MEC516/BME516: Fluid Mechanics I

Chapter 1: Introduction

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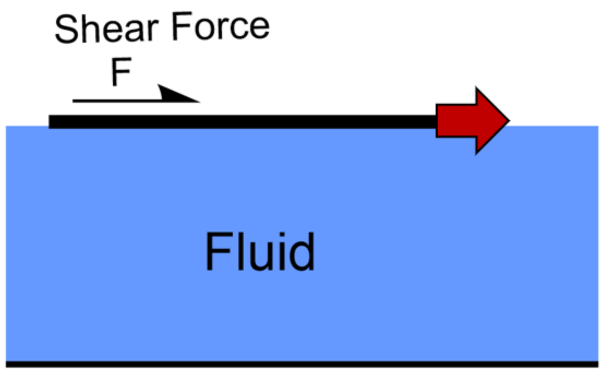
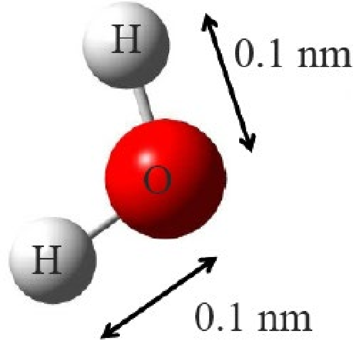
Overview

- Basic Definitions:
  - Definition of a fluid
  - Temperature and pressure



- The Continuum Approximation

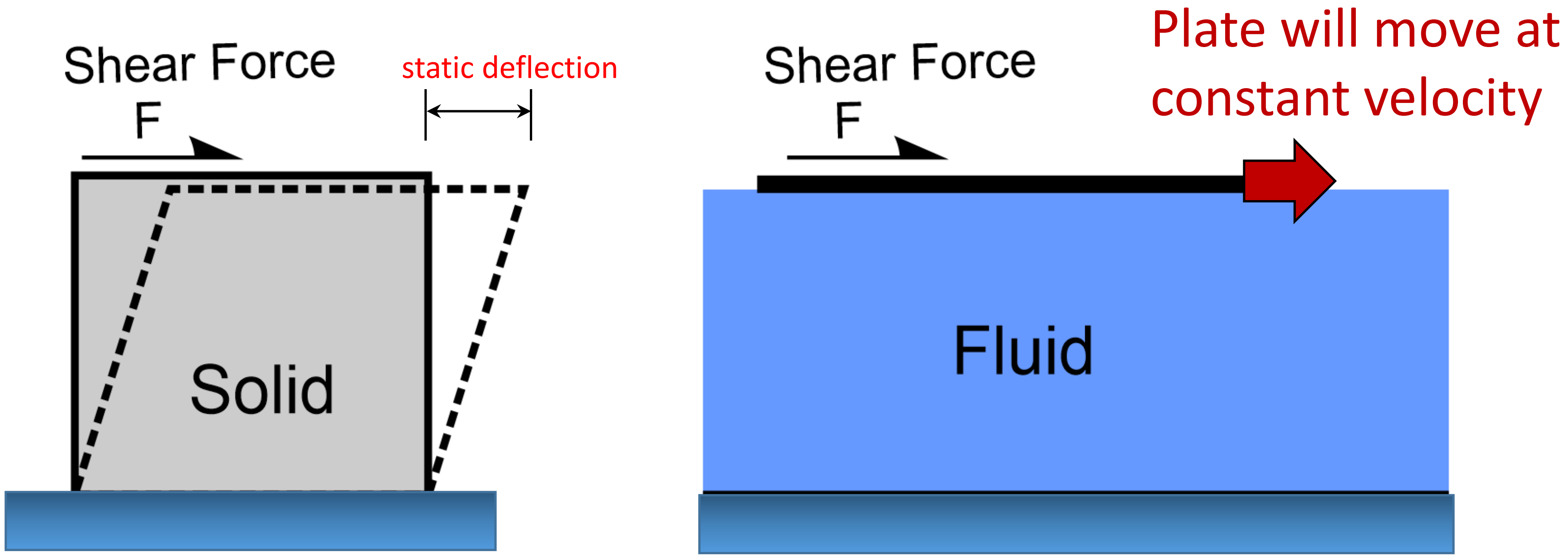


- Dimensions, Units & Dimensional Homogeneity

$$J \equiv \frac{kg\ m}{s^2}\ m = \frac{kg\ m^2}{s^2} \qquad \left\{\frac{M\ L^2}{T^2}\right\}$$

