Al-Mustaqbal University

Department of Biomedical Engineering

Third Stage / 1st Course

“Transport Phenomena for BME”

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Lecture note 1

Introduction to transport phenomena for biomedical engineering

Course Syllabus (2024 – 2025)

Introduction to fluids: - dimensions and units; Analysis of Fluid Behavior; Measures of Fluid (Density, Specific Weight, Specific Gravity); ideal gas law; Viscosity.

- **Fluid statics**: - Pressure at a Point; Basic Equation for Pressure Field; Pressure Variation in a Fluid at Rest (Incompressible Fluid, Compressible Fluid); Measurement of Pressure; Manometry (Piezometer Tube, U-Tube Manometer, Inclined-Tube Manometer).

- **Elementary Fluid Dynamics - The Bernoulli Equation**: - Newton's Second Law; F = ma along a Streamline; F = ma Normal to a Streamline; Physical Interpretation; Static, Stagnation, Dynamic, and Total Pressure; Examples of Use of the Bernoulli Equation (Free Jets, Confined Flows, Flowrate Measurement, The Energy Line and the Hydraulic Grade Line).

- **Dimensional Analysis**: - Dimensional Analysis; Buckingham Pi Theorem; Determination of Pi Terms; Some Additional Comments about Dimensional Analysis; Determination of Pi Terms by Inspection

Course Syllabus (2023 - 2024)

- **Viscous Flow in Pipes: - General Characteristics of Pipe Flow (Laminar or Turbulent** Flow, Entrance Region and Fully Developed Flow, Pressure and Shear Stress); Fully Developed Laminar Flow (From F = ma Applied Directly to a Fluid Element, From Dimensional Analysis, Energy Considerations); Dimensional Analysis of Pipe Flow (Major Losses, Minor Losses, Noncircular Conduits, Pipe Flow Examples, Single Pipes, Multiple Pipe Systems); Pipe Flow Examples; Pipe Flowrate Measurement (Pipe Flowrate Meters, Volume Flowmeters).
- **The physical and flow properties of blood and other fluids: - Rheology; The** capillary viscometer and laminar flow in tubes (Hagen-Poiseuille equation for laminar flow of …. , Laminar flow of a Newtonian fluid through …. , Hagen-Poiseuille equation for laminar flow of a ….); The Rabinowitsch equation for the flow of a non- Newtonian …. ; Other useful flow relationships

Transport phenomena

- Transport Phenomena" is a core subject in the field of biomedical engineering, focusing on the study of fundamental physical processes that control the transfer of energy, mass, and momentum between different systems.
- These processes include heat transfer, mass transfer, and fluid mechanics, which are essential for understanding how biological and engineered systems related to medicine function.
- In the context of biomedical engineering, the significance of transport phenomena is evident in applications such as the design of medical devices, drug delivery, and biological processes.
- This subject helps students gain a deep understanding of the mechanisms that influence the transport of materials and energy in living systems, allowing them to apply this knowledge to innovative engineering solutions that enhance healthcare.

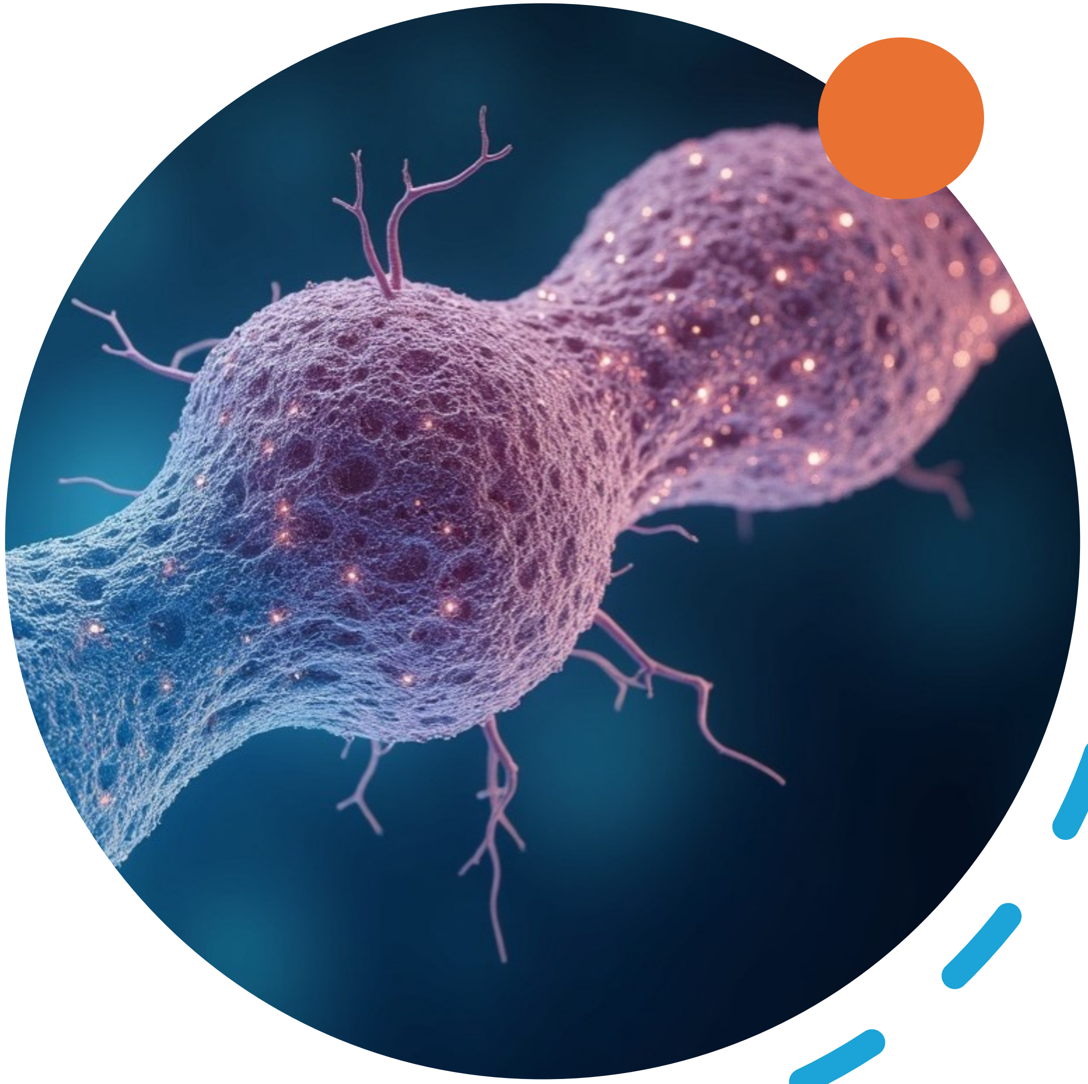
The roles of transport phenomena in biological systems

