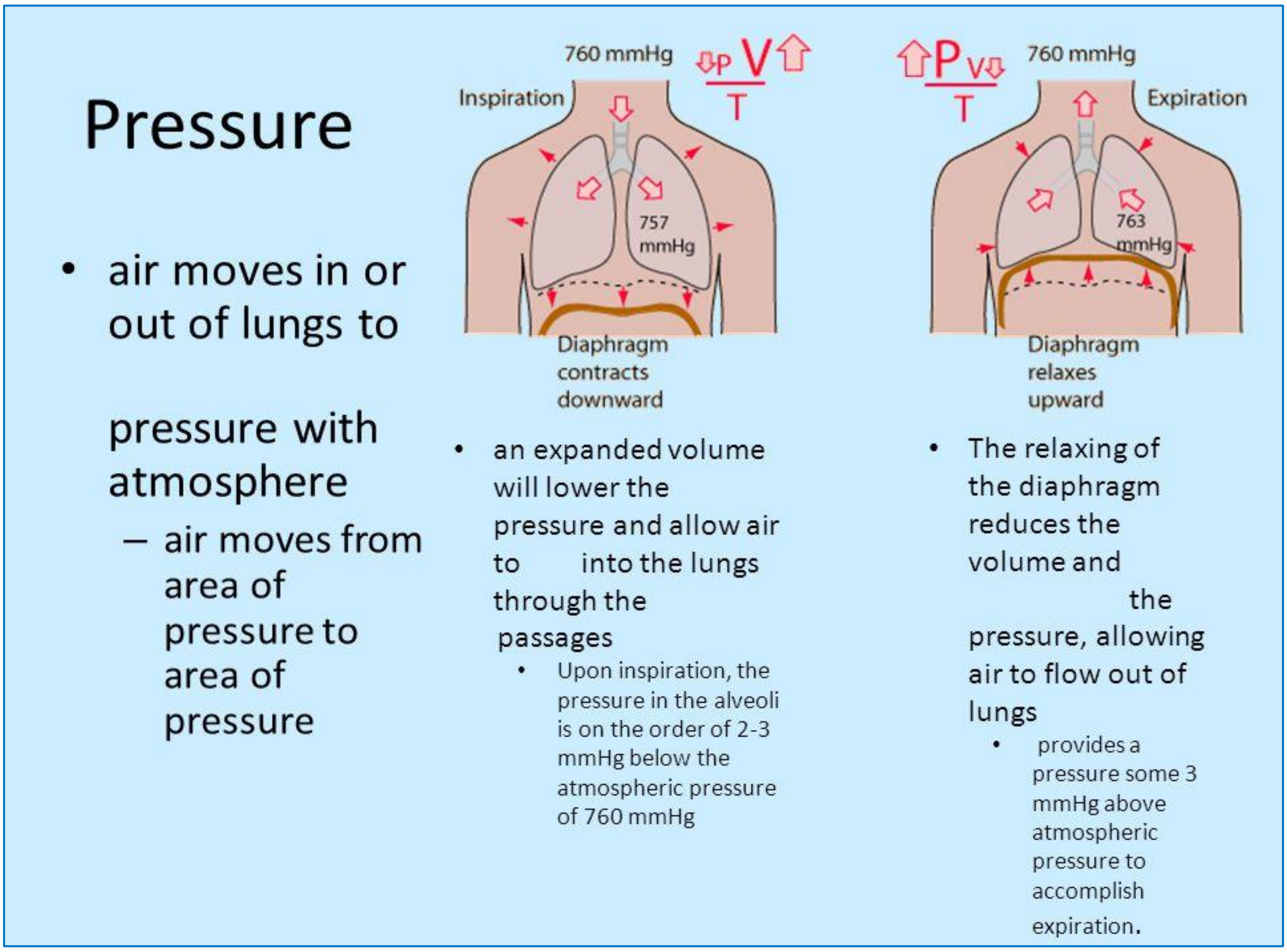
The red color is caused by the red blood cells (erythrocytes). A nearly clear fluid called blood plasma accounts for the other 55%. The combination of red blood cells and plasma causes blood to have flow properties different from those of a fluid like water. Beside red blood cells and plasma, there are some important blood components, such as the white blood cells (leukocytes), present in small amounts. The blood also contains platelets. Platelets are involved in the clotting function of blood.

Typical Pressures in Humans

Body system	Gauge pressure in mm Hg
Blood pressures in large arteries (resting)	
Maximum (systolic)	**100–140**
Minimum (diastolic)	**60–90**
Blood pressure in large veins	**4–15**
Eye	**12–24**
Brain and spinal fluid (lying down)	**5–12**
While filling	**0–25**
When full	**100–150**
Chest cavity between lungs and ribs	**−8 to −4**
Inside lungs	**−2 to +3**
Esophagus	**−2**
Stomach	**0–20**
Intestines	**10–20**
Middle ear	**<1**

The Role of Pressure in the Respiratory System

Pressure also plays an essential role in the respiratory system, as it is responsible for the breathing mechanism. Pressure differences between the lungs and the atmosphere create a potential for air to enter the lungs, resulting in inhalation. The mechanism resulting in inhalation is due to lowering of the diaphragm, which increases the volume of the thoracic cavity surrounding the lungs, thus lowering its pressure as determined by the ideal gas law. The reduction in pressure of the thoracic cavity, which normally has a negative gauge pressure, thus keeping the lungs inflated, pulls air into the lungs, inflating the alveoli and resulting in oxygen transport needed for respiration. As the diaphragm restores and moves upwards, pressure within the thoracic cavity increases, resulting in exhalation. The cycle repeats itself, resulting in the respiration which as discussed is mechanically due to pressure changes. Without pressure in the body, and the corresponding potential that it has for dynamic bodily processes, essential functions such as blood circulation and respiration would not be possible.

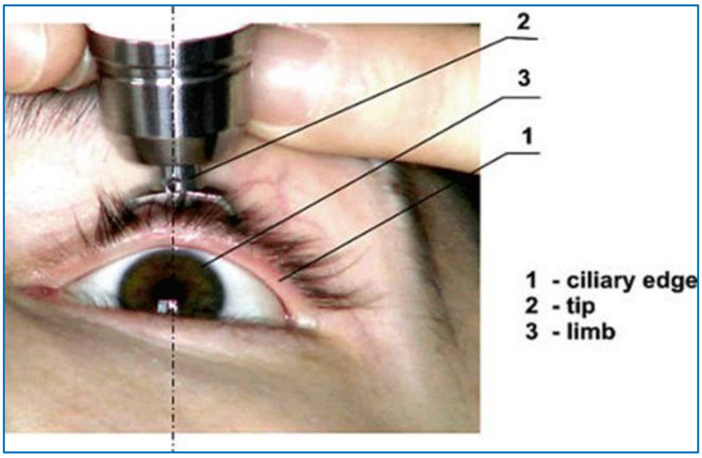


Pressure in the Eye

The shape of the eye is maintained by fluid pressure, called *intraocular pressure*, which is normally in the range of 12.0 to 24.0 mm Hg. When the circulation of fluid in the eye is blocked, it can lead to a buildup in pressure, a condition called *glaucoma*. The net pressure can become as great as 85.0 mm Hg, an abnormally large pressure that can permanently damage the optic nerve. To get an idea of the force involved, suppose the back of the eye has an area of 6.0 cm^2, and the net pressure is 85.0 mm Hg. Force is given by $F = PA$. To get F in newtons, we convert the area to m^2 ($1\ m^2 = 10^4\ cm^2$). Then we calculate as follows:

$F = h\rho gA = (85.0\times10^{-3} m)(13.6\times10^{3}\ kg/m^{3})(9.80\ m/s^{2})(6.0\times10^{-4} m^{2}) = 6.8\ N.$

This force is the weight of about a 680-g mass. A mass of 680 g resting on the eye A normal force here would be the weight of about 120 g, less than one-quarter of our initial value.



People over 40 years of age are at greatest risk of developing glaucoma and should have their intraocular pressure tested routinely. Most measurements involve exerting a force on the (anesthetized) eye over some area (a pressure) and observing the eye's response. A noncontact approach uses a puff of air and a measurement is made of the force needed to indent the eye. If the intraocular pressure is high, the eye will deform less and rebound more vigorously than normal. Excessive intraocular pressures can be detected reliably and sometimes controlled effectively.

Surface tension

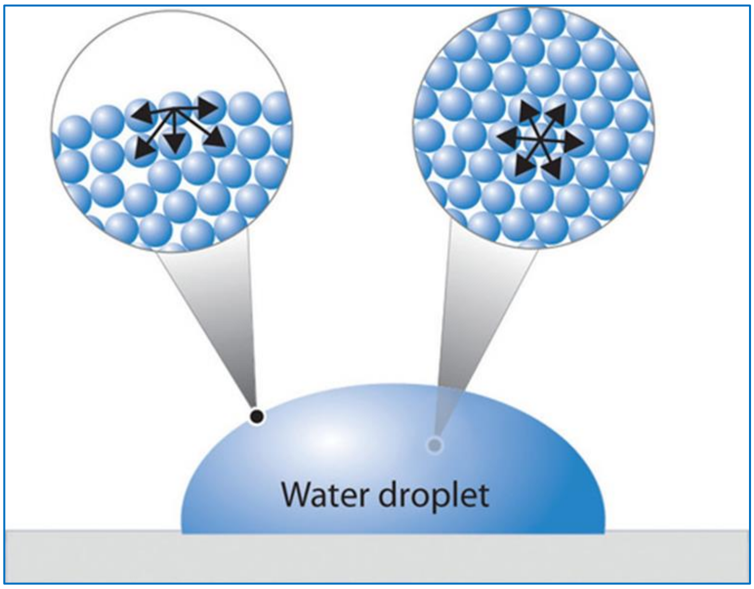
Surface tension is the tendency of liquid surfaces to shrink into the minimum surface area possible.

Surface tension allows insects (e.g. water striders), usually denser than water, to float and slide on a water surface. At liquid–air interfaces, surface tension results from the greater attraction of liquid molecules to each other than to the molecules in the air.

Cause of Surface tension

- Due to the cohesive forces a molecule is pulled equally in every direction by neighboring liquid molecules, resulting in a net force of zero.
- The molecules at the surface do not have the same molecules on all sides of them and therefore are pulled inward.

- This creates some internal pressure and forces liquid surfaces to contract to the minimum area.



There is also a tension parallel to the surface at the liquid-air interface which will resist an external force, due to the cohesive nature of water molecules.

Surface tension is responsible for the shape of liquid droplets. Although easily deformed, droplets of water tend to be pulled into a spherical shape by the imbalance in cohesive forces of the surface layer. In the absence of other forces, drops of virtually all liquids would be approximately spherical. The spherical shape minimizes the necessary "wall tension" of the surface layer according to Laplace's law.

Another way to view surface tension is in terms of energy. A molecule in contact with a neighbor is in a higher state of energy than if it were alone (with some contact with a neighbor). The interior molecules have as many neighbors as they can possibly have, but the boundary molecules are missing neighbors (compared to interior molecules) and therefore have a higher energy. For the liquid to minimize its energy state, the number of higher energy boundary molecules must be minimized. The minimized number of boundary molecules results in a minimal surface area. As a result of surface area minimization, a surface will assume the smoothest shape. Since any curvature in the surface shape results in greater area, a higher energy will also result.

Effects of surface tension

Several effects of surface tension can be seen with ordinary water:

A. Beading of rainwater on a waxy surface, such as a leaf.

B. Formation of drops occurs when a mass of liquid is stretched.

C. Flotation of objects denser than water occurs when the object is nonwearable, and its weight is small enough to be borne by the forces arising from surface tension.

D. Separation of oil and water (in this case, water and liquid wax) is caused by a tension in the surface between dissimilar liquids.

E. Tears of wine is the formation of drops and rivulets on the side of a glass containing an alcoholic beverage.

Physical units

Surface tension, represented by the symbol γ (alternatively σ or T), is measured in force per unit length. Its SI unit is newton per meter but the cgs unit of dyne per centimeter is also used. For example,

$$\gamma = 1\,\frac{\text{dyn}}{\text{cm}} = 1\,\frac{\text{erg}}{\text{cm}^2} = 1\,\frac{10^{-7}\ \text{m}\cdot\text{N}}{10^{-4}\ \text{m}^2} = 0.001\,\frac{\text{N}}{\text{m}} = 0.001\,\frac{\text{J}}{\text{m}^2}.$$

Methods of measurement

Because surface tension manifests itself in various effects, it offers a number of paths to its measurement. Which method is optimal depends upon the nature of the liquid being measured, the conditions under which its tension is to be measured, and the stability of its surface when it is deformed. An instrument that measures surface tension is called tensiometer.

- Du Noüy ring method: The traditional method used to measure surface or interfacial tension. Wetting properties of the surface or interface have little influence on this measuring technique. Maximum pull exerted on the ring by the surface is measured.
- Wilhelmy plate method: A universal method especially suited to check surface tension over long time intervals. A vertical plate of known perimeter is attached to a balance, and the force due to wetting is measured.
- Spinning drop method: This technique is ideal for measuring low interfacial tensions. The diameter of a drop within a heavy phase is measured while both are rotated.

- Pendant drop method: Surface and interfacial tension can be measured by this technique, even at elevated temperatures and pressures. Geometry of a drop is analyzed optically. For pendant drops the maximum diameter and the ratio between this parameter and the diameter at the distance of the maximum diameter from the drop apex has been used to evaluate the size and shape parameters in order to determine surface tension.
- Bubble pressure method (Jaeger's method): A measurement technique for determining surface tension at short surface ages. Maximum pressure of each bubble is measured.
- Drop volume method: A method for determining interfacial tension as a function of interface age. Liquid of one density is pumped into a second liquid of a different density and time between drops produced is measured.
- Capillary rise method: The end of a capillary is immersed into the solution. The height at which the solution reaches inside the capillary is related to the surface tension by the equation discussed below.

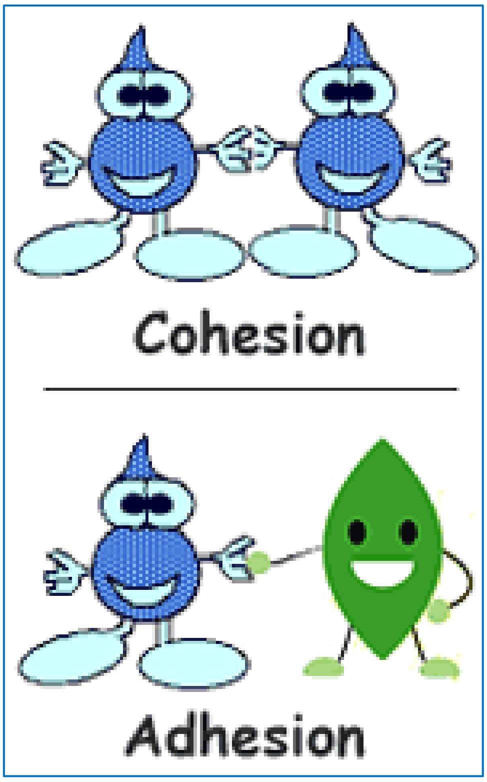
Cohesion and Adhesion in Liquids

Attractive forces between molecules of the same type are called *cohesive forces*. Liquids can, for example, be held in open containers because cohesive forces hold the molecules together.

Attractive forces between molecules of different types are called *adhesive forces*. Such forces cause liquid drops to cling to windowpanes, for example. In this section we examine effects directly attributable to cohesive and adhesive forces in liquids.

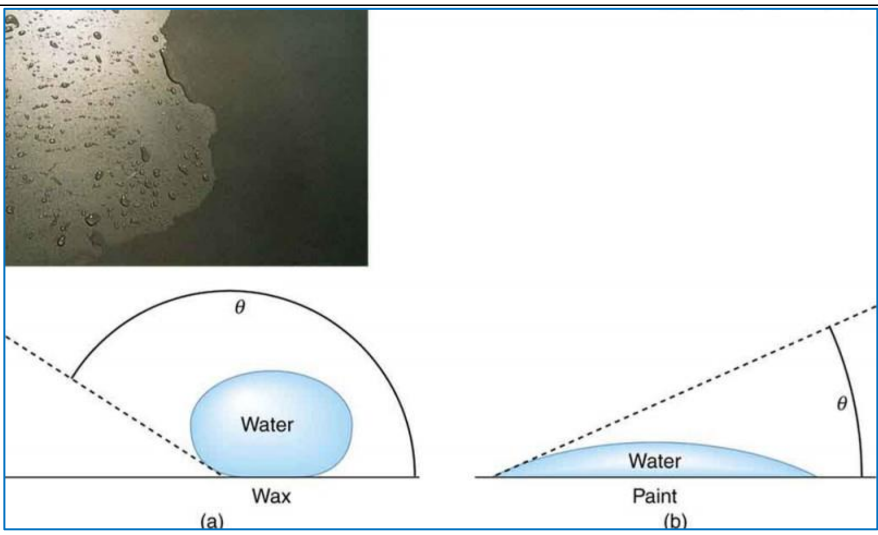
Adhesion and Capillary Action

Competition between the forces of adhesion and cohesion are important in the macroscopic behavior of liquids. An important factor in studying the roles of these two forces is the angle θ between the tangent to the liquid surface and the surface. The *contact angle* θ is directly related to the relative strength of the cohesive and adhesive forces. The larger the strength of the cohesive force relative to the adhesive force, the larger θ is, and the more the liquid tends to form a droplet. The smaller θ is, the smaller the relative strength, so that the adhesive force is able to flatten the drop.



Contact angle

The angle θ between the tangent to the liquid surface and the surface is called the contact angle.