Fluid Mechanics is the study of fluids at rest (*fluid statics*) and in motion (*fluid dynamics*)

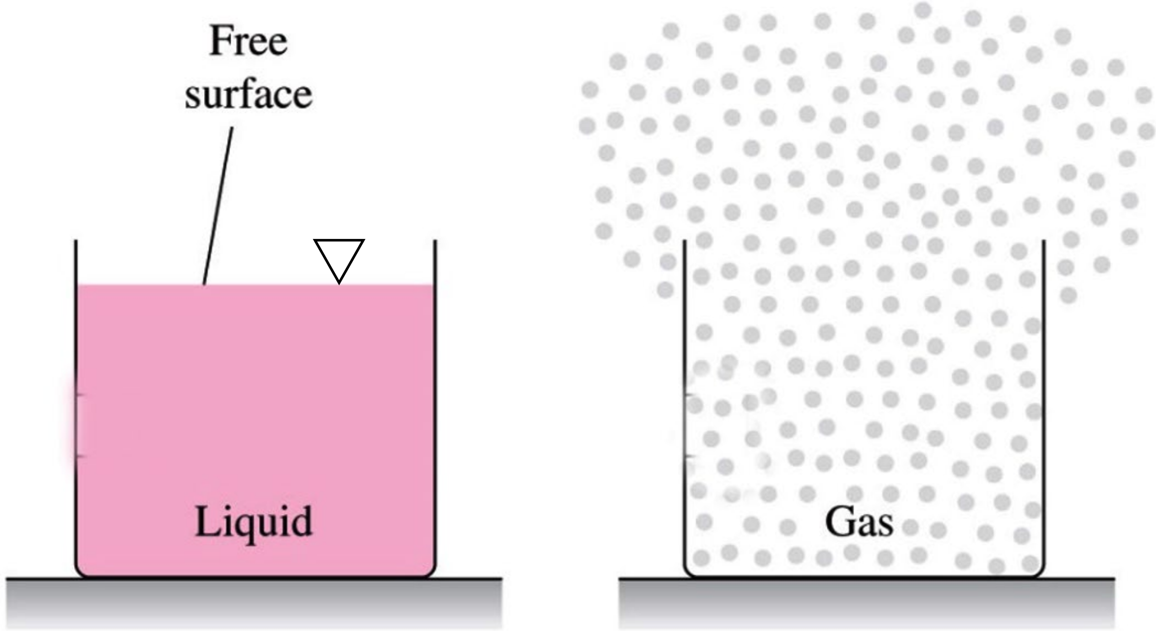
- What is a fluid? (How does a fluid differ from a solid?)



- Unlike a solid: **A fluid cannot resist shear stress**
- A fluid will deform continuously for any applied shear force, no matter how small

There are two main classes of fluids: **Gases** and **Liquids**

- Gases expand to fill their container – molecules are widely spaced
- Liquids retain their volume and form a free surface – molecules are more closely spaced



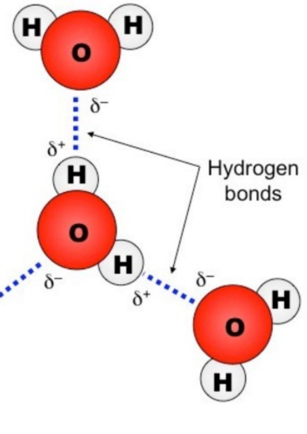
Glass contains **two** fluids: water and air