1. **Control of biological functions:**

- In order for cells, organs, and tissues to function properly, nutrients and regulators of growth must be able to move rapidly to and through them. Organisms control the concentrations of molecules in their tissues and organs. Consequently, specialized mechanisms have evolved to regulate the movement of molecules across and within cells

2. **Disease treatments:**

- Many organs, such as the lungs, liver, and kidneys, are organized to enable the rapid exchange of molecules between the blood and tissues.
- change in transport processes are important factors in a number of diseases, such as atherosclerosis, cancer, and kidney diseases.



The roles of transport phenomena in biological systems

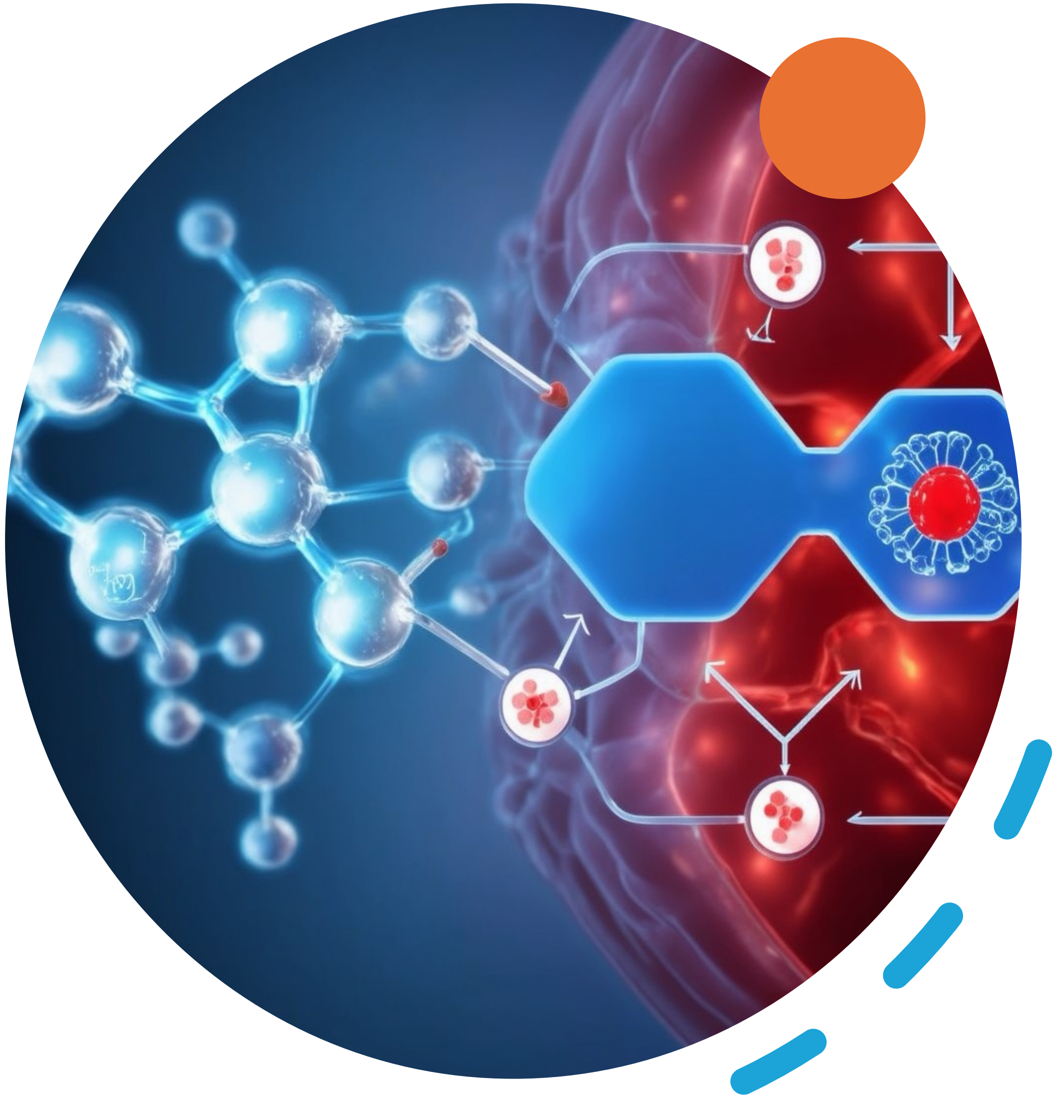
3. **Design and operation of biomedical devices**

- Transport phenomena involve the integrated study of momentum, mass, and energy transfer, as well as the thermodynamics and kinetics of chemical reactions. For the biomedical engineer, a mechanistic understanding of transport processes is important for the characterization of physiological and cellular processes, the design and operation of a number of devices, and the development of new therapies. Examples of biomedical devices influenced by transport processes include kidney dialysis machines, heart-lung bypass machines (heart-lung machine also called the pump or CPB pump is a machine that temporarily takes over the function of the heart and lungs during open-heart surgery by maintaining the circulation of blood and oxygen throughout the body.), and membrane oxygenators.