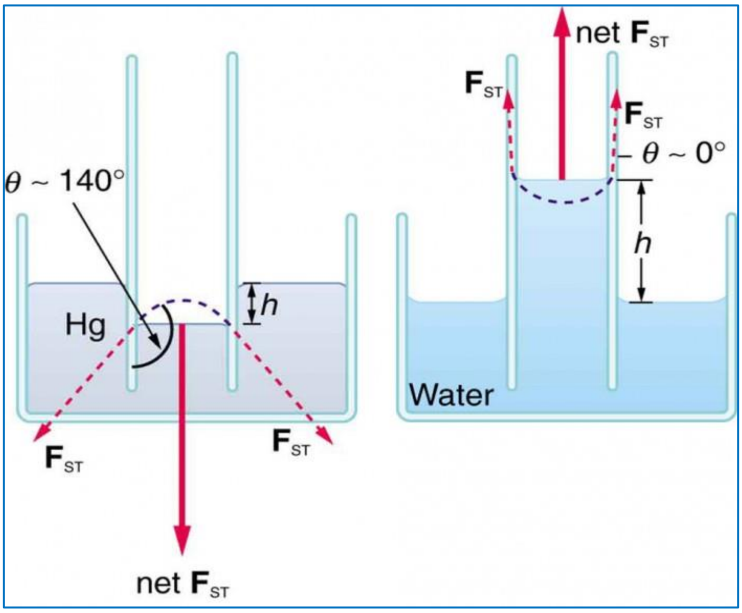


One important phenomenon related to the relative strength of cohesive and adhesive forces is *capillary action*—the tendency of a fluid to be raised or suppressed in a narrow tube, or *capillary tube*. This action causes blood to be drawn into a small-diameter tube when the tube touches a drop.

Capillary action

The tendency of a fluid to be raised or suppressed in a narrow tube, or capillary tube.

If a capillary tube is placed vertically into a liquid capillary action will raise or suppress the liquid inside the tube depending on the combination of substances. The actual effect depends on the relative strength of the cohesive and adhesive forces and, thus, the contact angle θ given in the table. If θ is less than 90º, then the fluid will be raised; if θ is greater than 90º, it will be suppressed. Mercury, for example, has a very large surface tension and a large contact angle with glass. When placed in a tube, the surface of a column of mercury curves downward, somewhat like a drop. The curved surface of a fluid in a tube is called a meniscus. The tendency of surface tension is always to reduce the surface area. Surface tension thus flattens the curved liquid surface in a capillary tube. This results in a downward force in mercury and an upward force in water, as seen in Figure 8.



Contact Angles of Some Substances	
Interface	**Contact angle Θ**
Mercury–glass	**140º**
Water–glass	**0º**
Water–paraffin	**107º**
Water–silver	**90º**

Organic liquids (most)–glass	**0°**
Ethyl alcohol–glass	**0°**
Kerosene–glass	**26°**

A simple relationship determines how far the water is pulled up the. The force upwards due to the surface tension is given by the following relationship:

$$F_{up} = \gamma\,(2\pi a)\cos\theta$$

in this relationship, γ is the liquid-air surface tension at 20° C, $2\pi a$ is the circumference of the tube, and θ is the contact angle of water on glass, a measure of the attraction of the liquid to the walls. The opposing force down is given by the force of gravity on the water that is pulled above the reservoir level.

$$F_{down} = \rho g(h\pi a^2)$$

Here, $\rho = 1000\ kg/m^3$ is the density of water, $g = 9.8\ m/s^2$ is the acceleration due to gravity, and $(h\pi a^2)$ is the volume of the water in the column above the reservoir.

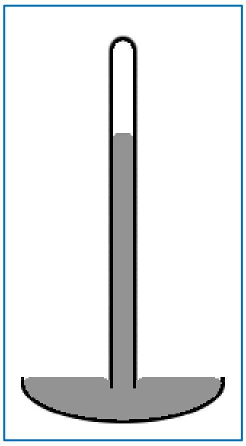
Measuring Surface Tension

One method to measure the surface tension of a liquid is to measure the height the liquid rises in a capillary tube. By setting the two forces above equal, we find the surface tension to be:

$$\gamma = \frac{\rho g a}{2}\frac{h}{\cos\theta}$$

For pure water and clean glass, the contact angle is nearly zero. In a typical high school lab, this may not be the case, but θ is small and we assume that $\cos\theta$ is close to 1.

$$\gamma = \frac{\rho g a}{2}\frac{h}{\cos\theta}$$



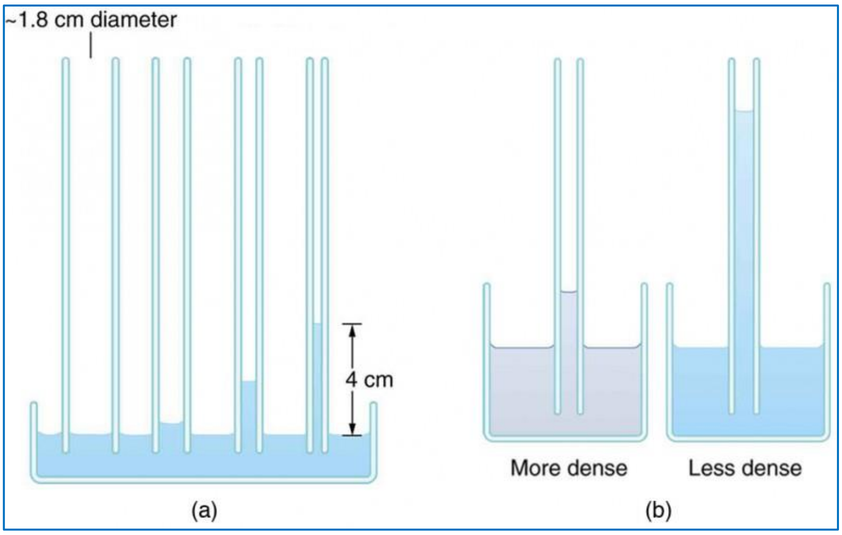
where

- h is the height the liquid is lifted,
- γ is the liquid–air surface tension,
- ρ is the density of the liquid,
- a is the radius of the capillary,
- g is the acceleration due to gravity,
- θ is the angle of contact

Note that students must convert ρ, g, a and h into SI units before entering them into the equation. The SI unit for surface tension is J/m^2 (or N/m).

The accepted value of the surface tension of water in air at 20^o C is $\gamma = 0.073\ J/m^2$. However, you must use pure water and extremely clean glass to get this result. Usually, the measured surface tension is at least half of this number.

If we look at the different factors in this expression, we might see how it makes good sense. The height is directly proportional to the surface tension γ, which is its direct cause. Furthermore, the height is inversely proportional to tube radius—the smaller the radius a, the higher the fluid can be raised, since a smaller tube holds less mass. The height is also inversely proportional to fluid density ρ, since a larger density means a greater mass in the same volume.



Example:

Can capillary action be solely responsible for sap rising in trees? To answer this question, calculate the radius of a capillary tube that would raise sap 100 m to the

top of a giant redwood, assuming that sap's density is 1050 kg/m³, its contact angle is zero, and its surface tension is the same as that of water at 20.0º C.

Strategy

The height to which a liquid will rise as a result of capillary action is given by $h = \frac{2\gamma cos\theta}{\rho g a}$ **and every quantity is known except for** a**.**

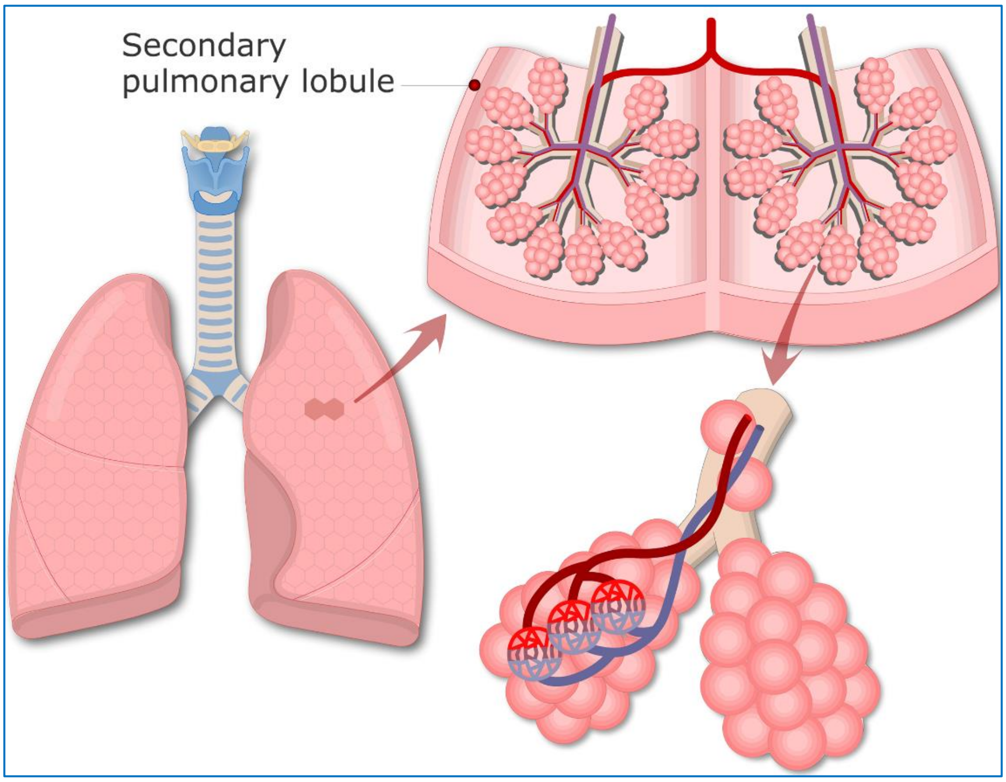
Solution

Solving for a **and substituting known values produces**

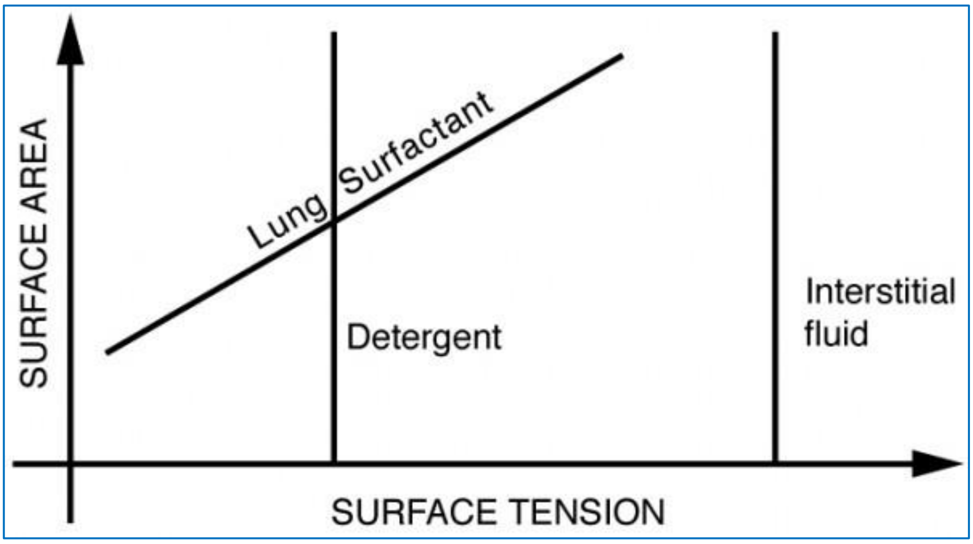
$$a = \frac{2\gamma cos\theta}{\rho g h} = \frac{2(0.0728\ N/m)\ cos(0)}{(1050\ Kg/m^3)(9.8\ m/s^2)(100\ m)} = 1.41x10^{-7}m$$

Surface tension in our body

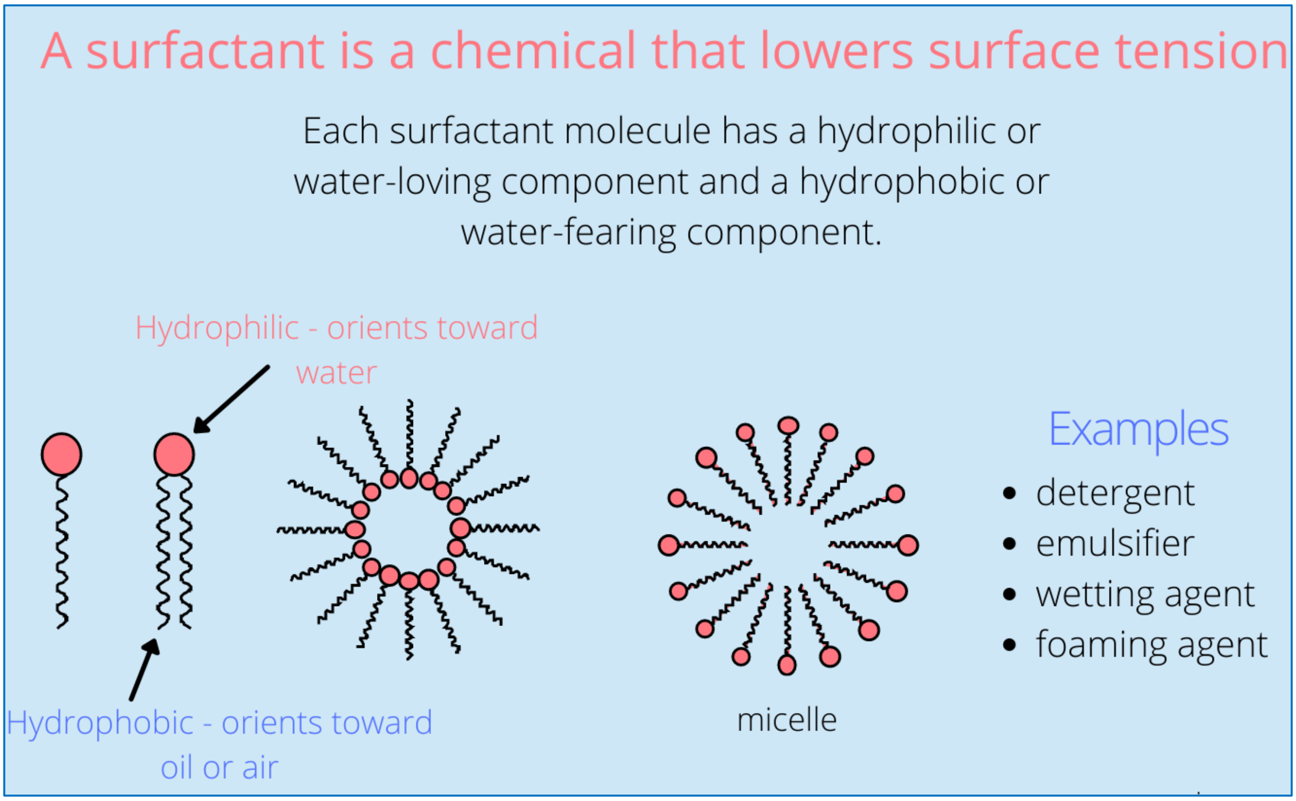
Our lungs contain hundreds of millions of mucus-lined sacs called *alveoli*, which are very similar in size, and about 0.1 mm in diameter. You can exhale without muscle action by allowing surface tension to contract these sacs. Medical patients whose breathing is aided by a positive pressure respirator have air blown into the lungs but are generally allowed to exhale on their own. Even if there is paralysis, surface tension in the alveoli will expel air from the lungs. Since pressure increases as the radii of the alveoli decrease, an occasional deep cleansing breath is needed to fully reinflate the alveoli. Respirators are programmed to do this, and we find it natural, as do our companion dogs and cats, to take a cleansing breath before settling into a nap.

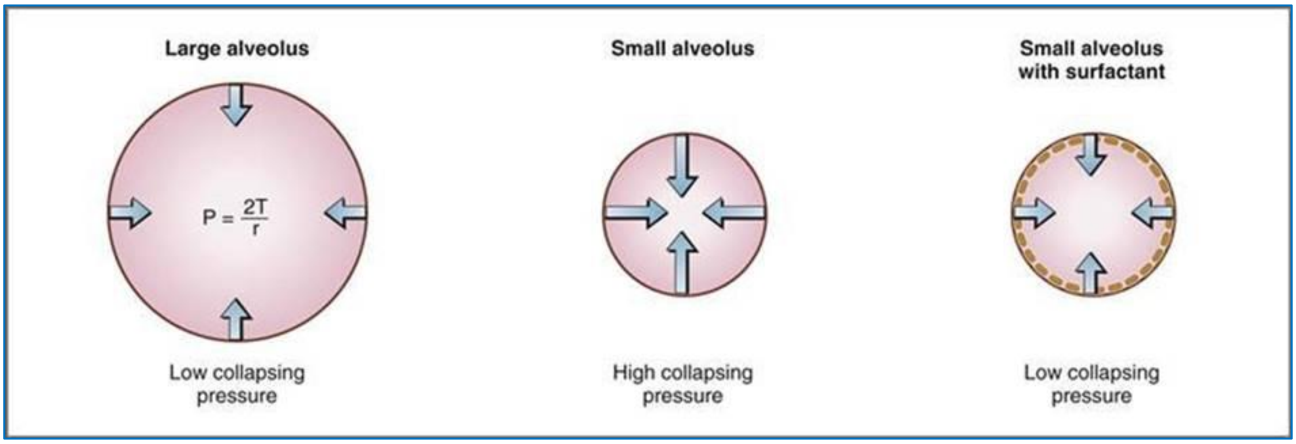


The tension in the walls of the alveoli results from the membrane tissue and a liquid on the walls of the alveoli containing a long lipoprotein that acts as a surfactant (a surface-tension reducing substance). The need for the surfactant results from the tendency of small alveoli to collapse and the air to fill into the larger alveoli making them even larger. During inhalation, the lipoprotein molecules are pulled apart and the wall tension increases as the radius increases (increased surface tension). During exhalation, the molecules slide back together, and the surface tension decreases, helping to prevent a collapse of the alveoli.