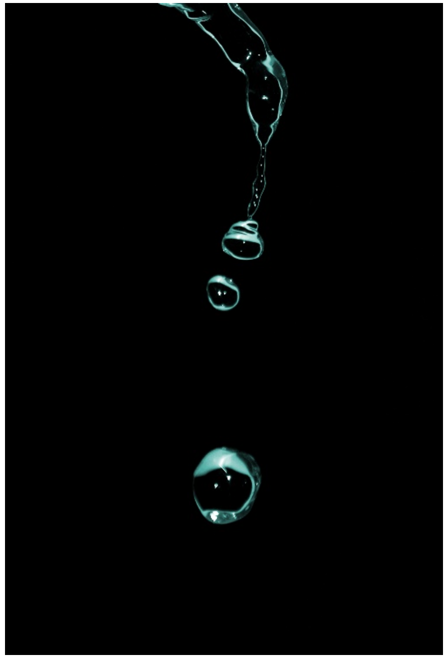
Not all fluids are liquid!

Air is a fluid
CO_2 gas is a fluid
Water vapor is a fluid

- Closely space molecules in liquids have strong cohesive forces → free droplets tend to form spheres due to ***surface tension***

Water
H_2O





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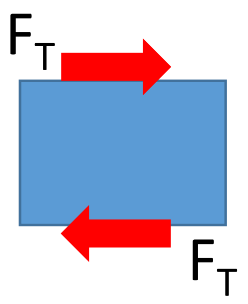
- Most liquids are about O(10^3) times more dense than gases at ambient conditions:

Density of ambient air (near STP): $\rho_{air} \approx 1.2$ kg/m^3

Density of liquid water: $\rho_{water} \approx 1000$ kg/m^3

Concept of a Fluid

- We know: Fluids cannot resist shear stress



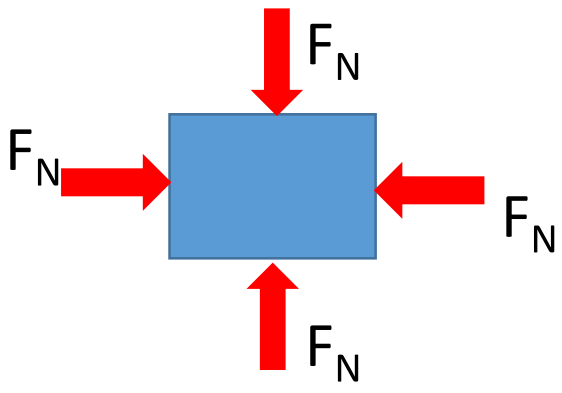
Can a fluid resist normal stress?