4. **Genetic and molecular medicine and therapies:**

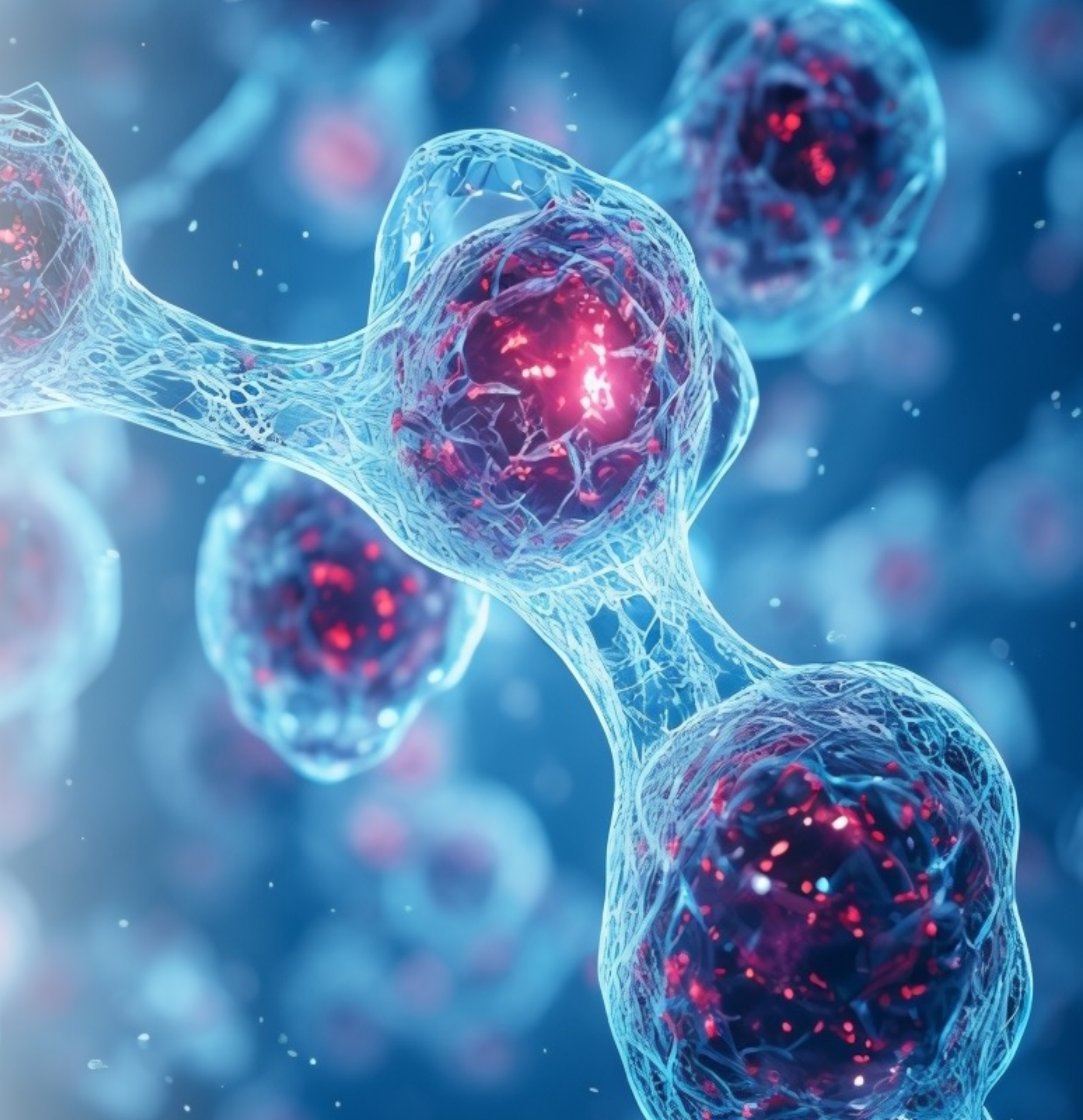
- Genetic and molecular medicine involves understanding and treating diseases at the genetic and molecular level. It includes the study of the molecular basis of diseases, the application of genetic and genomic knowledge to prevention, diagnosis, and treatment, and the development of targeted molecular therapies.

- The field of transport phenomena is sufficiently advanced that the basic processes can be characterized mathematically. The predictive capabilities of models are quite good, even for complex biological systems. Analytical and numerical solutions are already available for many commonly encountered problems pertaining to a number of natural phenomena, as well as to the design of many technologies.