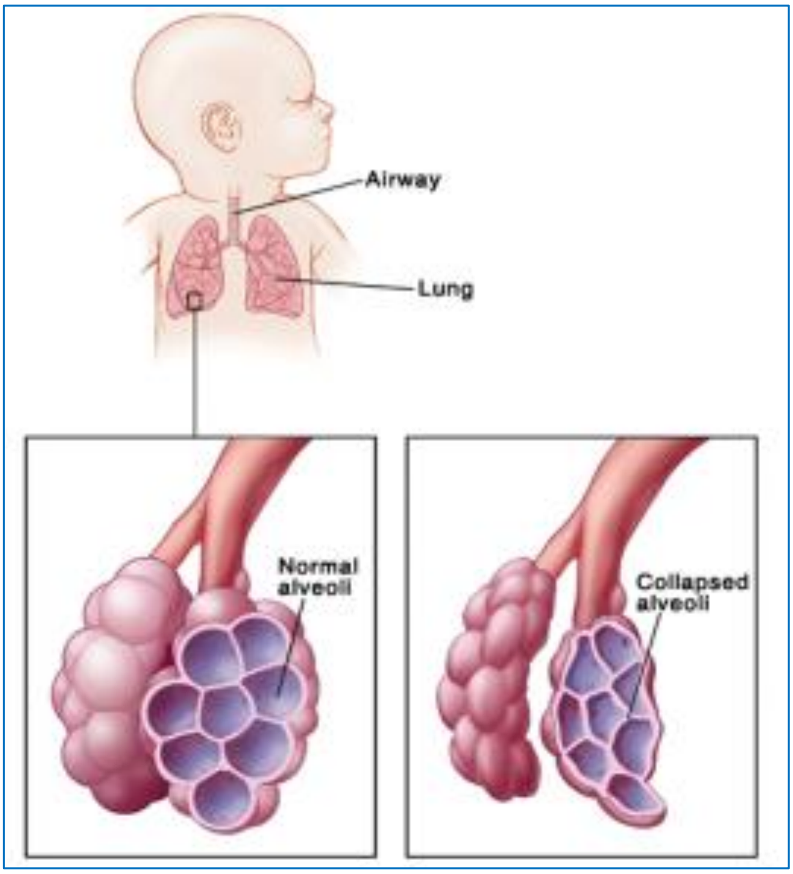


The surfactant therefore serves to change the wall tension so that small alveoli don't collapse, and large alveoli are prevented from expanding too much. This tension change is a unique property of these surfactants and is not shared by detergents (which simply lower surface tension).





If water gets into the lungs, the surface tension is too great, and you cannot inhale. This is a severe problem in resuscitating drowning victims. A similar problem occurs in newborn infants who are born without this surfactant—their lungs are very difficult to inflate. This condition is known as *hyaline membrane disease* and is a leading cause of death for infants, particularly in premature births. Some success has been achieved in treating hyaline membrane disease by spraying a surfactant into the infant's breathing passages. Emphysema produces the opposite problem with alveoli. Alveolar walls of emphysema victims deteriorate, and the sacs combine to form larger sacs. Because pressure produced by surface tension decreases with increasing radius, these larger sacs produce smaller pressure, reducing the ability of emphysema victims to exhale. A common test for emphysema is to measure the pressure and volume of air that can be exhaled.



Quiz (2)

Q1:Compare between:

1- Elastic deformation and plastic deformation

2- Types of levers

3- Stress and Strain

4- Ductile and Brittle materials

Q2: Show that the human body organs have some elastic properties?

Q3: Draw stress – strain curve and explain why stress can decrease with the increase of strain?

Q4: Define the following terms:

Atmospheric pressure- Absolute Pressure - Surface tension - Contact angle

Q5: Discuss the role of pressure in the respiratory system?

Q6: Explain how the surface tension control the size of the alveoli?

Q7: A wire of length 2 m and cross-sectional area 10^{-4} m^2 is stretched by a load 102 kg. The wire is stretched by 0.1 cm. Calculate longitudinal stress, longitudinal strain and Young's modulus of the material of wire.

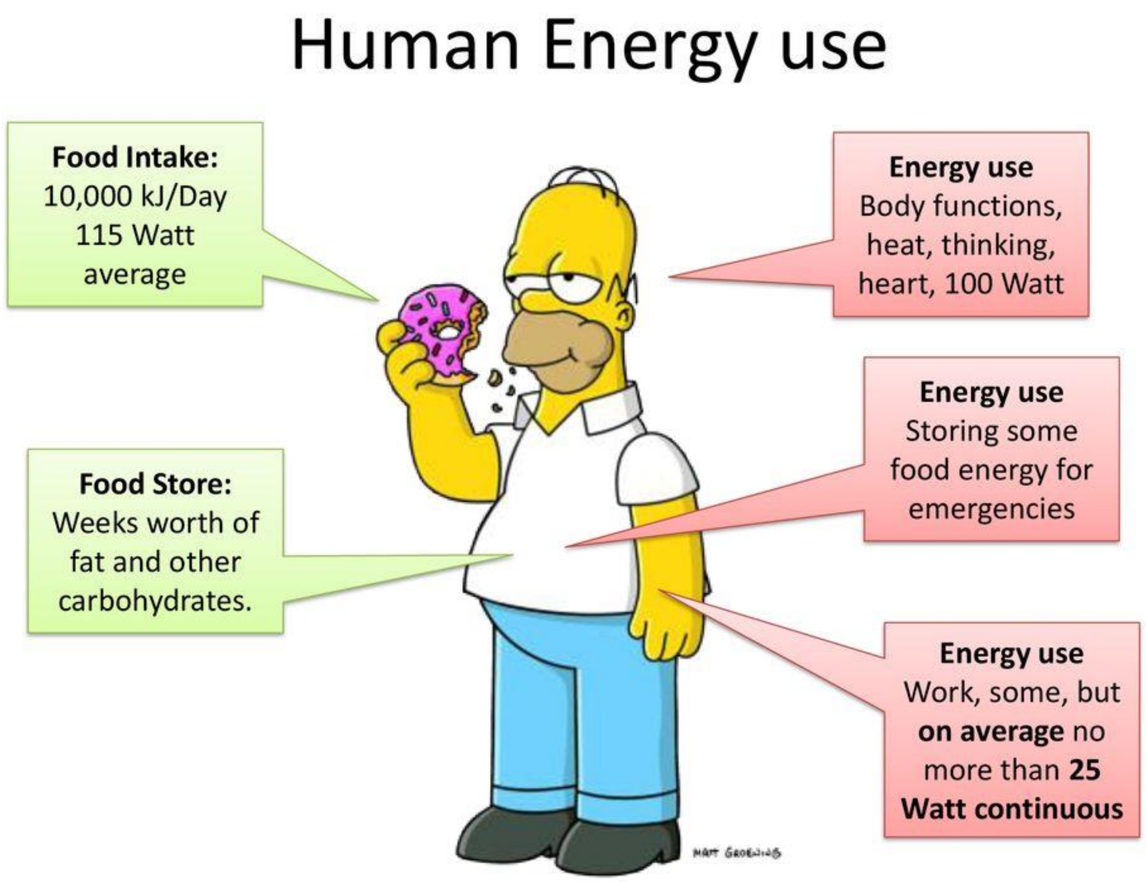
Q8: A mild steel wire of radius 0.5 mm and length 3 m is stretched by a force of 49 N. calculate a) longitudinal stress, b) longitudinal strain c) elongation produced in the body if Y for steel is 2.1×10^{11} N/m^2.

Q9: A tank filled with water of up to 5m height. Calculate the pressure exerted on the bottom of the tank. (Acceleration due to Gravity = 9.8 m/sec^2, Density of water = 1000 kg / m^3).

Q10: The pressure exerted by a liquid at a depth of 2.5 m is 36750 Pa. What is the density of the liquid, Gravity = 9.8 m/sec^2?

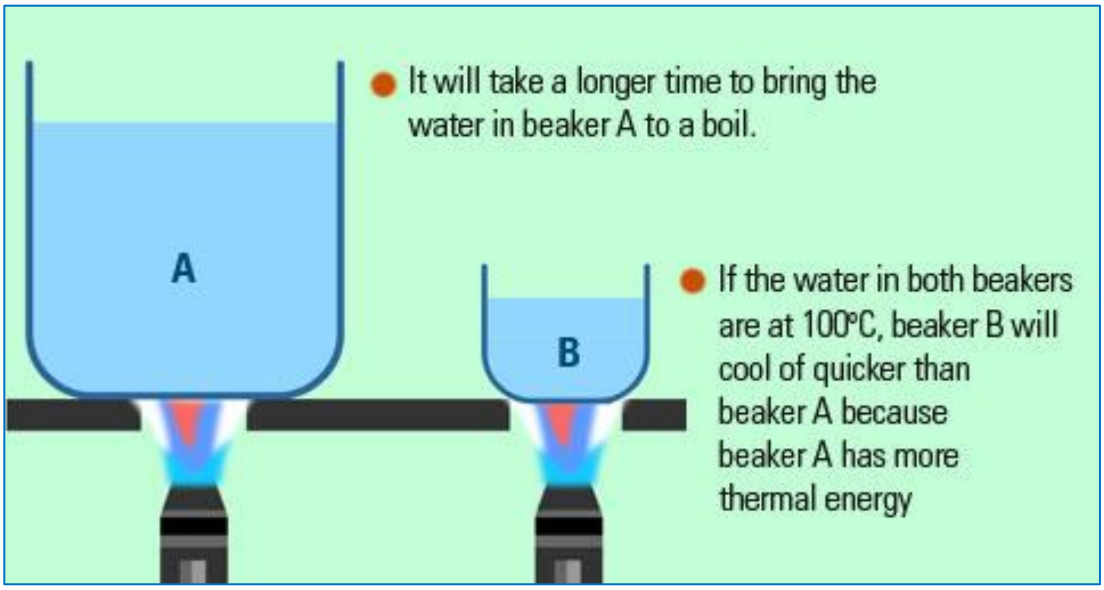
Chapter 3

Heat and temperature in the human body



Basic concepts of temperature and heat

Temperature is a measurement of the average amount of heat or particles thermal energy that present in a substance. It gives an average measurement which is independent on the number of particles, or we can say that is independent on the size of particles; for example, the temperature of small size of bowl filled with boiled water is same as the temperature of big size of bowl. It does not depend on the number of particles. We feel temperature every day of our atmosphere. In summer, we feel hot due to high temperature while in winter, we feel cold due to less temperature. When we boil water, we increase temperature while when we freeze or cold something, we low temperature. So, it is also said to measure the capacity of an object to transfer its heat energy to another object.

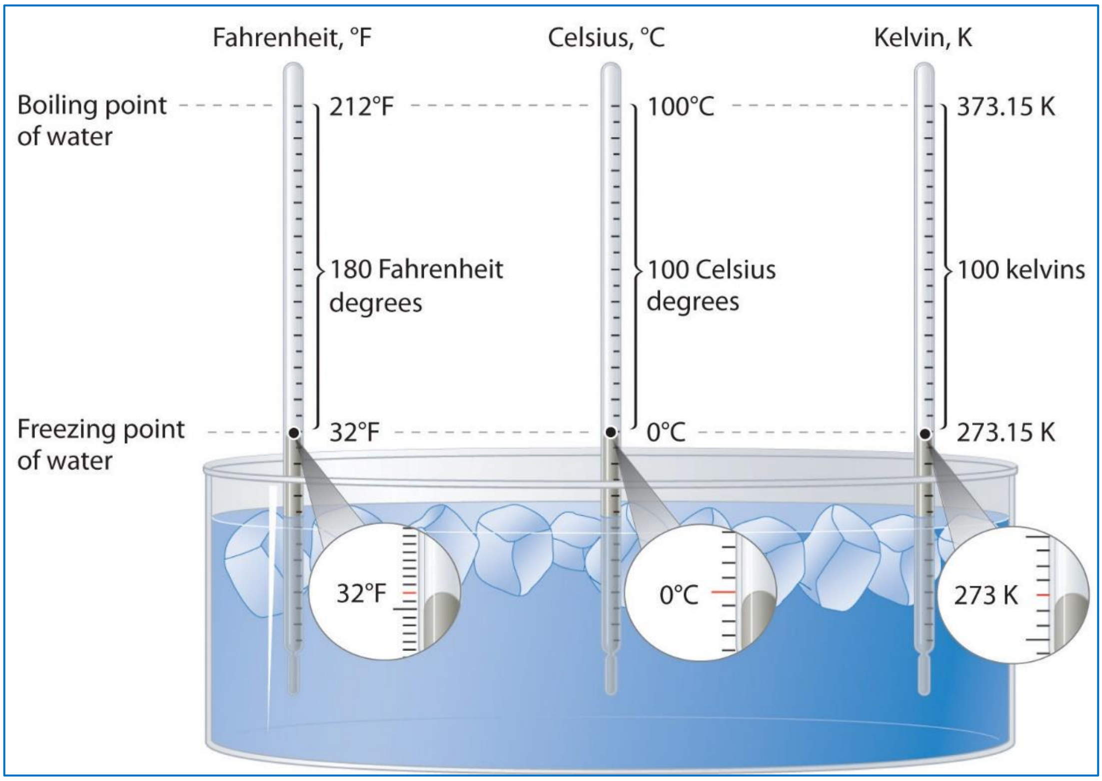


Temperature scales:

Temperature scales differ in two ways: the point chosen as zero degrees, and the magnitudes of incremental units or degrees on the scale.

1. **The Celsius scale:** is based on 0 °C for the freezing point and 100 °C for the boiling point of water, with the interval between the two being divided into 100 parts.
2. **The Kelvin Scale:** The solid, liquid, and gaseous phases of water can exist in equilibrium at 273.16 °C (the triple point temperature). The kelvin is defined as 1/273.16 of the triple point temperature.

3. **The Fahrenheit Scale**: The Fahrenheit temperature scale is based on 32 °F for the freezing point of water and 212 °F for the boiling point of water, with the interval between the two being divided into 180 parts.



The following table shows the temperature conversion formulas for conversions to and from the Celsius scale.

To convert from…	Use this equation…
Celsius to Fahrenheit	$T_F = 9/5\, T_C + 32$
Fahrenheit to Celsius	$T_C = 5/9(T_F - 32)$
Celsius to Kelvin	$T_K = T_C + 273.15$
Kelvin to Celsius	$T_C = T_K - 273.15$
Fahrenheit to Kelvin	$T_K = 5/9(T_F - 32) + 273.15$
Kelvin to Fahrenheit	$T_F = 9/5(T_K - 273.15) + 32$

Examples

1. Convert 27° C to Kelvin?		
$T_K = T_C + 273$	$T_K = 27 + 273$	$T_K = 300$ K
2. What is the temperature in °C of a 256 K object?		
$T_C = (T_K) - 273$	$T_C = 256 - 273$	$T_C = -17$ °C

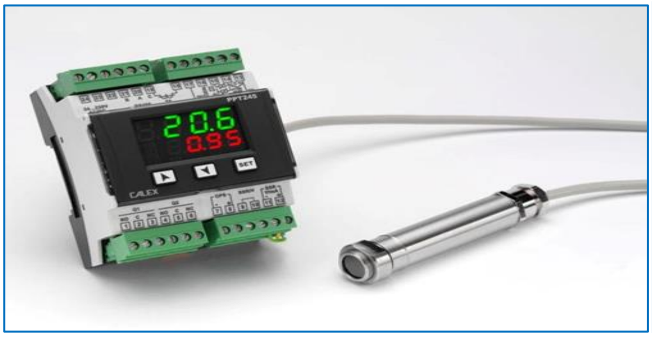
3. Body temperature is 37°C. Convert this to Fahrenheit?			
$T_F = 9/5\ T_C + 32$	$T_F = (9/5)(37) + 32$	$T_F = 66.6 + 32$	$T_F = 98.6°$
4. Convert the normal human body temperature (98.6°F) to Celsius.			
$T_C = 5/9\ (T_F - 32)$	$T_C = 5/9\ (98.6 - 32)$	$T_C = 5/9\ (66.6)$	$T_C = 37°C$
5. Convert 60 degrees Fahrenheit to Kelvin?			
$T_K=5/9(T_F-32) +273.15$	$T_K = 5/9\ (60 -32) + 273.15$		$T_K = 288.71\ K$
6. Convert room temperature in Kelvin 293K to Fahrenheit.?			
$T_F = 9/5(T_K - 273) + 32$	$T_F = 9/5(293 - 273) + 32$	$T_F = 9/5(20) + 32$	$T_F = 68\ °$

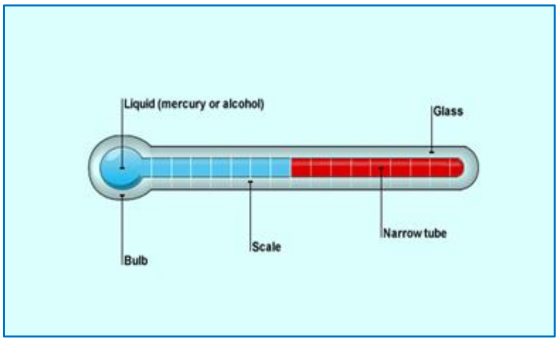
Thermometers

A thermometer is a device that measures temperature or a temperature gradient. A thermometer has two important elements:

- ✓ A temperature sensor (e.g. the bulb of a mercury-in-glass thermometer or the digital sensor in an infrared thermometer) in which some change occurs with a change in temperature
- ✓ Some means of converting this change into a numerical value (e.g. the visible scale that is marked on a mercury-in-glass thermometer or the digital readout on an infrared model).

Thermometers are widely used in industry to monitor processes, in meteorology, in medicine, and in scientific research.





Types of Thermometers

<u>Contact thermometers</u>

- ❖ Liquid-in-glass
- ❖ Electrical
  - ❖ Resistance thermometers

❖ Thermocouples

Non-contact thermometers

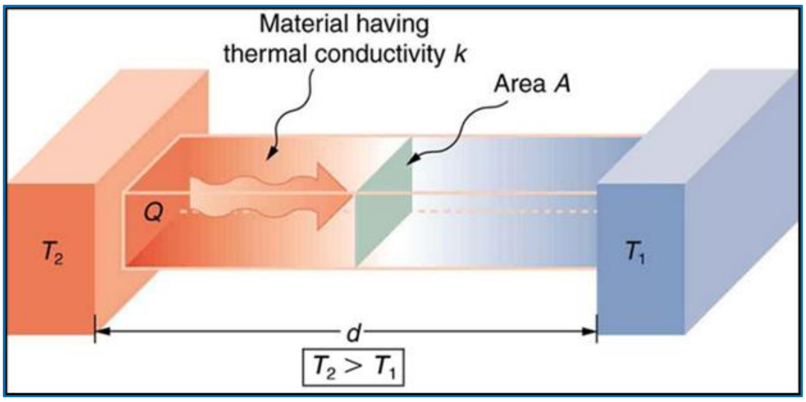
❖ Infra-red radiation thermometers

Heat transfer modes

Temperature differences cause the flow of heat from a high temperature to a low temperature. There are three modes of heat transfer: conduction, convection, and radiation.