(a) Yes, but only liquids

(b) Yes, but only gases

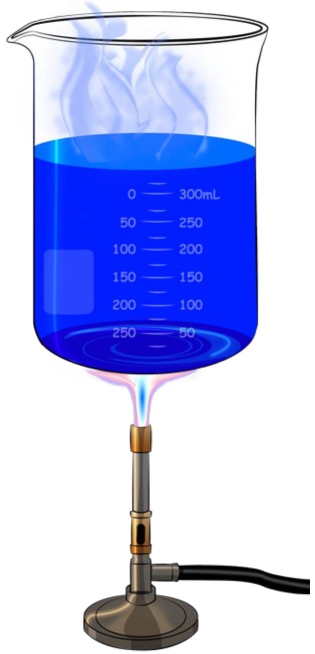
Ans. (c) Yes, both liquids and gases

(d) No. Fluids cannot resist normal stress



- Normal stress in a static fluid is called *pressure*

Temperature and Pressure

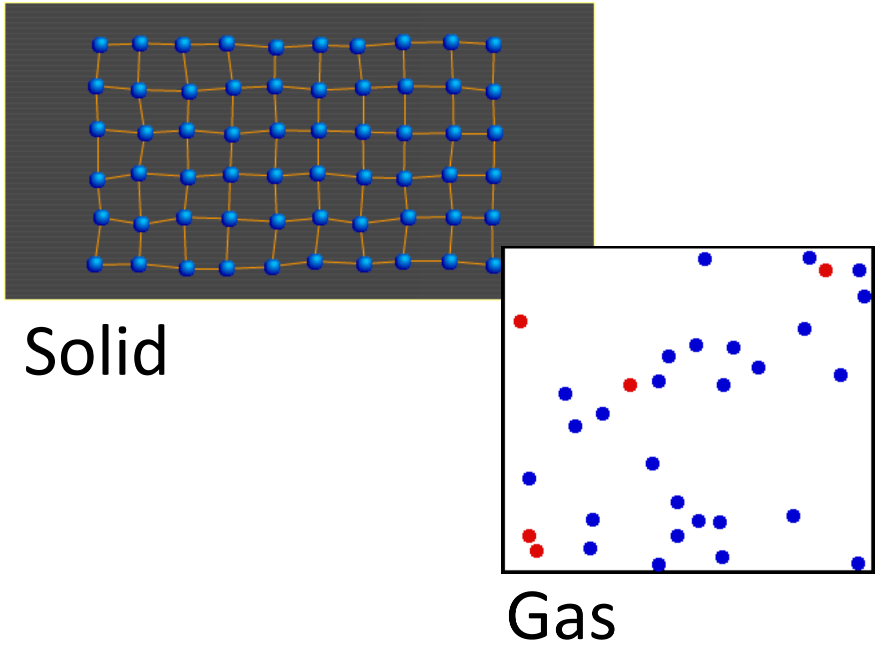


- If we add heat (or work) to substance, temperature increases

- But fundamentally, what is going on?
  - What is "temperature"?

- Temperature is a measure of kinetic energy of the atoms or molecules. "Jiggles"

- The "jiggling" becomes more energetic as temperature increases



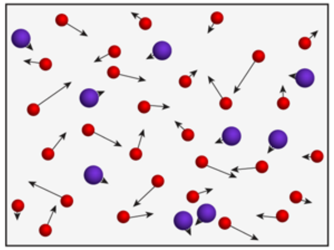
Temperature and Pressure


Richard Feynman

- At the atomic/molecular scale, thermal energy **<u>is</u>** kinetic energy
- In thermodynamics we call this "internal energy" (U)
- Evidence of this atomic jiggling was first seen in 1827!

"Brownian motion" of small particles, caused by random molecular motion. Add heat and the "jiggling" will get faster.

Temperature & Pressure



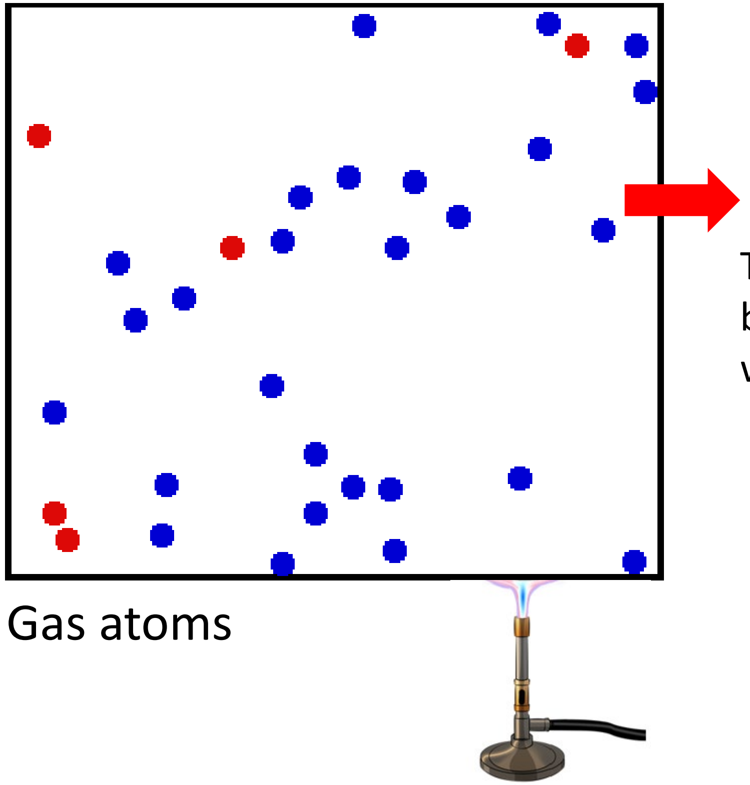
- Fundamentally, what is pressure? (“Force per unit area” provides no physical insight)

- When atoms bounce off the wall, they impart a force on the walls
- The change in momentum ($m \Delta\vec{v}$) **<u>causes</u>** the pressure force

- Put these two concepts together:

  Why does pressure increase if you heat a sealed container?