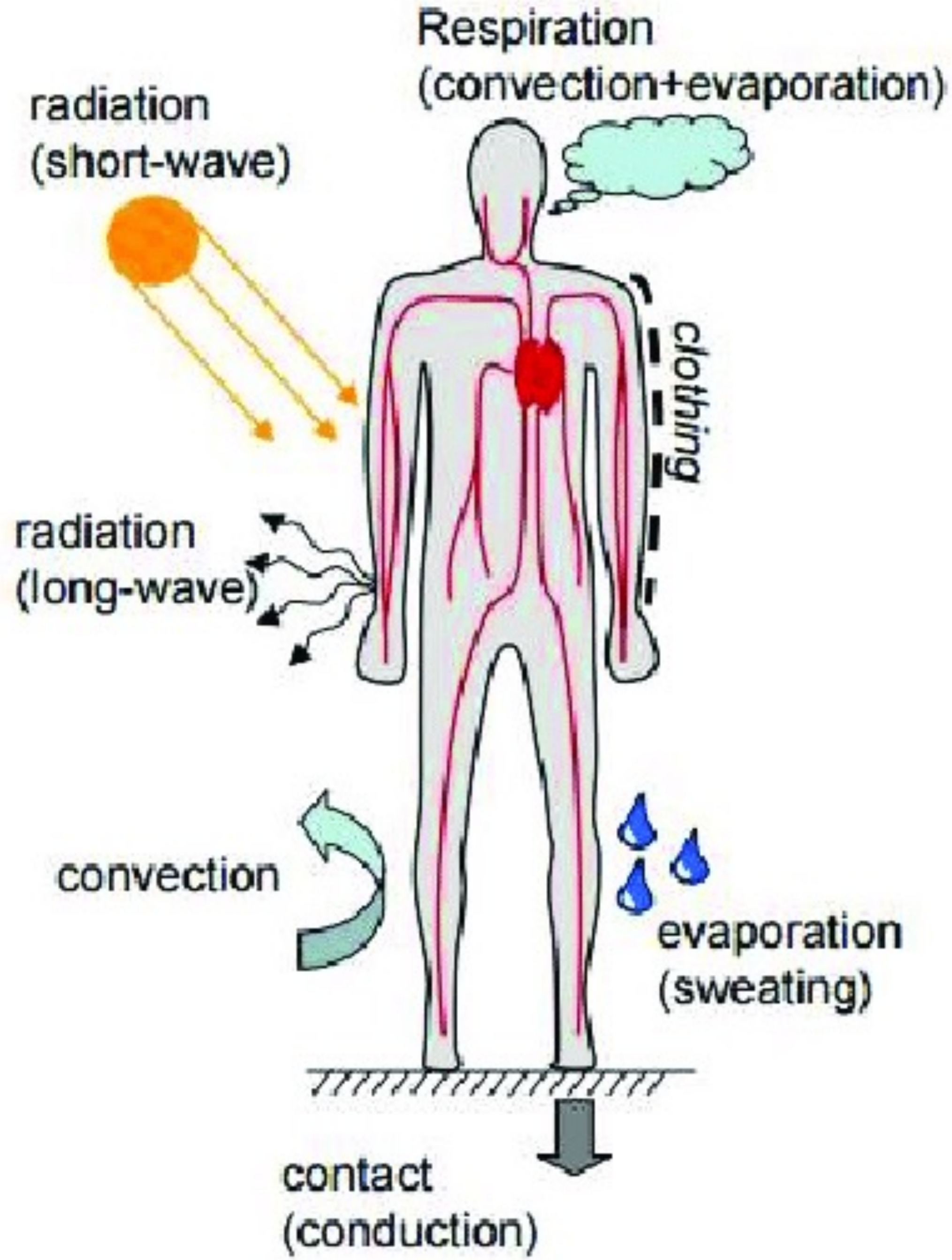
phenomenon transport in biomedical engineering

- The phenomenon of transport refers to the process by which physical quantities (such as heat, mass, or momentum) are transferred from one point to another within a system.
- This process occurs due to differences in physical properties like temperature, concentration, or velocity between different regions of the system.
- There are three main types of transport phenomena:
- **Heat Transfer**
- **Mass Transfer**
- **Momentum Transfer**



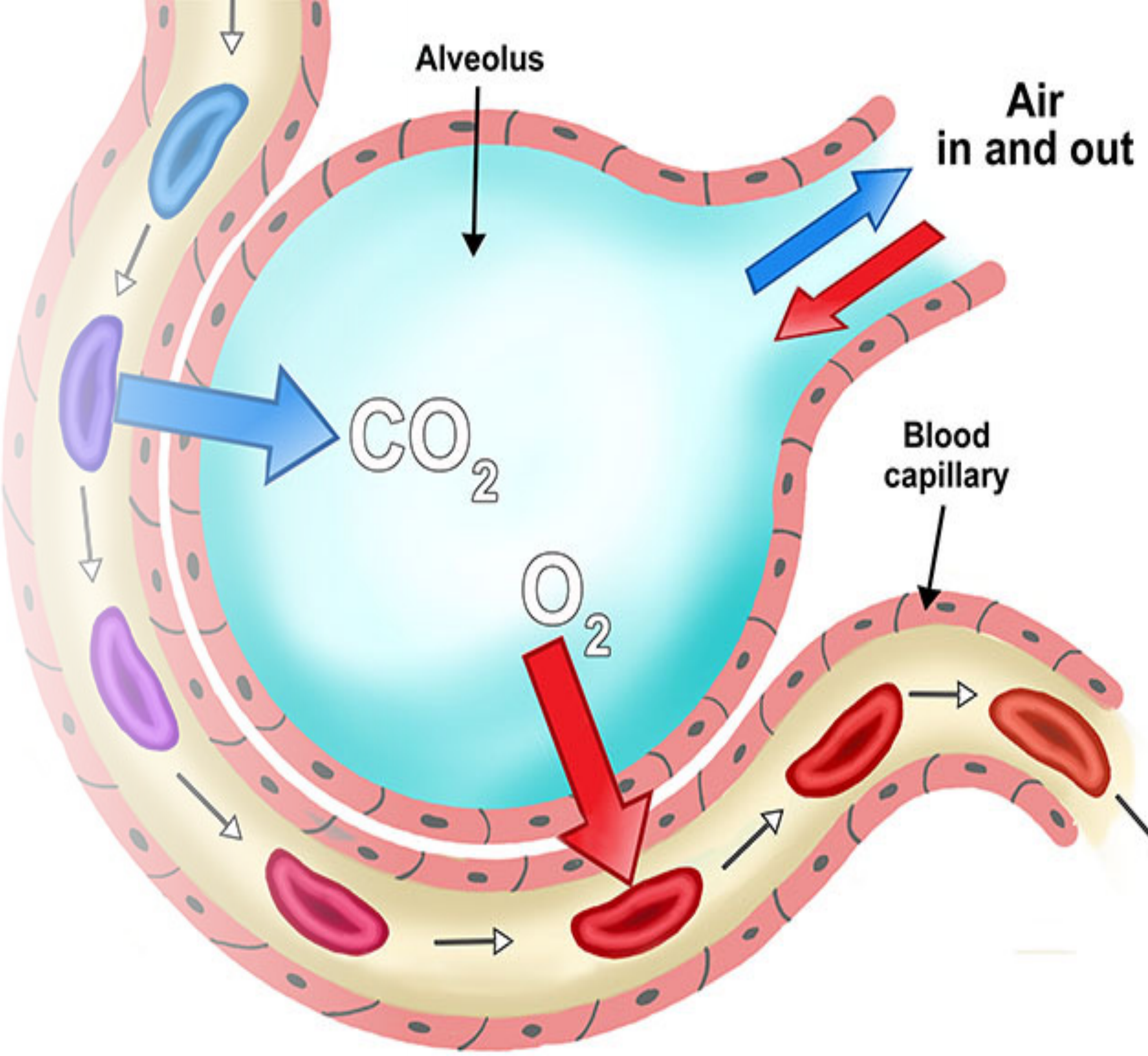
Heat Transfer:

- **Heat Transfer**: The process of transferring thermal energy from a region of higher temperature to a region of lower temperature. This occurs through three primary mechanisms:
- conduction (through solids),
- convection (through fluids and gases),
- radiation (across space without the need for a medium).



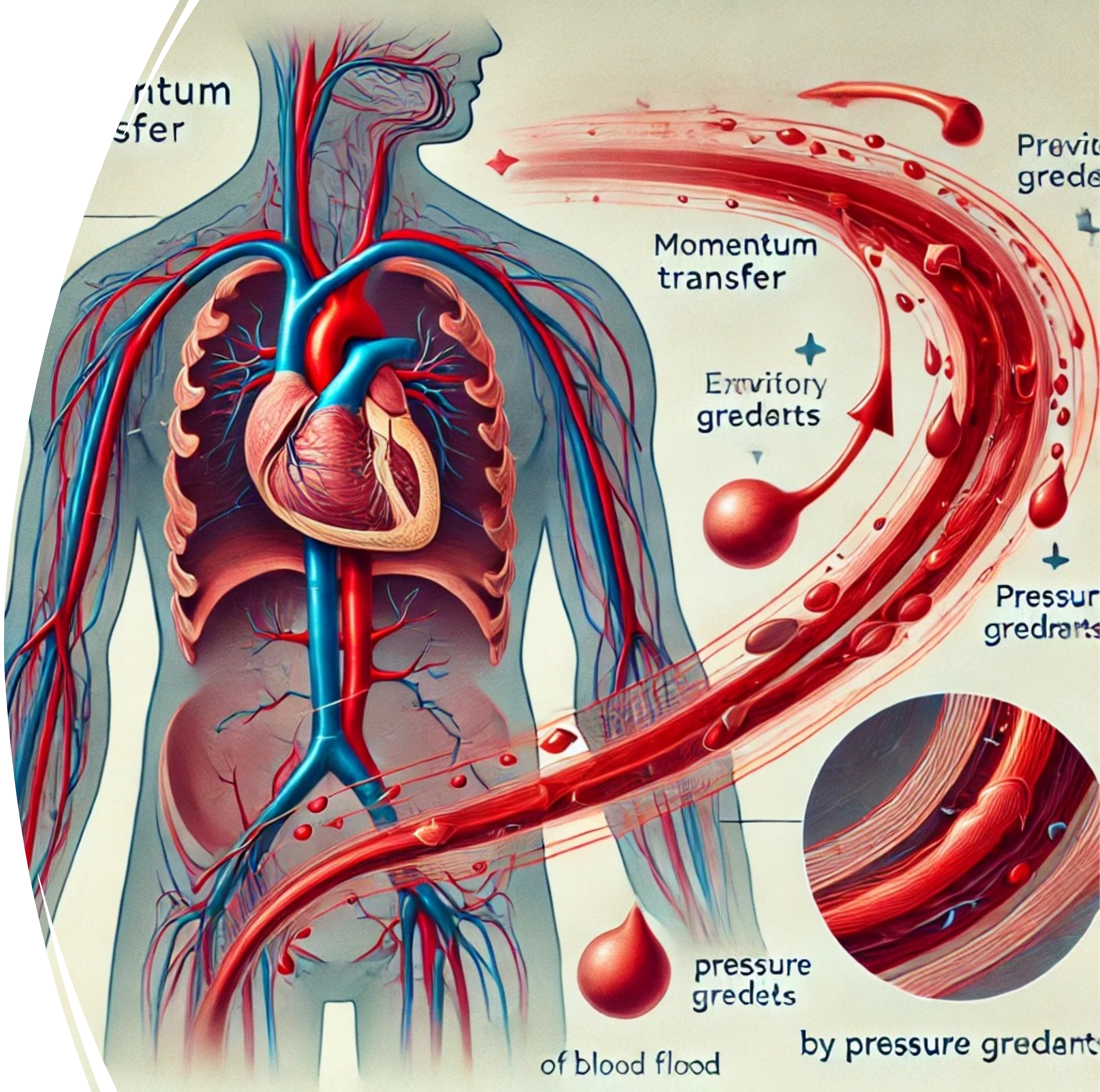
Mass Transfer

- The process by which molecules or substances move from an area of higher concentration to an area of lower concentration.
- This includes biological processes like the diffusion of oxygen in the blood or the movement of drugs across cells.