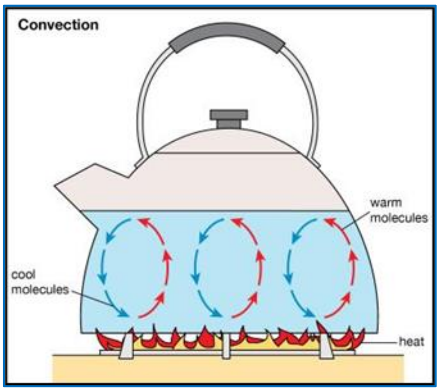
Conduction

The basic microscopic mechanism of conduction is the motion of molecules and electrons. It can occur in solids, liquids and gases. In non-metallic solids the transfer of heat energy is due mainly to lattice vibrations. structure. In metallic solids we have both lattice vibrations and random motions of free electrons. Consequently, metals are more conductive than non - metals. In gases, we have mainly random motions of molecules. In liquids we have partly random molecular motions and some sort of vibration of the liquid lattice.



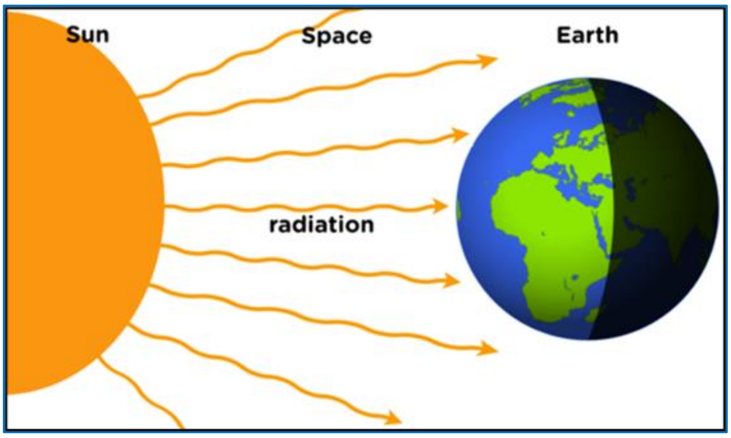
Convection

Convection is associated with the transport of a mass of liquid or gas. It can be Forced i.e. when assisted by a pump or fan, or free (also called natural convection) when the motion of a fluid occurs due to density differences. If there is an electrical heating element at the corner of a room and air is blown onto the element by a fan, this is forced convection. In the absence of a fan the air surrounding the heating element will get hotter, its density will decrease, and the air will move upwards causing natural circulation within the room, as the hot air is replenished by colder air, which gets hot and rises again.



Radiation

Radiation involves electromagnetic waves which are emitted by a body because of its temperature. The electromagnetic radiation has a broad spectrum from radio waves to x -rays. Between the two extremes a narrow portion of the radiation spectrum is the visible light, and a broader one covers the thermal radiation. The earth is heated by sun's radiation.



Specific Heat

The specific heat is the amount of heat per unit mass required to raise the temperature by one degree Celsius. The relationship between heat and temperature change is usually expressed in the form shown below where c is the specific heat. The relationship does not apply if a phase change is encountered, because the heat added or removed during a phase change does not change the temperature.

$$Q = cm\Delta T$$

Q: heat added; c: specific heat; m: mass; ΔT: change in temperature

Heat capacity

The heat capacity of a defined system is the amount of heat (usually expressed in calories, kilocalories, or joules) needed to raise the system's temperature by one degree (usually expressed in Celsius or Kelvin).

$$C = \frac{Q}{\Delta T} \qquad c = \frac{Q}{m\Delta T}$$

Heat Capacity — Specific Heat Capacity

Using the specific heat capacity of water (4200 J/kg°C), how much energy is needed to increase the temperature of 600 g of water by 80°C in a kettle?

Note: mass = 600 g = 0.6 kg

energy = mass x specific heat capacity x temperature change

energy = 0.6 x 4200 x 80

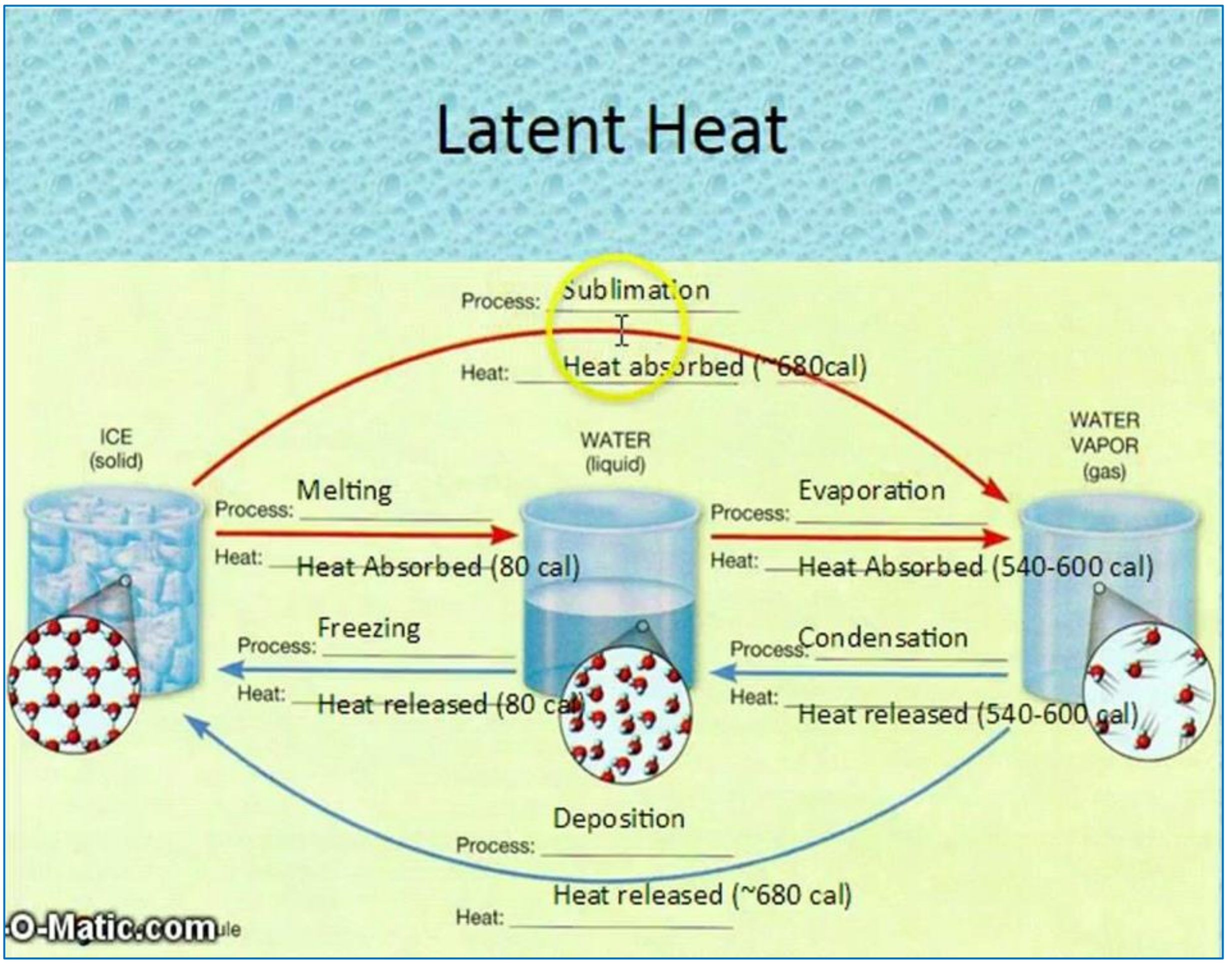
= 201 600 J

Latent heat

Latent heat, energy absorbed or released by a substance during a change in its physical state (phase) that occurs without changing its temperature. The latent heat associated with melting a solid or freezing a liquid is called the heat of fusion; that associated with vaporizing a liquid or a solid or condensing a vapor is called the heat of vaporization. The latent heat is normally expressed as the amount of heat (in units of joules or calories) per mole or unit mass of the substance undergoing a change of state.

$$L = \frac{Q}{m}$$

Specific Latent Heat (L), Heat Energy (Q), Mass (m)

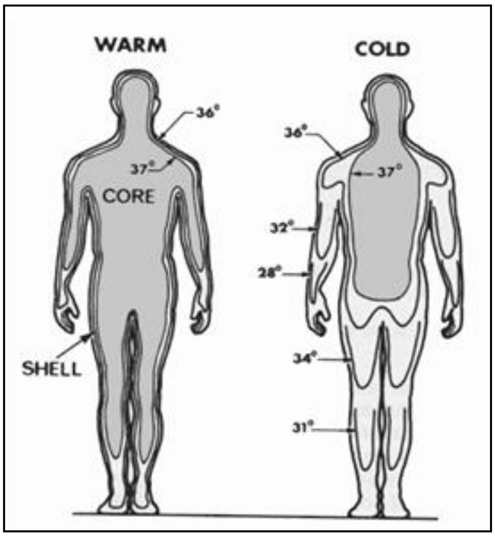


Temperature measurements in healthcare

Medical thermometry illustrates some of the options for temperature measurement. For example:

- Thermography
- Infrared tympanic (ear) thermometers

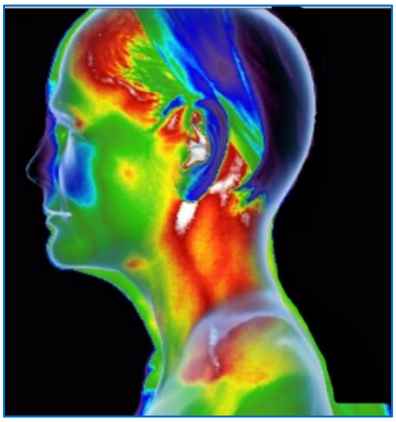
Thermography



Historically, temperature has been proved to be a very good indicator of health. Since 400 BC temperature has been used for clinical diagnosis. Human, being a homeotherm, is capable of maintaining a constant temperature of the body, which may be different from surrounding temperature. The body of homeotherms can be divided into two parts, viz. the inner core and the outer periphery. The core temperature is preserved within a narrow limit (approximately 42–33 °C). This regulation of inner core temperature is essential for normal performance of human body. Change of core temperature by a few degrees is considered as a clear indication of probable illness. The body controls its temperature by a physiological process, called thermoregulation.

Thermoregulation

The human body regulates temperature by keeping a close balance between heat gain and heat loss. The normal core temperature regulates between 36.5 degrees Celsius and 37.5 degrees Celsius. The hypothalamus keeps the temperatures at a set temperature sweating when the body is to hot and shivering when the body is to cold.



In exercise the body's ability to thermoregulate is challenged. For example, heat is produced from metabolism (metabolism meaning all reactions occurring in the body.) The heat from exercise is produced from working muscle contractions. (In this process the core body can rise above 40 degrees Celsius.) For Thermoregulation water is very important (hence: sweating, shivering, even urination is a form of heat loss.)

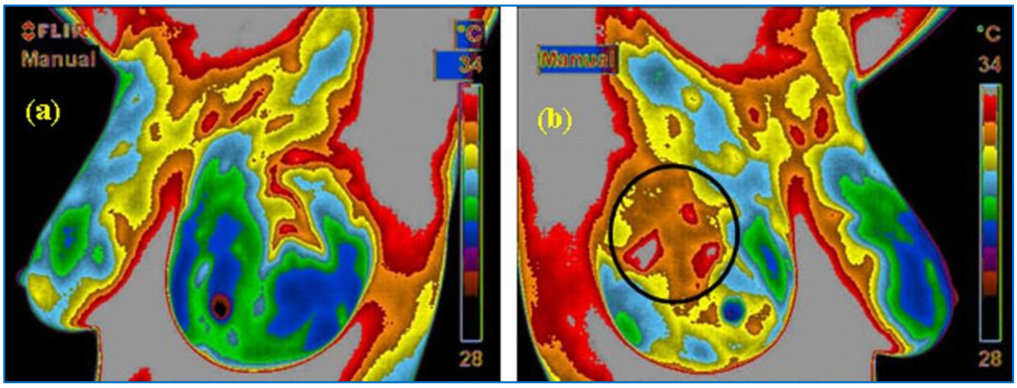
What is Infrared Thermography (IRT)?

Infrared- below last visible color (red) •Therm - Greek word for heat •Graph- writing or representation for a specified process. Basically, a graphical representation of heat. All normal matter emits electromagnetic radiation when it has a temperature above absolute zero. The radiation represents a conversion of a body's thermal energy into electromagnetic energy and is therefore called thermal radiation. It is a spontaneous process of radiative distribution of entropy.

IRT in medical science

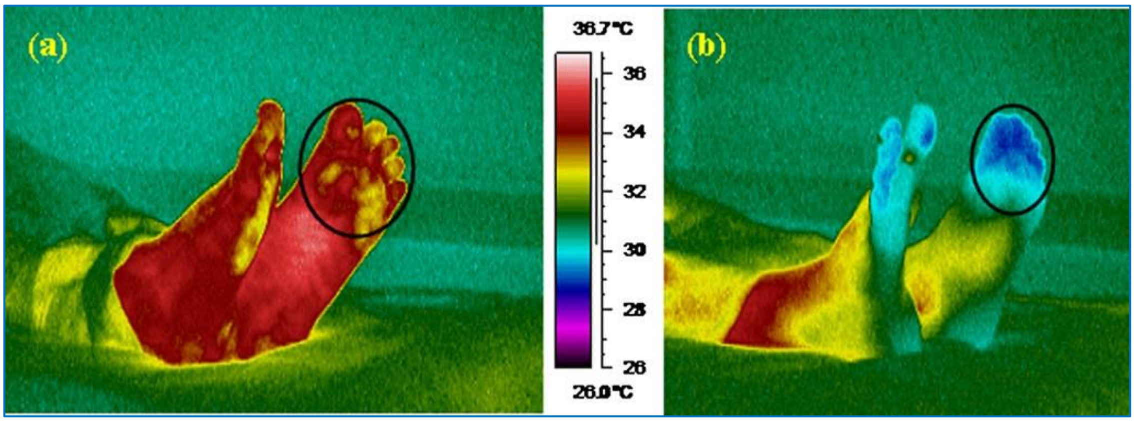
Breast cancer detection

Tumors generally have an increased blood supply and an increased metabolic rate which leads to localized high temperature spots over such areas, rendering them to be visualized by IRT. Blood vessels produced by cancerous tumors are simple endothelial tubes devoid of a muscular layer. Such blood vessels fail to constrict in response to sympathetic stimulus like a sudden cold stress and show a hyperthermic pattern due to vasodilatation.



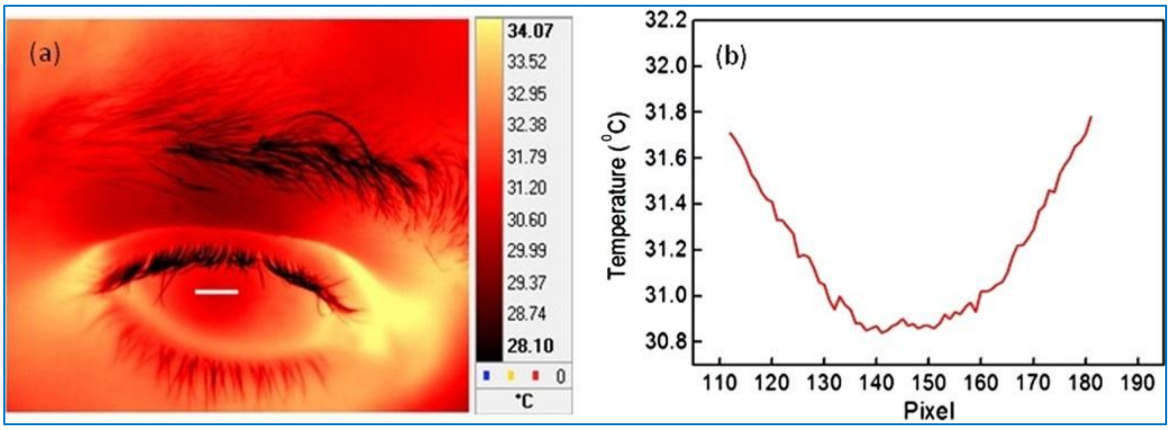
Diagnosis of diabetic neuropathy and vascular disorder

Both vascular disorder and diabetic neuropathy cause changes in skin surface temperature, which makes IRT a suitable tool for diagnosing diabetic neuropathy or vascular disorders. diabetes at-risk subjects have significantly higher mean foot temperature (30.2 ± 1.3 ºC) compared to the normal subjects (26.8 ± 1.8 ºC). Thermoregulatory sweating disorder signified early sympathetic damages in diabetic feet, which can be detected in the initial stages using IRT.



Diagnosis of dry eye syndrome and ocular diseases

The ocular surface temperature is greater in the dry eye subjects (32.38 ± 0.69 ºC) compared to the controls (31.94 ± 0.54 ºC)



Also, temperature at different regions such as lateral orbit (reference point), upper and lower eyelids, caruncle, medial and lateral conjunctiva and cornea was measured, and it was observed that, for subjects suffering from Graves' ophthalmopathy, temperature differences between the reference point and other regions are significantly higher compared to the corresponding temperature differences in the controls. It has also been found that, IRT is useful in studying follow-up effects of methylprednisolone pulse therapy.

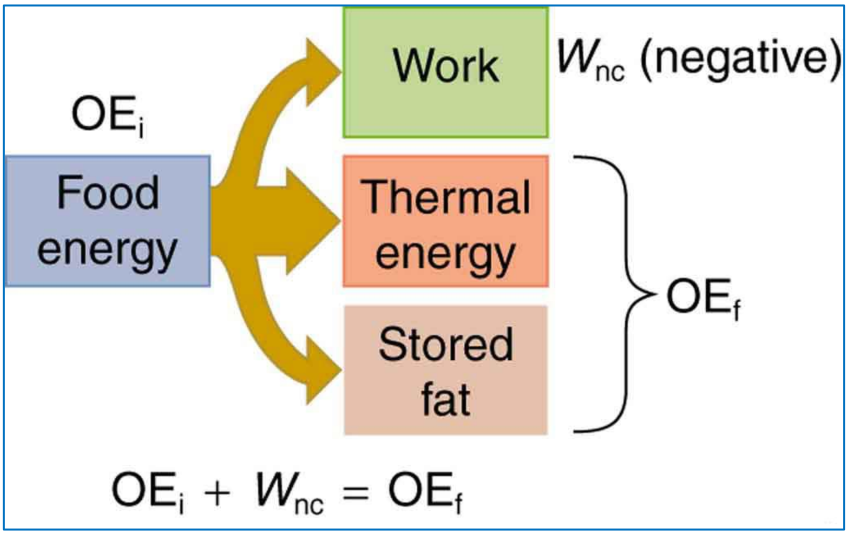
Infrared tympanic Ear Thermometer

Body temperature is routinely monitored in clinical settings with infrared ear thermometers which measure the infrared energy emitted from the patient's eardrum in a calibrated length of time. A short tube with a protective sleeve is inserted into the ear, and a shutter is opened to allow radiation from the tympanic membrane to fall on an infrared detector for a period which is typically from 0.1 to 0.3 seconds in the varieties surveyed. The device beeps when data collection is completed, and a readout of temperature is produced on a liquid crystal display.