Momentum Transfer

- Refers to the movement of mass or fluid as a result of external forces acting on it, such as the motion of fluids or gases under the influence of forces like gravity or pressure.
- This concept is closely related to fluid mechanics.



What is a fluid?

A fluid is a substance that continually deforms (flows) under an applied shear **stress**

What is a fluid mechanics?

The study of fluids at rest or in motion and the interactions between a solid and a fluid either flowing past or acting on the solid in some manner.

What is biofluid mechanics (biological fluid mechanics)?

Biofluid mechanics (or biological fluid mechanics) is the study of the motion of biological fluids in any possible context (e.g. blood flow in arteries).

What is a fluid mechanics?

What is a mechanics?

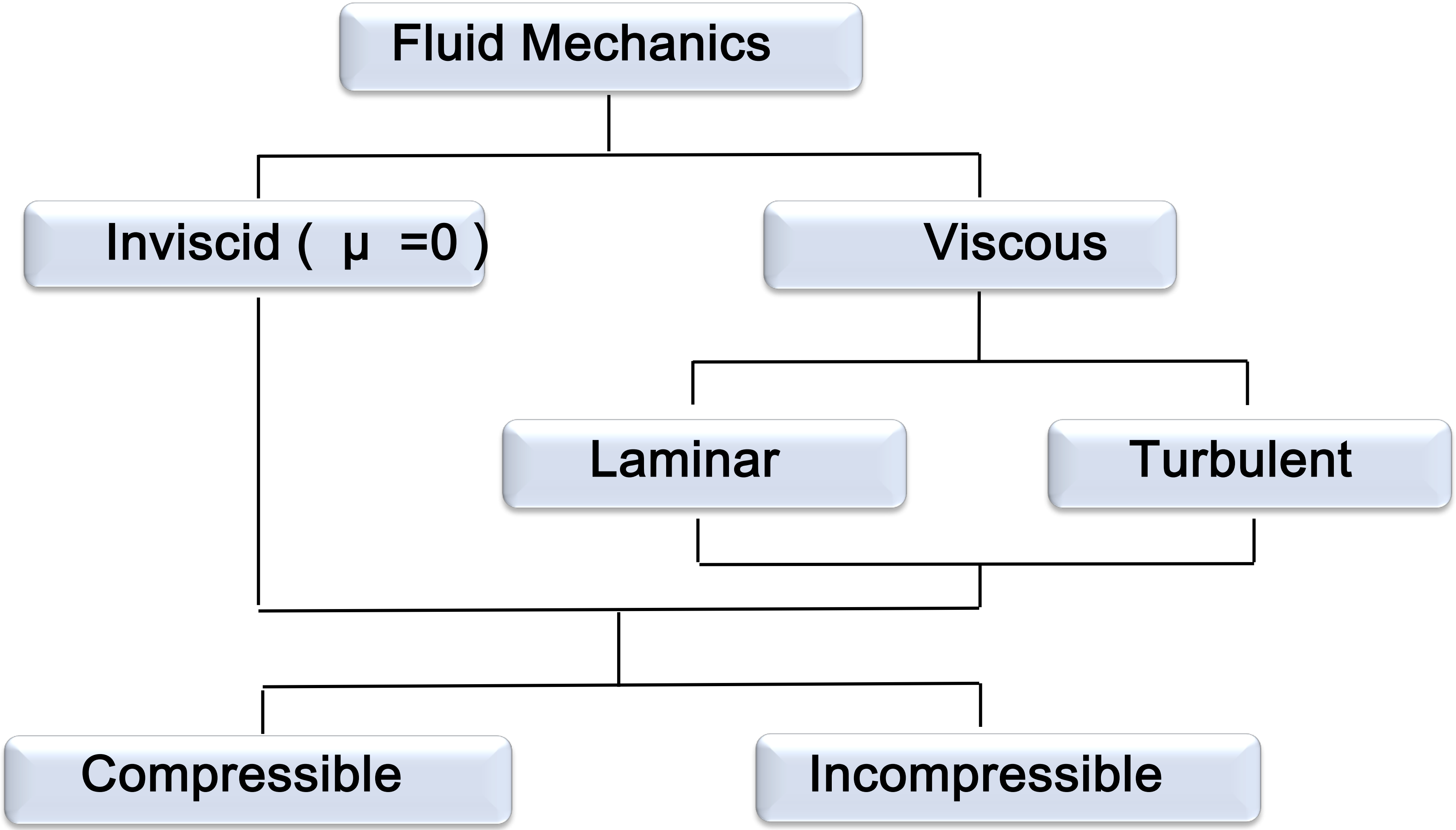
Mechanics is essentially the application of the laws of force and motion. Conventionally, it is divided into two branches, static's and dynamics.

What is a fluid Mechanics?

The study of fluids at **rest** or in **motion** and the interactions between a solid and a fluid either flowing past or acting on the solid in some manner. Or, branch of applied mechanics concerned with the static's and dynamics of fluids.

Fluid mechanics covers a wide array of phenomena that occur in nature (with or without human intervention), in biology, and in numerous engineered, invented, or manufactured situations. There are few aspects of our lives that do not involve fluids, either directly or indirectly.

Classification of Fluid Mechanics



Some Characteristics of Fluids

Solid	Liquid	Gas
➢ Hard	➢ Soft	
➢ Small space between molecules	➢ Large space between molecules	➢ Very large space between molecules
➢ Large intermolecular cohesive forces that allow the solid to maintain its shape.	➢ The intermolecular forces are smaller than for solids	➢ Negligible cohesive intermolecular forces
➢ The molecules have restricted movement	➢ The molecules have more freedom of movement.	➢ The molecules have very large freedom of movement
➢ Not easily deformed.	➢ Liquids can be easily deformed (but not easily Compressed) and can be poured into containers or forced through a tube	➢ Easily deformed (and compressed) and Will completely fill the volume of any container in which they are placed.

Note:- Both liquids and gases are fluids.

Dimensions and Units

Dimensions and Units

In our study of fluid mechanics, we will be dealing with a different of fluid **characteristics, it is necessary to develop a system for describing these characteristics** both qualitatively and quantitatively.

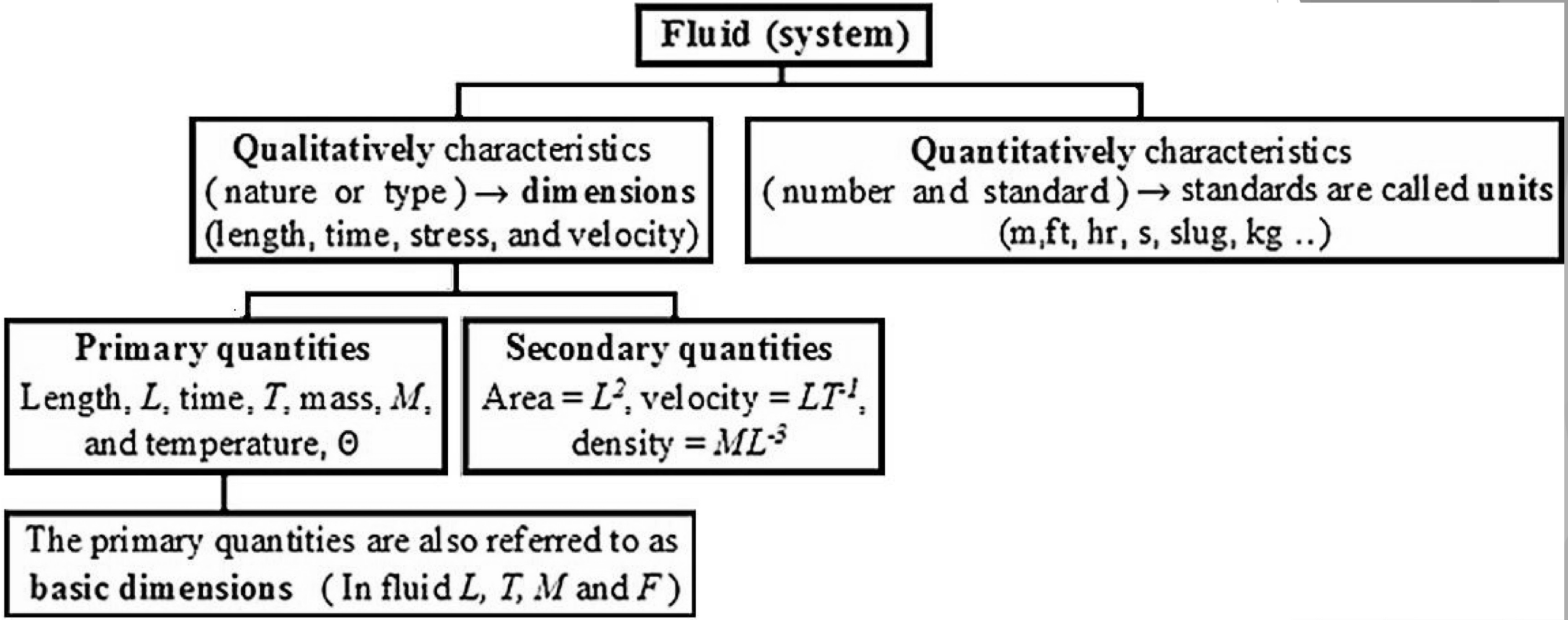
- The qualitative (Dimensions) aspect serves to identify the nature, or type, of the characteristics (such as length, time, stress, and velocity),
- The quantitative (Units) aspect provides a numerical measure of the characteristics. The quantitative description requires both a number and a standard by which various quantities can be compared. A standard for length might be a meter or foot, for time an hour or second, and for mass a slug or kilogram.

Dimension	Symbol
Length	L
Time	T
Mass	M
Temperature	θ
Electrical Current	I

Systems of Units

- International System (SI)
- British Gravitational (BG) System

Dimensions and Units



For example, force has the same dimensions as mass, times and acceleration (by Newton's second law). Thus, in terms of primary dimensions,

Dimensions of force: $[Force] = \left[Mass\,\frac{Length}{Time^2}\right] = \left[\frac{ML}{T^2}\right]$

F = ma
a=length/time^2

Example (1): Calculate the dimensions of the following quantities. (a) Volume (b) Speed (c) Acceleration (d) Density (e) Velocity (f) Force (g) Pressure (h) Work.

Solution

(a) A Volume is given by multiplying three lengths together:

Dimension of volume $= L \times L \times L = L^3$ So [volume] $= L^3$

(b) Speed is the rate of change of distance with respect to time.

Dimensions of speed $= \frac{L}{T} = LT^{-1}$ So [speed] $= LT^{-1}$

(c) Acceleration is the rate of change of speed with respect to time

Dimensions of acceleration $= \frac{LT^{-1}}{T} = LT^{-2}$ So [acceleration] $= LT^{-2}$

(d) Density is the mass per unit volume, so using the dimension of volume we get:

Dimensions of volume $= \frac{M}{L^3} = ML^{-3}$ So [density] $= ML^{-3}$

(e) Velocity

Dimensions of velocity $= \left[\frac{Length}{Time}\right] = [LT^{-1}]$

(f) Force

Dimensions of force $= \left[Mass\,\frac{Length}{Time^2}\right] = \left[\frac{ML}{T^2}\right]$

Dimensional Homogeneity

The **law** of **dimensional homogeneity**

Every additive term in an equation must have the same dimensions.