Work, Energy, and Power in Humans

Energy Conversion in Humans

Our own bodies, like all living organisms, are energy conversion machines. Conservation of energy implies that the chemical energy stored in food is converted into work, thermal energy, and/or stored as chemical energy in fatty tissue. The fraction going into each form depends both on how much we eat and on our level of physical activity. If we eat more than is needed to do work and stay warm, the remainder goes into body fat.



Power Consumed at Rest

The *rate* at which the body uses food energy to sustain life and to do different activities is called the metabolic rate. The total energy conversion rate of a person *at rest* is called the basal metabolic rate (BMR) and is divided among various systems in the body, as shown in the following Table. The largest fraction goes to the liver and spleen, with the brain coming next. Of course, during vigorous exercise, the energy consumption of the skeletal muscles and heart increase markedly. About 75% of the calories burned in a day go into these basic functions. The BMR is a function of age, gender, total body weight, and amount of muscle mass (which burns more calories than body fat). Athletes have a greater BMR due to this last factor.

Organ	Power consumed at rest (W)	Oxygen consumption (mL/min)	Percent of BMR
Liver & spleen	23	67	27
Brain	16	47	19
Skeletal muscle	15	45	18
Kidney	9	26	10
Heart	6	17	7
Other	16	48	19
Totals	85W	250mL/min	100%

Energy consumption is directly proportional to oxygen consumption because the digestive process is basically one of oxidizing food. We can measure the energy people use during various activities by measuring their oxygen use. Approximately 20 kJ of energy are produced for each liter of oxygen consumed, independent of the type of food.

How is energy stored in the body?

The ultimate source of all energy on earth is the sun. Solar energy is harnessed by plants, which take carbon, hydrogen, oxygen, and nitrogen from their environment and manufacture either carbohydrate, fat, or protein. These foods possess stored energy. When we consume these foods, our digestive processes break them down into simple compounds that are absorbed into the body and transported to various cells. One of the basic purposes of body cells is to transform the chemical energy of these simple compounds into forms that may be available for immediate use or other forms that may be available for future use.

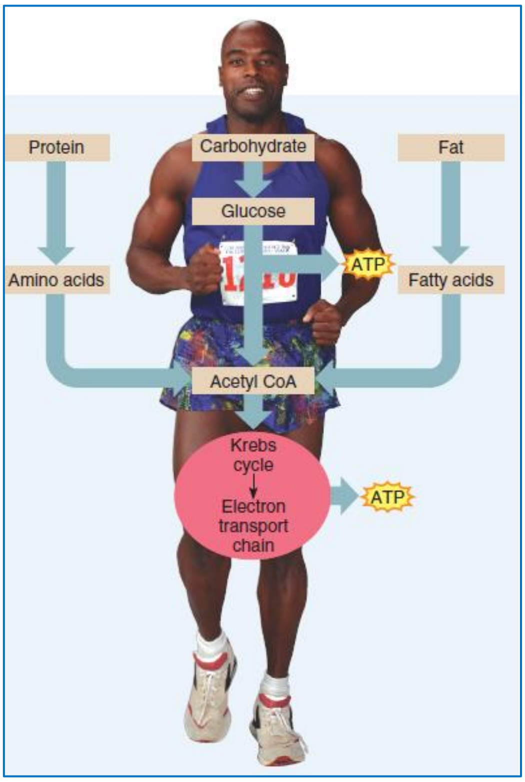
Energy in the body is available for immediate use in the form of adenosine triphosphate (ATP). It is a complex molecule constructed with high-energy bonds, which, when split by enzyme action, can release energy rapidly for a number of body processes, including muscle contraction. ATP is classified as a high-energy compound and is stored in the tissues in small amounts. It is important to note that ATP is the immediate source of energy for all body functions, and the other energy stores are used to replenish ATP at varying rates. Another related high-energy phosphate compound, phosphocreatine (PCr), is also found in the tissues in small amounts. Although it cannot be used as an immediate source of energy, it can rapidly replenish ATP. ATP may be formed from either carbohydrate, fat, or protein after those nutrients have undergone some complex biochemical changes in the body.

Because ATP and PCr are found in very small amounts in the body and can be used up in a matter of seconds, it is important to have adequate energy stores as a backup system. Your body stores of carbohydrate, fat, and protein can provide you with ample amounts of ATP, enough to last for many weeks even on a starvation diet. It is important to note that parts of each energy nutrient may be converted to the other two nutrients in the body under certain circumstances. For example, protein may be converted into carbohydrate during prolonged exercise, whereas excess dietary carbohydrate may be converted to fat in the body during rest.

What are the human energy systems?

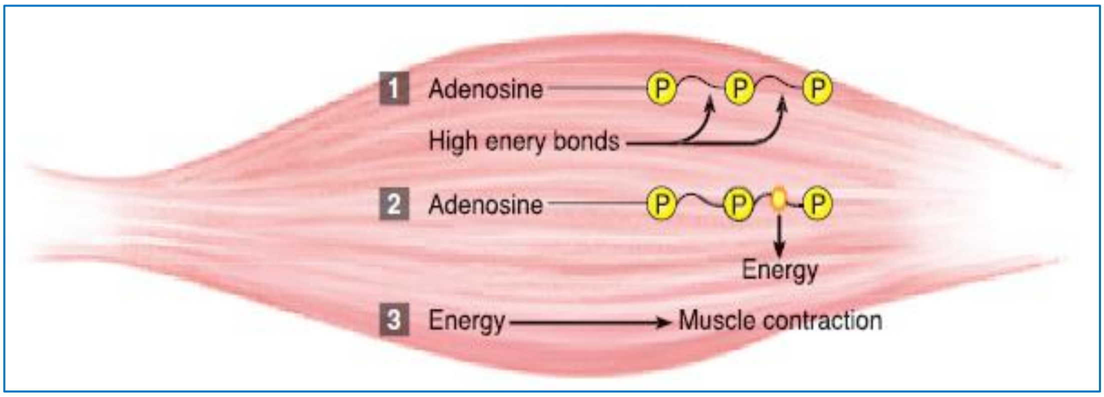
Sometimes humans needed to produce energy at a rapid rate, such as when sprinting to safety to avoid dangerous animals. Thus, a fast rate of energy production was an important human energy feature that helped ensure survival. At other times, our ancient ancestors may have been deprived of adequate food for long periods, and thus needed a storage capacity for chemical energy that would sustain life throughout these times of deprivation. Hence, the ability to store large amounts of energy was also important for survival. These two factors—rate of energy production and energy capacity—appear to be determining factors in the development of human energy systems.

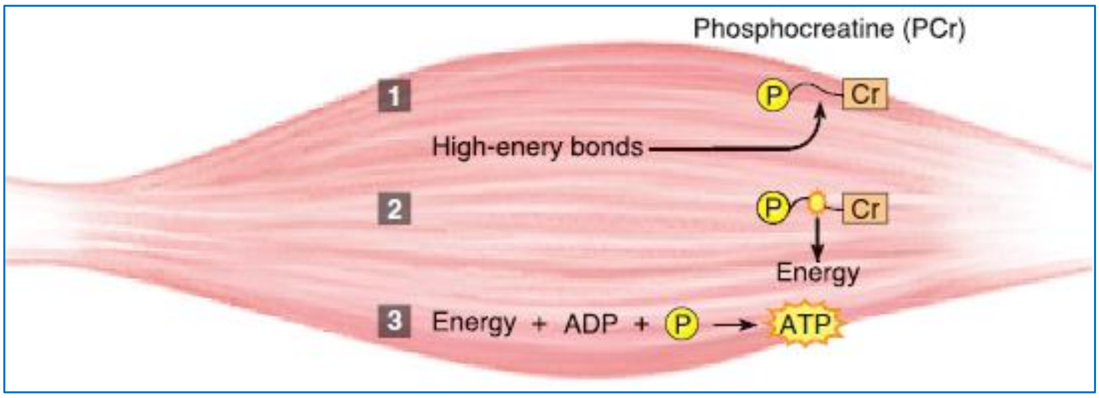
The human energy expenditure system can be classified to three energy, or power, systems: the ATP-PCr system, the lactic acid system, and the oxygen system.



- **The ATP-PCr system** is also known as the phosphagen system because both adenosine triphosphate (ATP) and phosphocreatine (PCr) contain phosphates. ATP is the immediate source of energy for almost all body processes, including muscle contraction. This high-energy compound, stored in the muscles, rapidly releases energy when an electrical impulse arrives in the muscle. No matter what you do, scratch your nose or lift 100 pounds, ATP breakdown makes the movement possible. ATP must be present for the muscles to contract. The body has a limited supply of ATP and must replace it rapidly if muscular work is to continue.

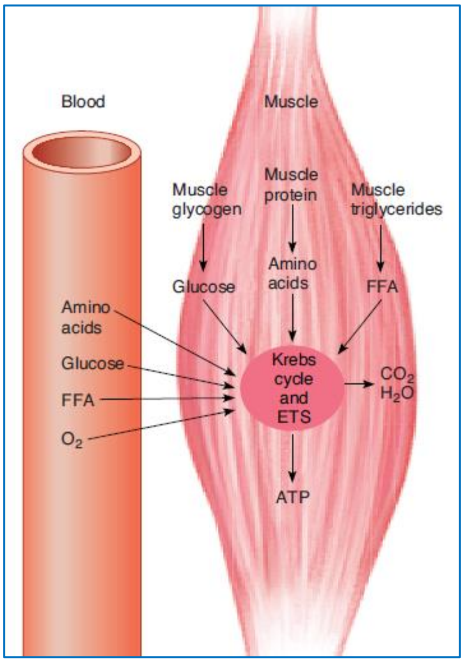
  PCr, which is also a high-energy compound found in the muscle, can help form ATP rapidly as ATP is used. Energy released when PCr splits is used to form ATP from ADP and P. PCr is also in short supply and needs to be replenished if used.





- **The lactic acid system** cannot be used directly as a source of energy for muscular contraction, but it can help replace ATP rapidly when necessary. If you are exercising at a high intensity level and need to replenish ATP rapidly, the next best source of energy besides PCr is muscle glycogen. To be used for energy, muscle glycogen must be broken down to glucose, which undergoes a series of reactions to eventually form ATP, a process called glycolysis. One of the major factors controlling the metabolic fate of muscle glycogen is the availability of oxygen in the muscle cell. In simple terms, if oxygen is available, a large amount of ATP is formed. This is known as aerobic glycolysis. If inadequate oxygen is available to meet the energy demands of the exercise task or to maintain a high level of aerobic glycolysis, then insufficient ATP is formed, and lactic acid is a by-product of the process to generate more ATP. This is known as anaerobic glycolysis; anaerobic glycolysis is the scientific term for the lactic acid energy system.

- The third system is **the oxygen system**. It is also known as the aerobic system. Aerobics is a term used by Dr. Kenneth Cooper in 1968. The oxygen system, like the lactic acid system, cannot be used directly as a source of energy for muscle contraction, but it does produce ATP in rather large quantities from other energy sources in the body. Muscle glycogen, liver glycogen, blood glucose, muscle triglycerides, blood FFA and triglycerides, adipose cell triglycerides, and body protein all may be ultimate sources of energy for ATP production and subsequent muscle contraction. To do this, glycogen and fats must be present within the muscle cell or must enter the muscle cell as glucose, FFA, or amino acids. Through a complex series of reactions metabolic by products of carbohydrate, fat, or protein combine with oxygen to produce energy, carbon dioxide, and water. These reactions occur in the energy powerhouse of the cell, the mitochondrion.



The whole series of events of oxidative energy production primarily involves aerobic processing of carbohydrates and fats (and small amounts of protein) through the Krebs cycle and the electron transfer system.

Although the rate of ATP production is lower, the major advantage of the oxygen system over the other two energy systems is the production of large amounts of energy in the form of ATP. However, oxygen from the air we breathe must be delivered to the muscle cells deep in the body and enter the mitochondria to be used.

Human Energy Metabolism

Human metabolism represents the sum total of all physical and chemical changes that take place within the body. The transformation of food to energy, the formation of new compounds such as hormones and enzymes, the growth of bone and muscle tissue, the destruction of body tissues, and a host of other physiological processes are parts of the metabolic process. Metabolism involves two fundamental processes, anabolism and catabolism.

Anabolism is a building-up process, or constructive metabolism. Complex body components are synthesized from the basic nutrients. For the active individual, this may mean an increased muscle mass through weight training or an increased number of cellular enzymes to better use oxygen following endurance-type training. Energy is needed for anabolism to occur.

Catabolism is the tearing-down process. This involves the disintegration of body compounds into their simpler components. The breakdown of muscle glycogen to glucose and eventually CO_2, H_2O, and energy is an example of a catabolic process. The energy released from some catabolic processes is used to support the energy needs of anabolism.

Metabolism is life. It represents human energy. The metabolic rate reflects how rapidly the body is using its energy stores, and this rate can vary tremendously depending upon a number of factors. For all practical purposes, the total daily energy expenditure (TDEE) may be accounted for by three factors: basal energy expenditure, increases due to eating a meal, and physical activity. Basal energy expenditure accounts for the largest component of TDEE, whereas physical activity is the most variable.

Body energy consumption

Occurs by the 5 following ways.

- Physical exertion or by voluntary movements.
- Mental exertion or mind activity.
- Physiological functions of the body. (involuntary activity).
- Body cellular metabolic and synthetic reactions.
- Energy lost by dissipation or nonspecific purposes.

Physical exertion: This is the way most of the energy of the body is spent in living animal and humans' beings. This is done due to the intention to move, perform or work. This may not be seen in plants as they do not move. The body energy is also consumed for muscle contractions and relaxation. We see this during walking, running, lifting, jumping, talking, shouting etc. Further body language also consumes energy. So, you can notice that when you are hungry your body language will be low and ineffective.

Mental exertion: This is the next way how energy is used in higher animals like humans. Good amount of energy is consumed for thinking, learning, memorizing. Hence during heartbeat, at least 20% of blood pumped from heart goes directly into the brain. This brain is high energy demanding organ, so it requires more glucose and oxygen from blood. Besides, anxiety and other behavior related functions need energy. Hence under stress you can notice eating more will reduce stress. So, Body first tries to fill up this energy need more than other energy needs. Even animals do some sort of brain and behavioral activity but low unlike humans.

Physiological functions: All the physiological functions in the body need energy. These include heartbeat, blood flow, breath (inspiration & expiration), digestion, intestinal contractions etc. require constant supply of energy. These are involuntary in nature without the intention of the animals. But are always active and energy demanding. The energy is mostly used up due to smooth muscle contractions in gut, blood vessels, lungs. The cardiac muscle in the heart is even more active and highly energy demanding. Also, blood vessel carry blood to corners of the body and bring back by veins by contractions and relaxations.

Body metabolic and synthetic reactions: Most of the body cell reactions like formation of proteins (translation), multiplication of genes, formation of genes demand energy. Also transport of salts, nutrients across the cell membrane, degradation of toxic waste (metabolism) require energy. Further enzymes are the key factors involved in above reactions. These enzymes perform only at body temperature. So, body tries to maintain heat at a constant by heat generation.

Energy lost by dissipation: The formed is quite valuable but still it is lost. Here the energy is dissipated from the body in the form of heat. Body tries to maintain constant fixed temperature to keep up the physiology. This temperature is generated by burning calories in muscles. During cold weather or atmospheric temperature, the body loses heat. So, you can remember during winter you will feel more hunger and crave for food. Also, energy is lost when material goes out of the body. This we prominently see during breathing, hot air goes out and cool air comes in. Also, to some extent heat is lost by due to urination, bowels evacuation.

How much energy do I need to consume daily?

The amount of energy consumed by a person depends on the person's weight and build. It has been found, however, that the amount of energy consumed by a person during a given activity divided by the surface area of the person's body is approximately the same for most people. Therefore, the energy consumed for various activities is usually quoted in Cal/m^2-hr. This rate is known as the metabolic rate. To obtain the total energy consumption per hour, we multiply the metabolic rate by the surface area of the person. The following empirical formula yields a good estimate for the surface area.

$$\textbf{Area } (m^2) = 0.202 \times W^{0.425} \times H^{0.725}$$

Here W is the weight of the person in kilograms, and H is the height of the person in meters.

The surface area of a 70-kg man of height 1.55 m is about 1.70 m^2. His metabolic rate at rest is therefore (40 Cal/m^2-hr)×1.70m^2 = 68 Cal/hr, or about 70 Cal/hr. This metabolic rate at rest is called the basal metabolic rate (BMR).

Quiz (3)

1- **Write on the different scales of temperature?**

2- **Illustrate the heat transfer modes?**

3- **<u>Define the following:</u>**

Heat capacity – specific heat capacity – latent heat- Thermoregulation- Energy- Work – Power - Anabolism – Catabolism- energy conservation law – work& energy theorem – kinetic energy – potential energy.

4- **Discuss the applications of Thermography?**

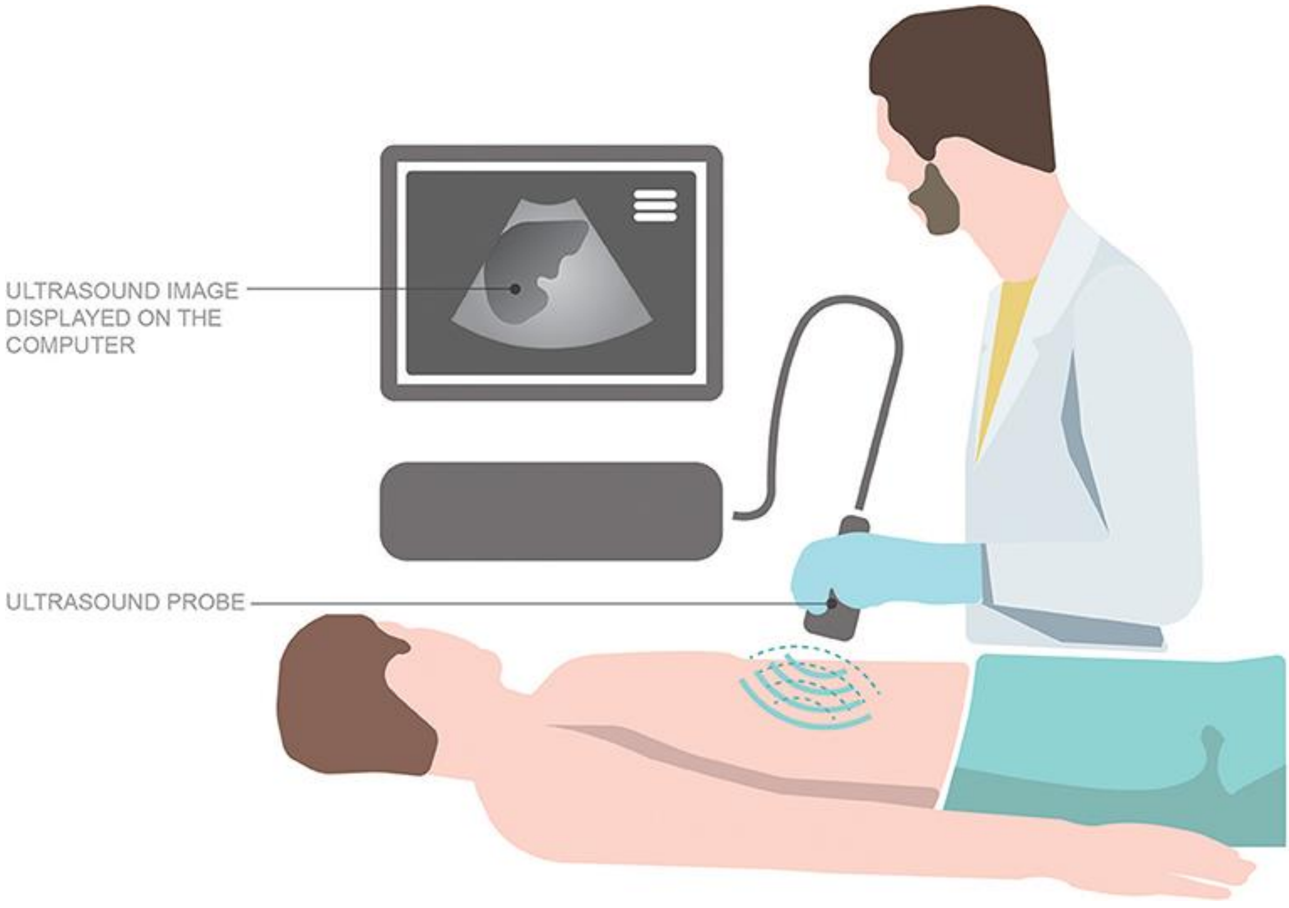
5- **What are the human energy systems?**

6- **Illustrate the human Body energy consumption?**

7- **Using the conversion between the temperature scales, complete the following table:**

Celsius (°C)	Kelvin (K)	Fahrenheit (°F)
120	……………………..	……………………..
……………………..	320	……………………..
……………………..	……………………..	-18

Chapter 4
Sound waves in medicine

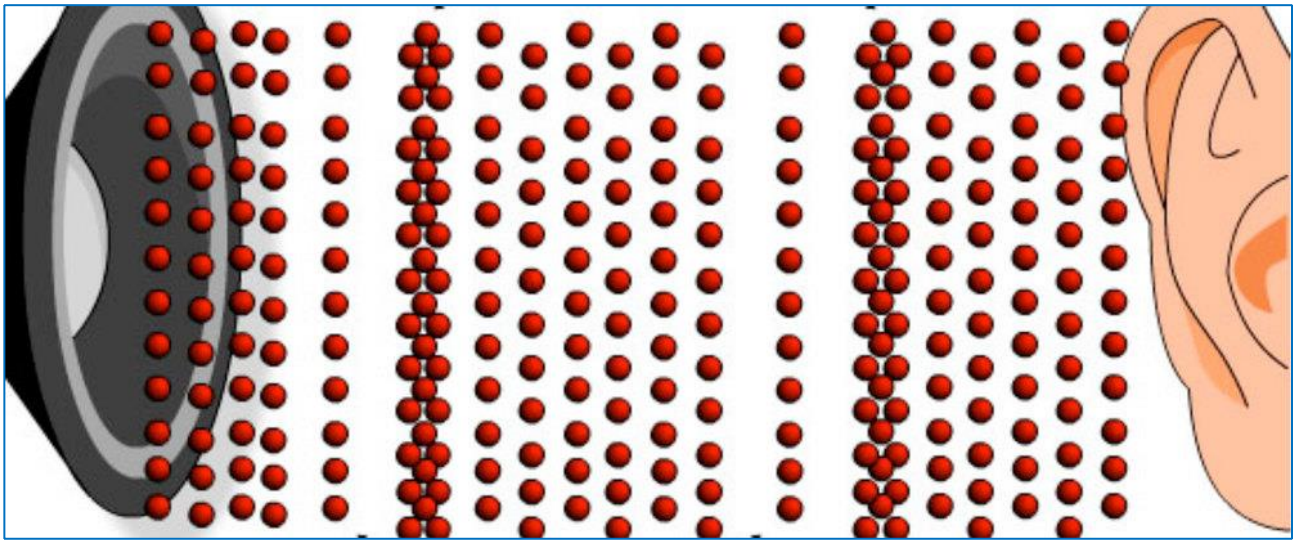


What is Sound?

Definitions

1- Sound is a form of energy. It can be generated, moved, can do work, can dissipate over time and distance, and can carry tremendous amounts of energy. Sound will continue only as long as there is energy in the system to keep it going.

2- Sound is defined as something that can be heard. It is a wave that is a series of vibrations traveling through a medium, especially those within the range of frequencies that can be perceived by the human ear. Sound can travel through many types of mediums, for example: gasses, liquids and solids. The compressions and rarefactions that move through the atmosphere are compressing and stretching the molecules of nitrogen and oxygen all around us. Sound cannot be heard in a vacuum, like outer space.



Sound is not thought of as a transverse wave because of the behavior of the particles in the medium.

Sound can be thought of as a longitudinal wave because of the vibrations of the particles of the medium.

Characteristics of Sound

- Sound can propagate through a medium such as air, water and solids as longitudinal waves and also as a transverse wave in solids.
- The sound waves are generated by a sound source, such as the vibrating diaphragm of a stereo speaker. The sound source creates vibrations in the surrounding medium.

As the source continues to vibrate the medium, the vibrations propagate away from the source at the speed of sound, thus forming the sound wave.

- At a fixed distance from the source, the pressure, velocity, and displacement of the medium vary in time.
- At an instant in time, the pressure, velocity, and displacement vary in space.
- During propagation, waves can be reflected, refracted, or attenuated by the medium.

Note that:

The particles of the medium do not travel with the sound wave. This is naturally obvious for a solid, and the same is true for liquids and gases (that is, the vibrations of particles in the gas or liquid transport the vibrations, while the average position of the particles over time does not change).

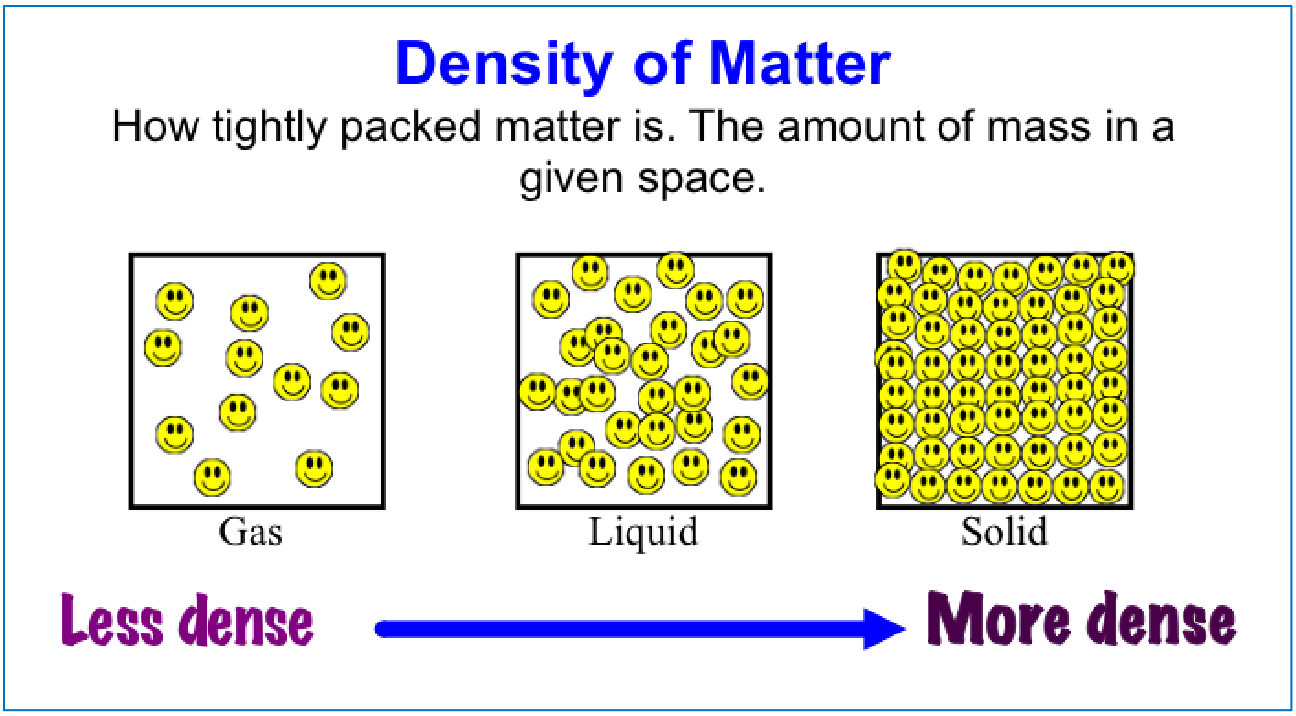
The behavior of sound propagation is generally affected by three things:

1- A complex relationship between the density and pressure of the medium. This relationship, affected by temperature, determines the speed of sound within the medium.

2- Motion of the medium itself. If the medium is moving, this movement may increase or decrease the absolute speed of the sound wave depending on the direction of the movement.

For example, sound moving through wind will have its speed of propagation increased by the speed of the wind if the sound and wind are moving in the same direction. If the sound and wind are moving in opposite directions, the speed of the sound wave will be decreased by the speed of the wind.

3- The viscosity of the medium. Medium viscosity determines the rate at which sound is attenuated. For many media, such as air or water, attenuation due to viscosity is negligible.



Sound units

1. The Decibel Scale

Decibel (dB), unit for expressing the ratio between two physical quantities, usually amounts of acoustic or electric power, or for measuring the relative loudness of sounds. When sound travels through an elastic medium, particles vibrate with variations in pressure amplitude reflected by the wave displacement of compression and rarefaction. The intensity of sound reflects the transmitted power per unit area and is roughly equivalent to the square of the pressure amplitude.

$$\text{Intensity} \sim \text{Pressure}^2$$

As the pressure amplitude doubles, the absolute intensity value increases by four times. The units of absolute intensity level are watts/m^2. Relative sound intensity is measured on the logarithmic scale with decibels (dB) were

$$\text{Relative Intensity (dB)} = 10\log_{10} I/I_o$$

I is the newly measured intensity, while I_o is the original signal intensity which functions as a reference.

2- **Sone** - a unit of perceived loudness equal to the loudness of a 1000-hertz tone at 40 dB above threshold, starting with 1 sone.

3- **Phon** - a unit of subjective loudness.

4- Hz, hertz = unit of sound frequency is called hertz (Hz)

Speed of Sound

The speed of a sound wave in air depends upon the properties of the air, namely the temperature and the pressure.

The pressure of air, like any gas, will affect the mass density of the air and the temperature will affect the strength of the particle interactions.

The sound waves are in a 3D circular pattern from the origin of the sound because the speed of the wave disturbances is constant. The speed of sound is about 331.5 m/s at 0º C or 1087 ft/s at 32º F, which translates to 740 mi/hr.

- Sound waves will travel faster in solids than they will in liquids and travel faster in liquids than they do in gases. A sound wave will travel faster in a less dense material than in a denser material. An example is: a sound wave will travel nearly three times faster in Helium as it will in air, which is mostly due to the lower mass of Helium particles as compared to air particles.
- The speed of sound is constant at a given temperature and is constant in each medium.
- The speed of sound changes with temperature changes. In air at 0º C the speed is about 331.5 m/s and increases about 0.60 m/s for every degree C increase in temperature. At 32º F the speed is about 1087 ft/s and increases 1.1 ft/s for every degree F increase in temperature.
- Sound travels faster in warmer temperatures than colder temperatures. The wavelength in warmer temperatures is slightly longer than at freezing temperatures. The frequency, or rate at which the waves pass a given point, of the sound does not change due to a change in temperature that is determined by the frequency at the source of the sound. Sound travels slower in higher layers of the atmosphere than it does just above the surface of the ocean and land.

Human Hearing

Unlike the senses of smell or taste, which rely on chemical interactions, hearing is a mechanical process in which the ear converts sound waves entering the ear into electrical signals the brain can understand.

How We Hear?

The ear is quite a piece of engineering, a complex organization of bones, hairs, nerves and cells. It is made up of three main parts, outer (1), middle (2) and inner (3 and 4). To hear naturally, each part of the ear needs to work well.

1.Sounds enter the ear canal

When these sound waves reach the ear, they travel down the ear canal and hit the eardrum, making it vibrate.

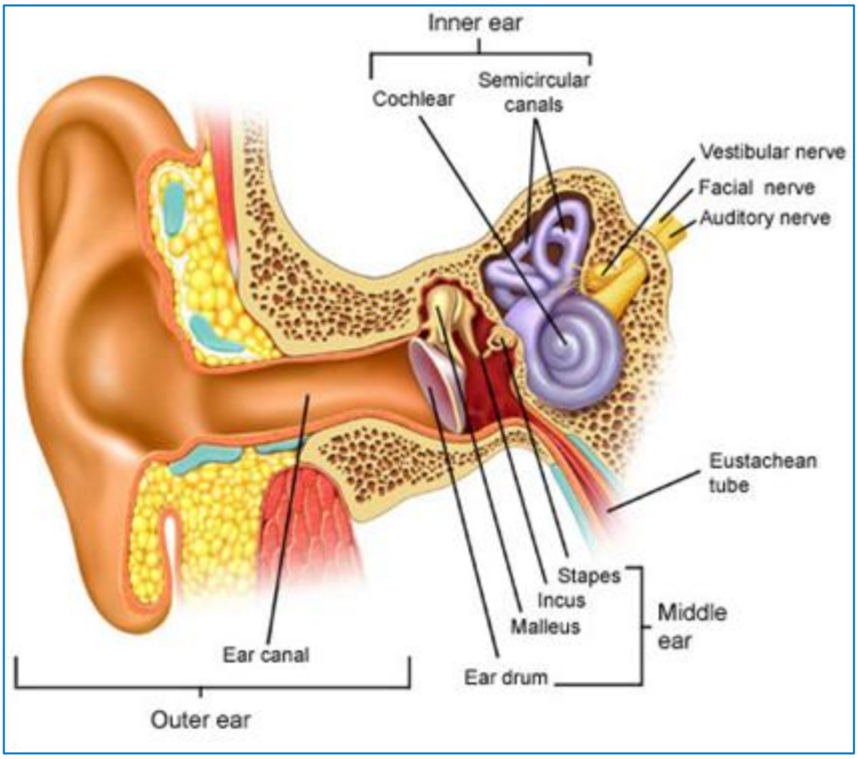
2.The ear drum and bones of hearing vibrate

Three tiny bones in the middle ear link the vibrating eardrum to a tiny bone structure in the inner ear called the cochlea.

3.Fluid moves through the inner ear

The cochlea is filled with liquid that carries the vibrations to thousands of tiny hair cells.

4.Hearing nerves communicate to the brain



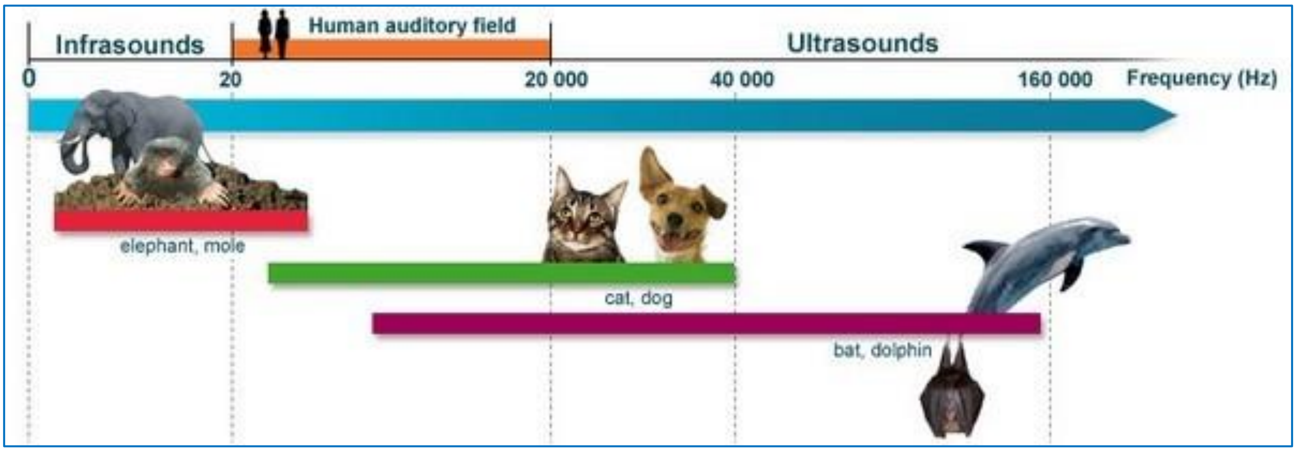
The movement in the fluid causes the cells to carry a message to the nerve that is connected to the brain, which turns the signals into what you hear. The movement in the fluid causes the cells to carry a message to the nerve that is connected to the brain, which turns the signals into what you hear.

To hear the sound traveling through the air, three things have to happen.

1- The sound has to be directed into the hearing part of the ear.
2- The ear has to sense the fluctuations in air pressure.
3- The fluctuations have to be translated into electrical signals that the brain can understand.