- For example (1), the equation for the velocity, V, of a uniformly accelerated body is

$$V = V_o + at$$

Where V_o is the initial velocity, a acceleration, and t the time interval. In terms of dimensions the equation is

$$LT^{-1} = LT^{-1} + LT^{-2}T$$

- For example (2), some equations that are known to be valid contain constants having dimensions. The equation for the distance, d, traveled by a freely falling body can be written as

$$d = 16.1t^2$$

Actually, This Eqn. is a special form of the well-known equation from physics for freely falling bodies,

$$d = \frac{g}{2}t^2$$

In which g is the acceleration of gravity = 32 ft/s^2

- For example (3), a commonly used equation for determining the volume rate of flow, Q, through the orifice is

$$Q = 0.61\, A\sqrt{2gh}$$

$$L^3T^{-1} = (0.61)(L^2)(\sqrt{2})(LT^{-2})^{1/2}(L)^{1/2}$$
$$L^3T^{-1} = (0.61)(\sqrt{2})(L^3T^{-1})$$

Dimensional Homogeneity

Dimensions	*FLT* System	*MLT* System
Acceleration	LT^{-2}	LT^{-2}
Time	T	T
Velocity	LT^{-1}	LT^{-1}
Area	L^2	L^2
Density	$FL^{-4}T^2$	ML^{-3}
Energy	FL	ML^2T^{-2}
Force	F	MLT^{-2}
Stress	FL^{-2}	$ML^{-1}T^{-2}$
Length	L	L
Mass	$FL^{-1}T^2$	M
Volume	L^3	L^3
Pressure	FL^{-2}	$ML^{-1}T^{-2}$
Work	FL	ML^2T^{-2}
Power	FLT^{-1}	ML^2T^{-3}
Viscosity (dynamic)	$FL^{-2}T$	$ML^{-1}T^{-1}$
Viscosity (kinematic)	L^2T^{-1}	L^2T^{-1}

Measures of Fluid Mass and Weight

Density :- The **density** is defined as its mass per unit volume.

$$\boldsymbol{\rho = \frac{m}{V}} \quad \rightarrow \quad \left(\frac{kg}{m^3}\right)$$

At a normal conditions (1 atm, 300 K)

- $\rho_{H_2O} = 1000 \text{ kg/m}^3$
- $\rho_{Air} = 1.22 \text{ kg/m}^3$

$$\boldsymbol{\rho = \frac{P}{RT}} \quad \rightarrow \quad \text{At the Ideal gas}$$

where p is the absolute pressure, the density, T the absolute temperature, and R is a gas constant.

Specific volume :- The specific volume is the volume per unit mass and is therefore the reciprocal of the density- that is,

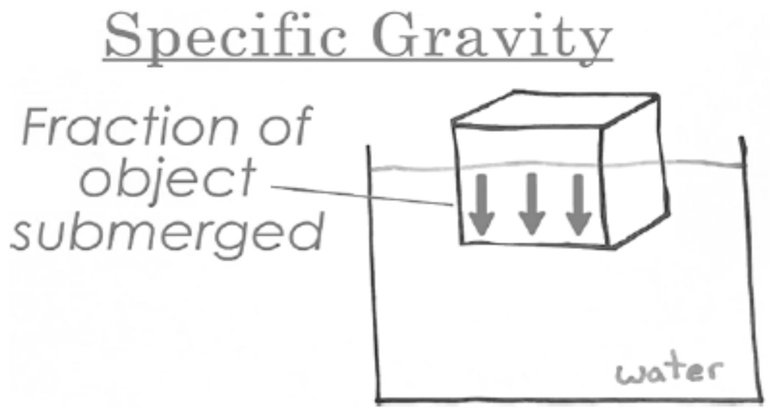
$$\boldsymbol{v = \frac{1}{\rho} = \frac{V}{m}}$$

Specific weight :- The **specific weight** of a fluid, is defined as its weight per unit volume. Thus, specific weight is related to density through the eq.

$$\boldsymbol{\gamma_s = \rho g} \quad \rightarrow \quad (N/m^3)$$

Measures of Fluid Mass and Weight

Specific gravity :- The **specific gravity** of a fluid (SG), is defined as the ratio of the density of the fluid to the density of water at some specified temperature.



$$S.G = \frac{\rho}{\rho_{H_2O}}$$

Where : – $\rho_{H_2O} = 1000 \frac{Kg}{m^3}$

If $\rho_{gold} = 19300 \frac{Kg}{m^3} \rightarrow \therefore S.G = 19.3$

If $\rho_{ketchup} = 1400 \frac{Kg}{m^3} \rightarrow \therefore S.G = 1.4$

H.W: What is the specific gravity of human blood, if the density of blood is 1060 kg/m^3?

Measures of Fluid Mass and Weight

Viscosity:- Viscosity (represented by $\boldsymbol{\mu}$) is a material property, unique to fluids, that measures the fluid's resistance to flow.

$$\mu = \frac{\tau}{\frac{du}{dy}} = \frac{\frac{N}{m^2}}{\frac{1}{s}} = \frac{N.s}{m^2} = \text{pa}.s = \frac{\text{kg}}{m.s}$$

$$Pois\ (p) = \frac{\text{g}}{m.s}$$

$$\text{Centipoise} = \text{cp} = 10^{-2}\ \text{p}$$

$$\frac{\text{Ib}_\text{f}.\text{s}}{\text{ft}^2} \quad \text{or} \quad \frac{\text{Ib}_\text{m}}{\text{ft}.\text{s}}$$

	Air	Water	Oil
$\mu\left[\frac{\text{kg}}{m.s}\right]$	1.8×10^{-5}	1.1×10^{-3}	0.38

Kinematic viscosity:-

$$\nu = \frac{\mu}{\rho} = \frac{\left[\frac{\text{kg}}{m.s}\right]}{\left[\frac{\text{kg}}{m^3}\right]} = \frac{m^2}{s}$$