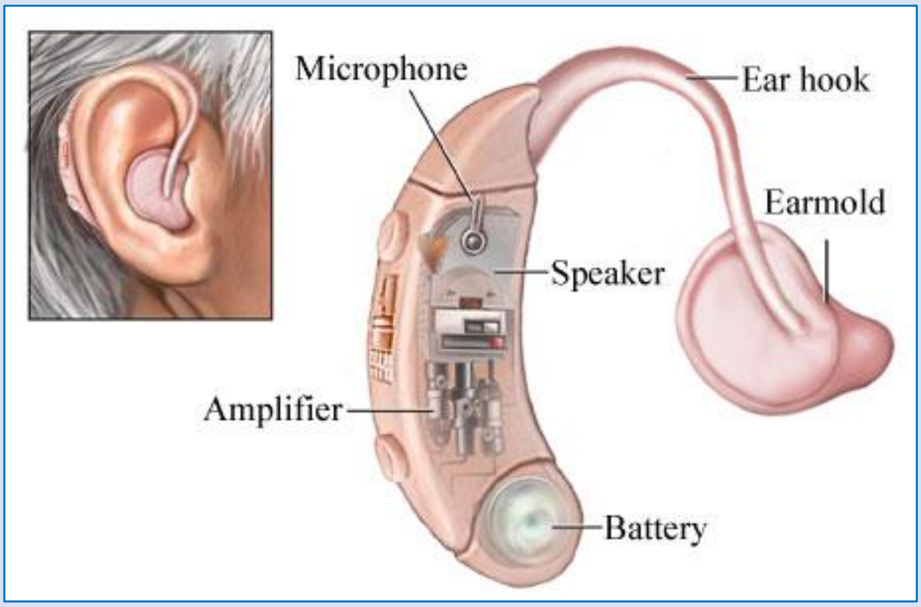
Range of Hearing

- The audible range of sound for human beings extends from about 20 Hz to 20000 Hz (one Hz = one cycle/s). Children under the age of five and some animals, such as dogs can hear up to 25 kHz (1 kHz = 1000 Hz). As people grow older their ears become less sensitive to higher frequencies.
- Sounds of frequencies below 20 Hz are called infrasonic sound or infrasound. If we could hear infrasound, we would hear the vibrations of a pendulum just as we hear the vibrations of the wings of a bee. Rhinoceroses communicate using infrasound of frequency as low as 5 Hz. Whales and elephants produce sound in the infrasound range. It is observed that some animals get disturbed before earthquakes. Earthquakes produce low-frequency infrasound before the main shock waves begin which possibly alert the animals.
- Frequencies higher than 20 kHz are called ultrasonic sound or ultrasound. Ultrasound is produced by dolphins, bats and porpoises. Moths of certain families have very sensitive hearing equipment. These moths can hear the high frequency squeaks of the bat and know when a bat is flying nearby and are able to escape capture. Rats also play games by producing ultrasound.



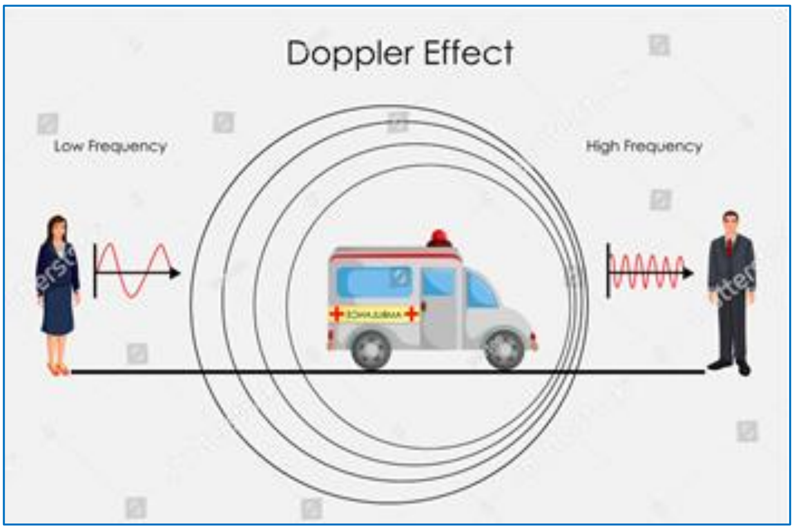
Hearing Aid

People with hearing loss may need a hearing aid. A hearing aid is an electronic, battery operated device. The hearing aid receives sound through a microphone. The microphone converts the sound waves to electrical signals. These electrical signals are amplified by an amplifier. The amplified electrical signals are given to a speaker of the hearing aid. The speaker converts the amplified electrical signal to sound and sends to the ear for clear hearing.



The Doppler effect

The Doppler effect (or the Doppler shift) is the change in frequency or wavelength of a wave for an observer who is moving relative to the wave source. It is named after the Austrian physicist Christian Doppler, who described the phenomenon in 1842. A common example of Doppler shift is the change of pitch heard when a vehicle sounding a horn approach and recedes from an observer. Compared to the emitted frequency, the received frequency is higher during the approach, identical at the instant of passing by, and lower during the recession.



Ultrasound imaging

Ultrasound waves

Ultrasound is sound waves with frequencies higher than the upper audible limit of human hearing. Ultrasound is no different from 'normal' (audible) sound in its physical properties, except in that humans cannot hear it. This limit varies from person to person and is approximately 20 kilohertz (20,000 hertz) in healthy, young adults. Ultrasound devices operate with frequencies from 20 kHz up to several gigahertz.

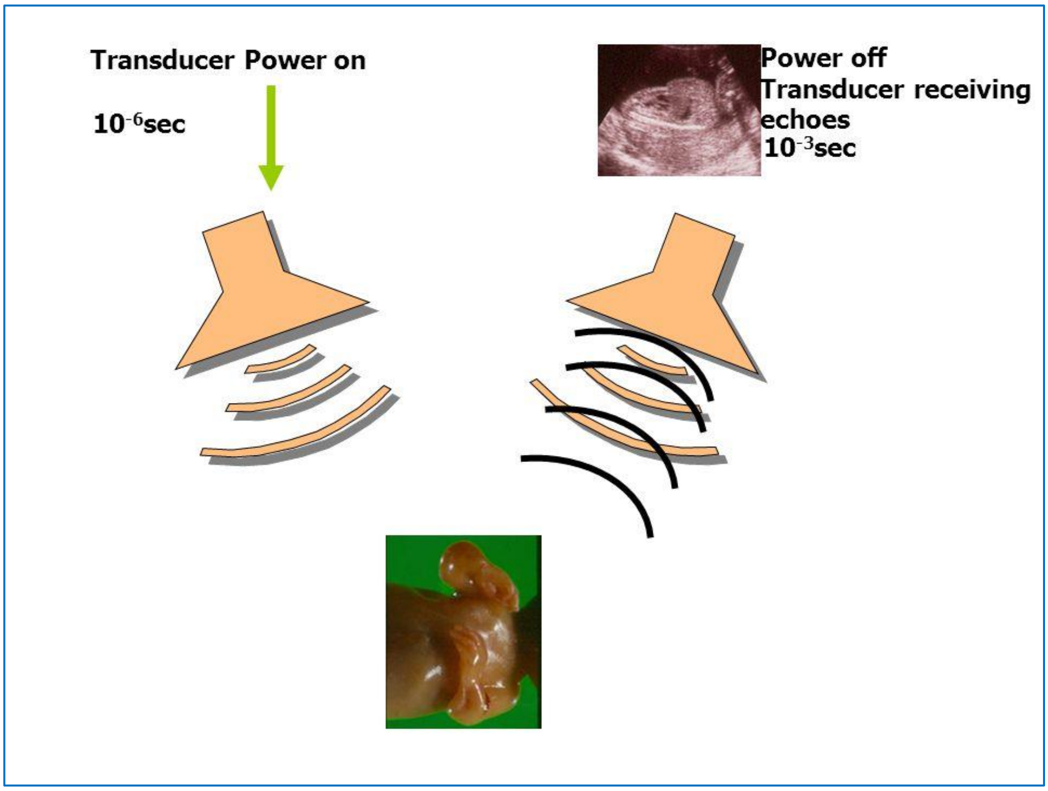
Ultrasound is used in many different fields. Ultrasonic devices are used to detect objects and measure distances. Ultrasound imaging or sonography is often used in medicine. In the nondestructive testing of products and structures, ultrasound is used to detect invisible flaws. Industrially, ultrasound is used for cleaning, mixing, and to accelerate chemical processes. Animals such as bats and porpoises use ultrasound for locating prey and obstacles.

From sound to image

The creation of an image from sound is done in three steps – producing a sound wave, receiving echoes, and interpreting those echoes.

1- Producing a sound wave

A sound wave is typically produced by a piezoelectric transducer encased in a plastic housing. Strong, short electrical pulses from the ultrasound machine drive the transducer at the desired frequency. The frequencies can be anywhere between 1 and 18 MHz, though frequencies up to 50–100 megahertz have been used experimentally in a technique known as biomicroscopy in special regions, such as the anterior chamber of the eye.



The sound is focused either by the shape of the transducer, a lens in front of the transducer, or a complex set of control pulses from the ultrasound scanner, in the (beamforming) technique. This focusing produces an arc-shaped sound wave from the face of the transducer. The wave travels into the body and comes into focus at a desired depth.

Materials on the face of the transducer enable the sound to be transmitted efficiently into the body (often a rubbery coating, a form of impedance matching). In addition, a water-based gel is placed between the patient's skin and the probe.

The sound wave is partially reflected from the layers between different tissues or scattered from smaller structures. Specifically, sound is reflected anywhere where there are acoustic impedance changes in the body: e.g. blood cells in blood plasma, small structures in organs, etc. Some of the reflections return to the transducer.

2- Receiving the echoes

The return of the sound wave to the transducer results in the same process as sending the sound wave, except in reverse. The returned sound wave vibrates the transducer, and the transducer turns the vibrations into electrical pulses that travel to the ultrasonic scanner where they are processed and transformed into a digital image.

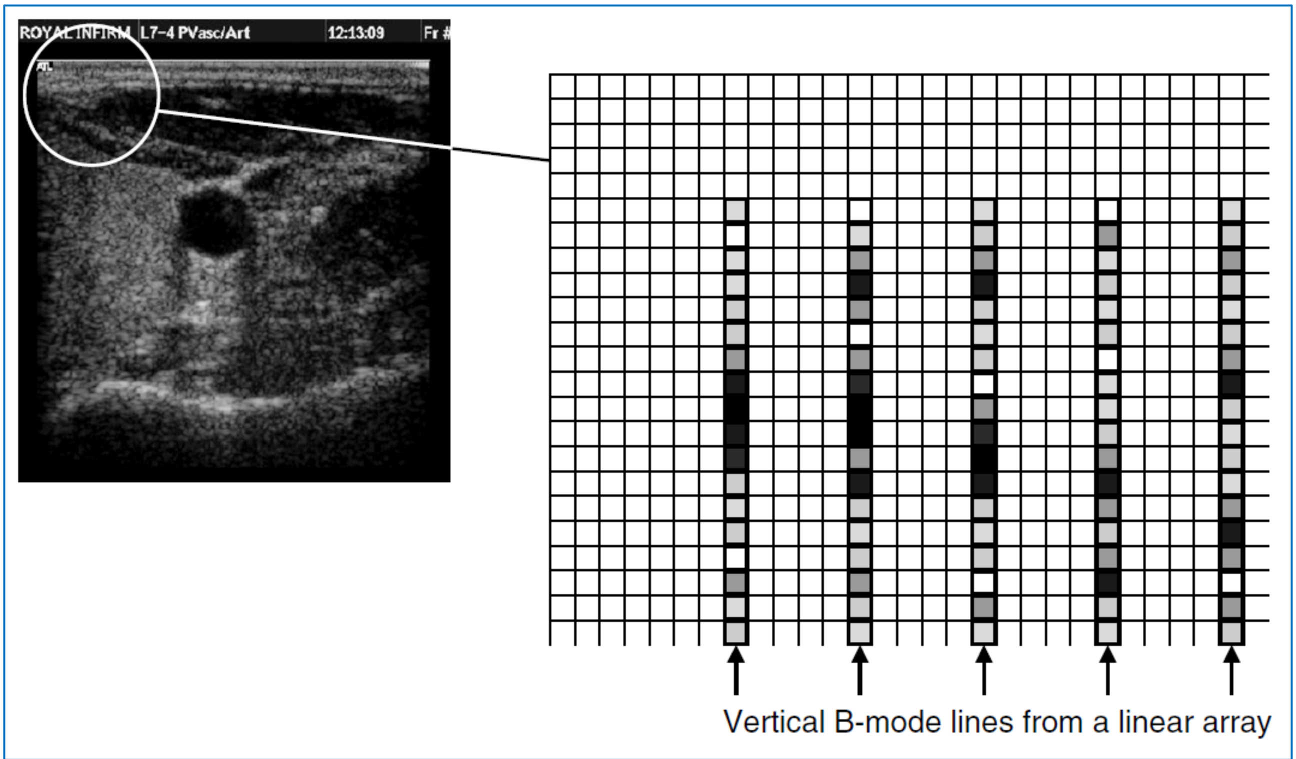
3- Forming the image

To make an image, the ultrasound scanner must determine two things from each received echo:

- How long it took the echo to be received from when the sound was transmitted.
- How strong the echo was?

Once the ultrasonic scanner determines these two things, it can locate which pixel in the image to light up and to what intensity.

Transforming the received signal into a digital image may be explained by using a blank spreadsheet as an analogy. First picture a long, flat transducer at the top of the sheet. Send pulses down the 'columns' of the spreadsheet (A, B, C, etc.). Listen at each column for any return echoes. When an echo is heard, note how long it took for the echo to return. The longer the wait, the deeper the row (1,2,3, etc.). The strength of the echo determines the brightness setting for that cell (white for a strong echo, black for a weak echo, and varying shades of grey for everything in between.) When all the echoes are recorded on the sheet, we have a greyscale image.



Ultrasound Transducer

Ultrasound is generated by a transducer which contains one or more crystals composed of ceramic or naturally occurring piezoelectric materials. Such an example is quartz which following exposure to an applied voltage will provide a consistent mechanical vibration of 32.768 kHz. A quartz crystal commonly provides the fundamental timing element for watches.

Examples of synthetic piezoelectric materials include ceramics such as lead-zirconate-titanate (PZT) or plastic composites such as polyvinylidene difluoride (PVDF).

The piezoelectric material converts an electrical pulse from the ultrasound machine's pulse generator into acoustic energy which can be transmitted for imaging. The electrical pulse induces a change in shape of the piezoelectric material. The expansion and contraction of the piezoelectric material propagates an acoustic wave with compression and rarefaction of a pressure amplitude front. Following interaction of the transmitted pulse with tissue, the transducer will function as a receiver and will detect the returning echoes. The returning acoustic energy deforms the piezoelectric material and generates a sequence of electric signals which are transferred to the ultrasound unit to help create a medical image. An ultrasound transducer can be used in both pulsed and continuous wave mode.

Types of Transducers

Modern-day medical transducers consist of either linear or curvilinear arrays composed of many rectangular piezoelectric elements. Within the transducer, there may be anywhere from 128 to 512 piezoelectric elements. Based upon the activation mode of how the ultrasound pulse is generated, transducers can be divided into two different types: (1) linear array and (2) phased array.

1- Linear Array

Within a linear array transducer, there is simultaneous activation of a small group of piezoelectric elements. A linear array has all the piezoelectric crystals set in a line across the transducer face.

This produces a rectangular ultrasound image and is usually used for:

• vessels

• vascular access

• needle guidance

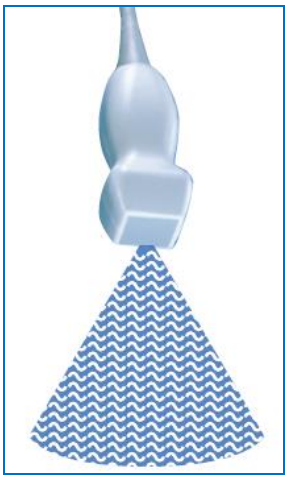
•musculoskeletal imaging

•small parts such as breast and thyroid

• foreign bodies

• anywhere we need a wide 'near field' but not a lot of depth as linear transducers tend to be higher in frequency than curved arrays.

2- Phased Array



In contrast to a linear array, a phased array transducer produces a single ultrasound pulse from all of the transducer piezoelectric elements. With a phased array, a time delay is introduced in the process of activating the piezoelectric elements across the face of the transducer. Through the introduction of this time delay, the ultrasound pulse can be directed without moving the transducer at all. When the phased array listens for the returning echoes, all of the transducer elements are recruited, and the aggregate information from all of these elements is used to generate an image.

This type of transducer is usually used for:

• cardiac imaging

• difficult or deep intercostal views of the abdomen

• sometimes for neonatal head imaging.

3- A curved array

A curved array is a transducer where the crystals are arranged along a curved surface, this produces a wide near field, and a wide far field. This produces an image with a curved upper and lower edge.

This type of transducer is usually used for:

- abdominal
- obstetric
- gynecology
- anywhere we need a lower frequency and good depth penetration
- the curved array transducer may be used if we are attempting

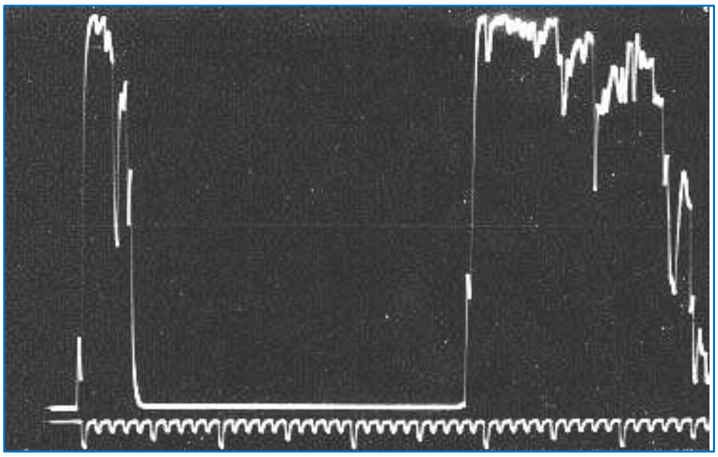
to visualize difficult or deep vessels in abdomen, leg or upper body.

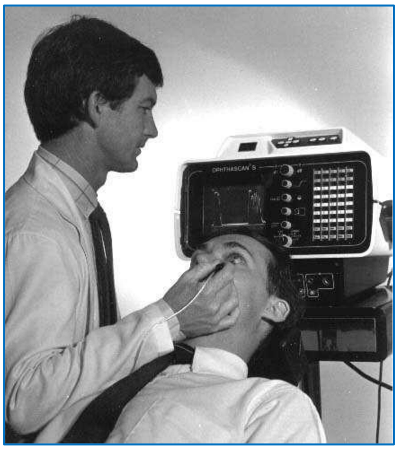
Types of Echo Display

The returning echo to the transducer can be displayed in one of three different ways: A-mode, B-mode, and M-mode.

1- A-Mode

A-mode represented the first type of ultrasound display and stands for amplitude mode.



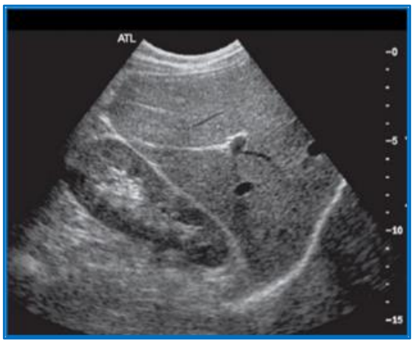


Echo amplitude was displayed on the vertical axis, while echo return time was displayed on the horizontal axis.

As described earlier, *echo return time is an indication of depth or distance of a tissue interface from the transducer*. One A-line of data was generated for each pulse repetition period. Initially, A-mode was used to evaluate midline displacement of the brain in patients suffering from a brain tumor. Today, A-mode can be used by ophthalmologists (eye doctors) for precise measurements of the eye.

2- B-Mode

B-mode displays a grayscale image of a tissue section and stands for brightness mode. The greater the intensity of the returning echo, then the greater the displayed signal brightness or level of echogenicity.



The returned echoes are displayed as a function of depth from the transducer and position across the sector scan of the emitted ultrasound beam.

Essentially, one 2D B-mode image is generated by a number of A-lines spanning across the transducer's field of view.

3- M-Mode

This technique stands for motion mode. This imaging approach uses the signal from B-mode imaging to describe the echoes of a moving structure such as the heart with the transducer oriented on a fixed position or tissue interface within the patient.

M-mode displays depth on the vertical axis and time on the horizontal axis.

By displaying successive ultrasound pulses next to each other, the change in the position of a single tissue interface can be monitored, and M-mode can be used to illustrate time-dependent motion. This display technique can be used to focus on the tissue interface of a beating heart and to help estimate the heart rate of a 6-week live fetus. M-mode can only focus on the motion of a single tissue interface or line through the patient. Given this limitation and advancements in two-dimensional echocardiography, this technique has been largely replaced by color Doppler imaging.

Components of an Ultrasound Machine

For the pulse echo method of ultrasound image acquisition, several hardware components are needed within the ultrasound machine including: a beam former, a pulser, a receiver, a scan converter, and a video display.

1- Beam Former

The beam former applies electronic delays to help align the phases of the echoes returning to the many individual elements of an array transducer. The realigned signals from all the transducer elements are then summated, creating an output signal which represents the acoustic information from a pulsed ultrasound beam.

2- Pulsar

The pulsar generates the electric voltage which is applied to the piezoelectric elements within the transducer and produces the acoustic signal.

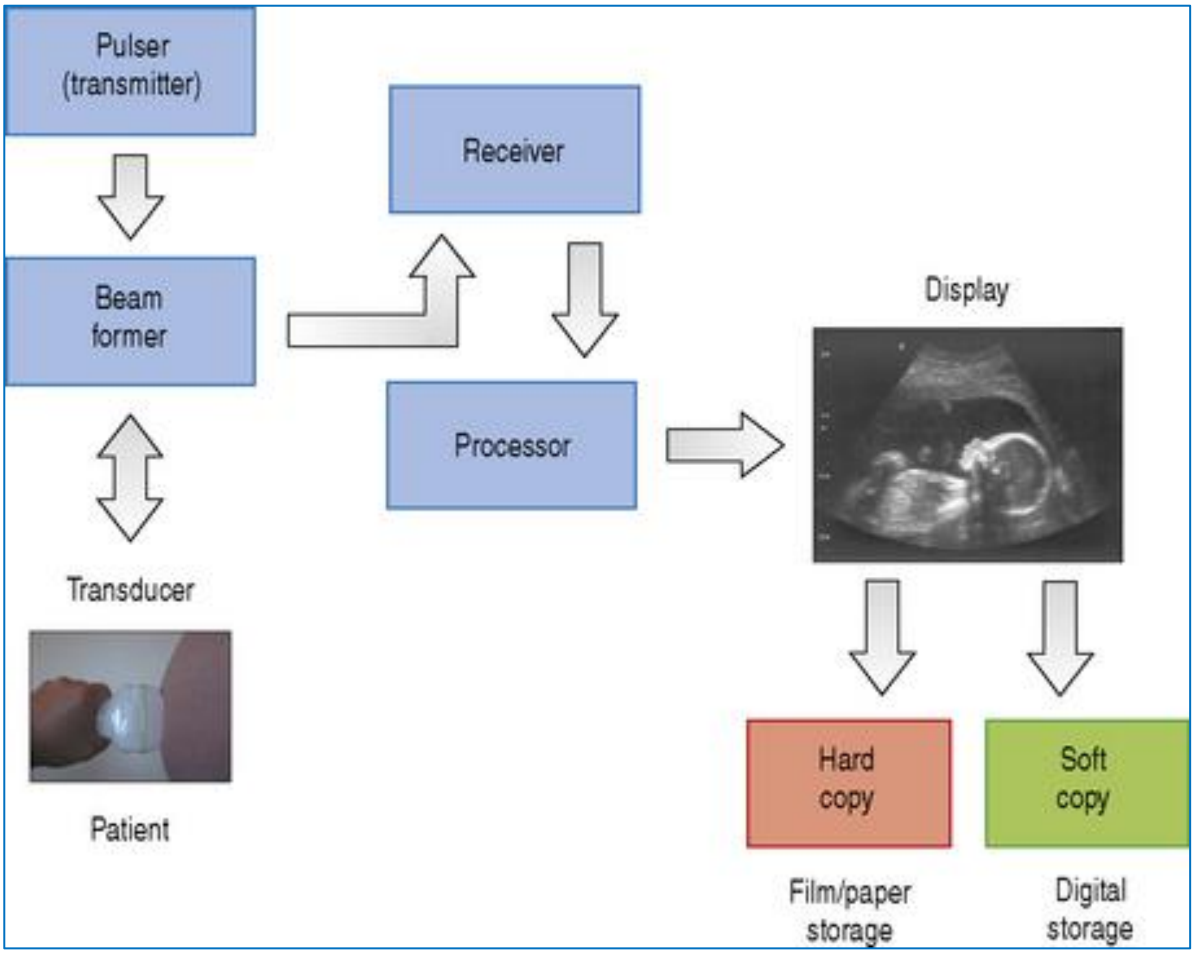
3- Receiver

The receiver accepts signal information from the beam former and performs postprocessing and filtering of noise and clutter.

4- Scan Converter

Scan converter is a device within the ultrasound machine that takes the signal information from the returning echo and translates it into a data format which can be displayed as a 2D image. The data format from scan acquisition and scan display are very different, and the scan converter is a critical hardware piece for a functional ultrasound machine to display a medical image that can be read by a clinician. Video Display

Once the digital information is acquired and assigned to a memory location, the digital to analog converter converts the matrix of digital data into an analog signal which can be displayed on a video monitor. In addition to the grayscale information from a 2D B-mode image, the video display can show information acquired from M-mode and Doppler ultrasound.

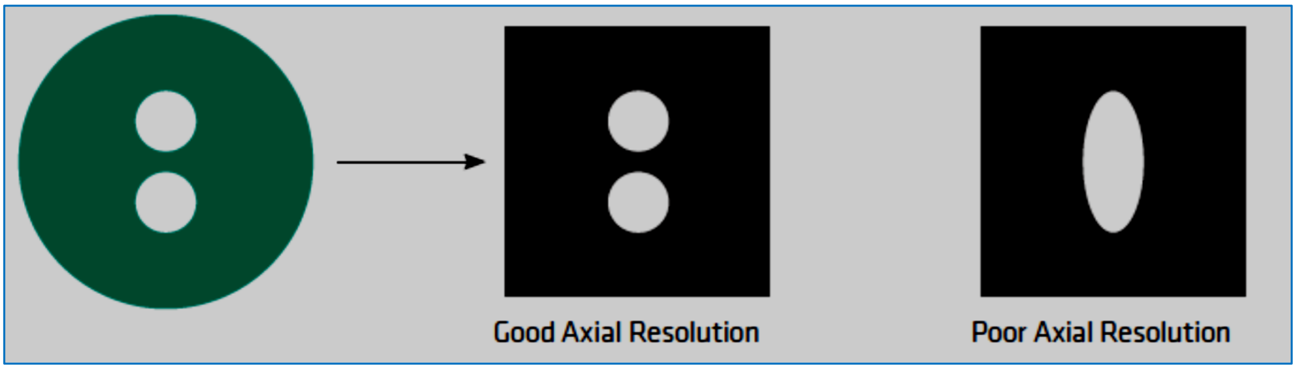


Resolution

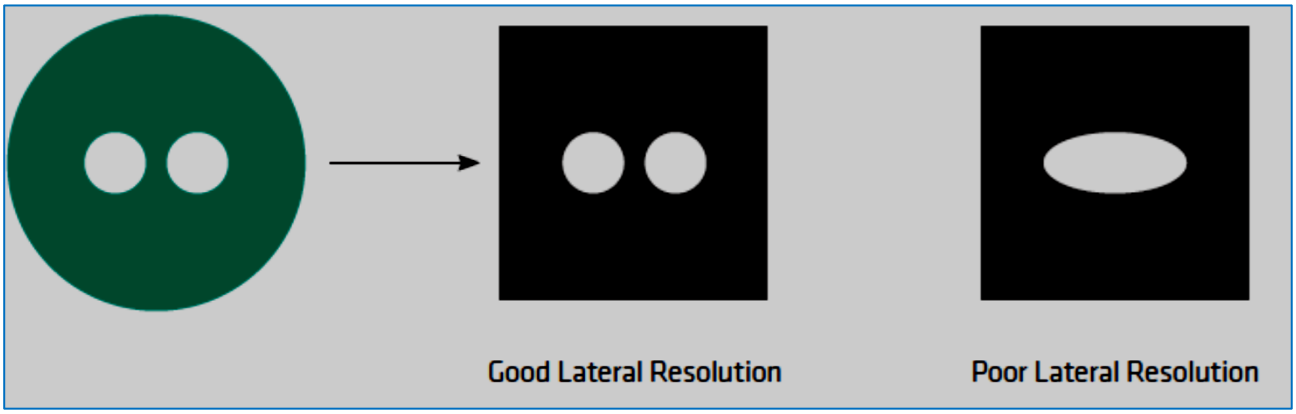
We speak about the resolution of the image – what this term means is 'how well we can distinguish the structures we need to see'. There are different types of resolution – Temporal, Contrast and Spatial:

- **Temporal Resolution** – how accurately we demonstrate a moving structure over time – this is important in Echocardiography and Obstetric scanning.
- **Contrast Resolution** – how well the system displays structures with differing reflection characteristics as different shades of grey in the image.
- **Spatial Resolution** – can be divided into two different types:

Axial Resolution is the ability of the system to display small structures along the axis of the beam as separate from each other (parallel to the beam) – If we have two small vessels one above the other it is important to see them separately on the image – not as if they were joined or smeared together.



Lateral Resolution is the ability of the system to display small structures side-by-side (same depth) as separate from each other (perpendicular to the beam). (Lateral Resolution is usually poorer than axial resolution due to the beam width).



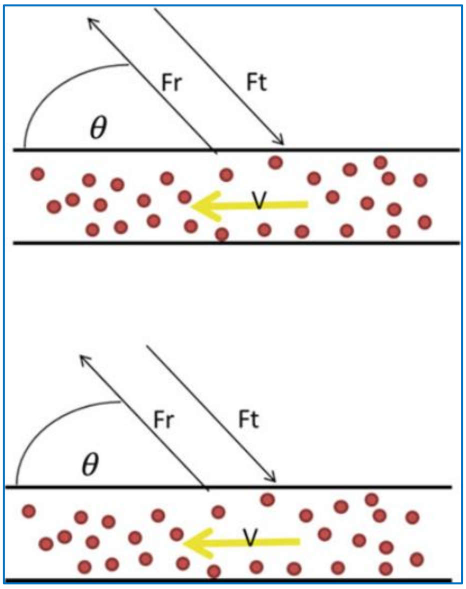
Doppler Ultrasound

Up to this point, discussion has focused upon the generation of grayscale ultrasound imaging. These grayscale images are composed from pressure amplitude information regarding returning echoes which have either been reflected or scattered. Additional imaging information can also be found in the frequency variation of the returning echoes. This detection of a change in echo frequency serves as the basis for Doppler ultrasound imaging.

Frequency shift occurs when incident sound energy reflects off a moving object. If the object is moving away from the source of sound, the returning echo travels at a lower frequency than the initial incident sound, while if the object is moving toward the source of sound, the returning echoes travel at a higher frequency than the initial incident sound. The Doppler frequency shift (F_d) is defined as the difference in frequency between the initial incident sound (F_t) and the returning echo (F_r).

$$F_d = F_t - F_r$$

Optimal imaging is performed with the transducer as close as parallel to the vessel of interest so that the cos (θ) is maximized. The velocity (V) is directly proportional to frequency shift. For Doppler ultrasound imaging, the moving object is usually a red blood cell in either a vein or artery. When the sound hits the moving red blood cell, the incident energy is both reflected and scattered. When the transducer detects the returning echo, the change in frequency can be used to measure the velocity of the blood. In addition, detailed color maps can be generated which outline the anatomy of the vasculature tree and potentially highlight such disease processes as atherosclerotic disease or plaque formation along the vessel wall.

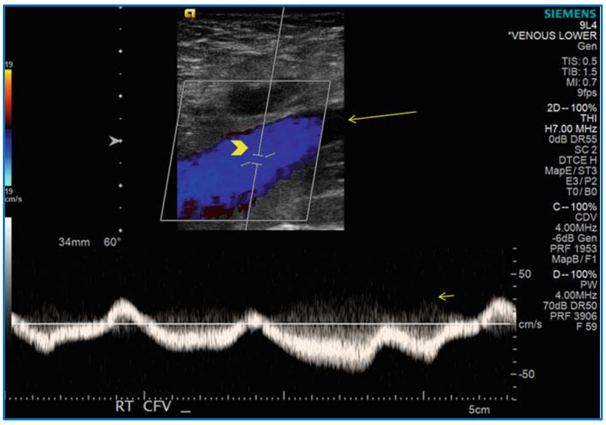


We have introduced two different concepts in this discussion, blood flow and blood velocity. Blood velocity measures the rate that a particle of interest, i.e., a red blood cell, travels per unit time. Blood velocity is measured in cm/sec. Blood flow measures the volume of blood that travels per unit time and is measured in cm^3/sec. Under conditions of fully developed, steady-state flow, the blood flow is related to the mean velocity by the following equation:

$$\textbf{Flow} = \textbf{V} * \textbf{A}$$

where V is the mean velocity and A is the cross-sectional area of the vessel.

Pulsed Doppler imaging can evaluate both velocity and range (or the distance from where the moving object originates). The transducer obtains information from a specific location of interest or the Doppler sample volume. The size of the Doppler sample volume can be changed by adjusting the amount of time that the transducer receives or listens for returning echoes. By first imaging with grayscale ultrasound imaging, the vessels of interest can be visualized, and the Doppler sample volume can be positioned within the lumen of the vessel which will be evaluated.



Duplex scanning is defined as this combined use of both grayscale and pulsed Doppler imaging. The velocity is represented on the vertical scale, while time is indicated on the horizontal scale. When flow is toward the transducer, this results in a positive frequency shift and a positive magnitude velocity value, while the opposite relation holds true for flow away from the transducer. Generally, flow toward the ultrasound transducer is color-coded as red, while flow away from the transducer is color-coded as blue.

Risks and side-effects

Ultrasonography is generally considered safe imaging with the World Health Organizations saying.

"Diagnostic ultrasound is recognized as a safe, effective, and highly flexible imaging modality capable of providing clinically relevant information about most parts of the body in a rapid and cost-effective fashion".

Diagnostic ultrasound studies of the fetus are generally considered to be safe during pregnancy. This diagnostic procedure should be performed only when there is a valid medical indication, and the lowest possible ultrasonic exposure setting should be used to gain the necessary diagnostic information under the "as low as reasonably practicable" or ALARP principle.

Quiz (4)

1- **<u>Define the following terms:</u>**

Sound – wavelength – amplitude – frequency – doppler effect

2- **<u>Compare between:</u>**

- Electromagnetic waves and mechanical waves
- Transverse waves and longitudinal waves
- Ultrasound transducers
- Ultrasound display mods
- Different types of resolutions

3- **What are the main characteristics of sound waves?**

4- **What is effect of the following parameters on the speed of the sound waves:**

Medium type – Temperature – Density of the medium – Viscosity of the medium

5- **Describe the mechanism of hearing?**

6- **Discuss applications of ultrasound?**

7- **Illustrate the mechanism of ultrasound image formation?**

8- **What are the components of an Ultrasound machine?**

References

1. University Physics with Modern Physics, by H. D. Young and R. A. Freedman, Addison-Wesley, 14e, ISBN 9780321973610 (2015).
2. R.A. Serway, J.W.Jewett, Physics for Scientists and Engineers, With Modern Physics, Translation of 8th American Edition, ISBN 978-960-461-509-4, Klidarithmos Publications, 2013, Athens (Greek Edition).
3. Lambers Monteith JL, Unsworth MH (1990) Principles of Environmental Physics. 2nd Edn., Edward Arnold, London. 291 pp. (UIUC ACES Stacks Call Number: 574.54 M76P1990.
4. Robert Splinter, Brett A. Hooper, “An Introduction to Biomedical Optics”, 1 edition, CRC Press, 2006.
5. Biomedical Optics: Principles and Imaging, L. V. Wang, H.-I. Wu, 2007, Wiley.