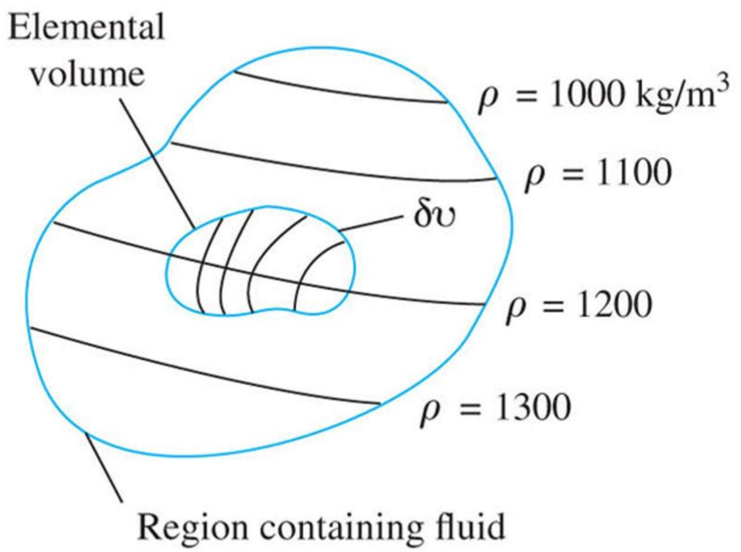
$\Delta\vec{v}$ increases as T increases



Gas atoms

The force of atoms bouncing off the wall <u>is</u> pressure

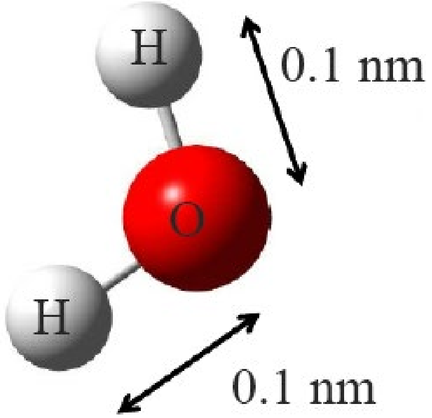
The Continuum Approximation



- Fluid properties are assumed to vary continuously, e.g. point density, $\rho(x, y, z)$

- We assume that $\rho(x, y, z)$ varies smoothly so we can use differential calculus

- Assumption **not** valid near the molecular/atomic scale
- Variables at a "point" actually represent an average over a small volume ($\delta V \approx 10^{-9}$ mm^3)



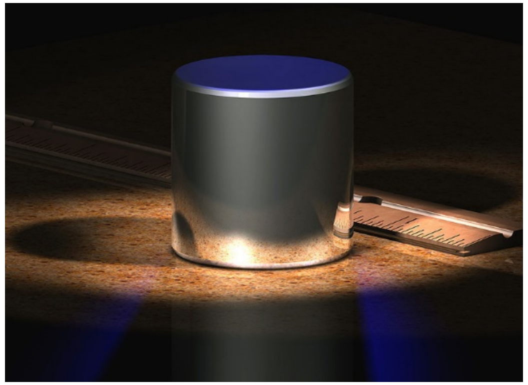
- Excellent approximation for most engineering purposes (breaks down at small length scales, e.g. nano-engineering)

Dimensions and Units

- In fluid mechanics we use four *Primary Dimensions*:

{ } has dimensions

Mass {M}   Length {L}   Time {T}   Temperature {Θ}



International Standard Kilogram (Bureau of Weights and Measures, Paris)

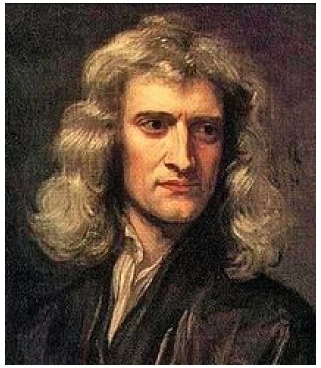
- A *unit* is way of attaching a number to the dimension, using an arbitrary measure

Primary dimension	SI unit ("International System")	BG unit ("British Gravitational System")	Conversion factor
Mass $\{M\}$	Kilogram (kg)	Slug (not pounds)	1 slug = 14.5939 kg
Length $\{L\}$	Meter (m)	Foot (ft)	1 ft = 0.3048 m
Time $\{T\}$	Second (s)	Second (s)	1 s = 1 s
Temperature $\{\Theta\}$	Kelvin (K)	Rankine (°R)	1 K = 1.8°R

$K = {}^oC + 273$ ${}^oR = {}^oF + 460$ $W = Mg$, $M = W/g$

$9.8\ m/s^2$
$32.2\ ft/s^2$

Secondary Dimensions



- The most important secondary dimension is Force {F}

- Using Newton's Second Law: $\mathbf{F} = ma \rightarrow \{F\} = \{M\ L\ T^{-2}\}$

- International System (SI): 1 N = 1 kg (1 m/s^2)
- British Gravitational System: 1 lb = 1 slug (1 ft/s^2)

- Important! "slug" is the unit of mass (not lb or lb_m) 1 slug= 14.59 kg

- Conversion tables in Appendix C of textbook

Secondary Dimensions

Table 1.2

Secondary dimension	SI unit	BG unit	Conversion factor
Area $\{L^2\}$	m^2	ft^2	$1\ m^2 = 10.764\ ft^2$
Volume $\{L^3\}$	m^3	ft^3	$1\ m^3 = 35.315\ ft^3$
Velocity $\{LT^{-1}\}$	m/s	ft/s	1 ft/s = 0.3048 m/s
Acceleration $\{LT^{-2}\}$	m/s^2	ft/s^2	$1\ ft/s^2 = 0.3048\ m/s^2$
Pressure or stress $\{ML^{-1}T^{-2}\}$	$Pa = N/m^2$	lbf/ft^2	$1\ lbf/ft^2 = 47.88\ Pa$
Angular velocity $\{T^{-1}\}$	s^{-1}	s^{-1}	$1\ s^{-1} = 1\ s^{-1}$
Energy, heat, work $\{ML^2T^{-2}\}$	$J = N \cdot m$	$ft \cdot lbf$	$1\ ft \cdot lbf = 1.3558\ J$
Power $\{ML^2T^{-3}\}$	W = J/s	$ft \cdot lbf/s$	$1\ ft \cdot lbf/s = 1.3558\ W$
Density $\{ML^{-3}\}$	kg/m^3	$slugs/ft^3$	$1\ slug/ft^3 = 515.4\ kg/m^3$
Viscosity $\{ML^{-1}T^{-1}\}$	$kg/(m \cdot s)$	$slugs/(ft \cdot s)$	$1\ slug/(ft \cdot s) = 47.88\ kg/(m \cdot s)$
Specific heat $\{L^2T^{-2}\Theta^{-1}\}$	$m^2/(s^2 \cdot K)$	$ft^2/(s^2 \cdot °R)$	$1\ m^2/(s^2 \cdot K) = 5.980\ ft^2/(s^2 \cdot °R)$

Why does energy have dimensions $\{ML^2T^{-2}\}$?

Secondary Dimensions

- Why does energy have dimensions $\{ML^2T^{-2}\}$?

- Energy has units of Joules $J \equiv N\,m$

- A Newton is defined by $F = ma$: $N \equiv \frac{kg\,m}{s^2}$

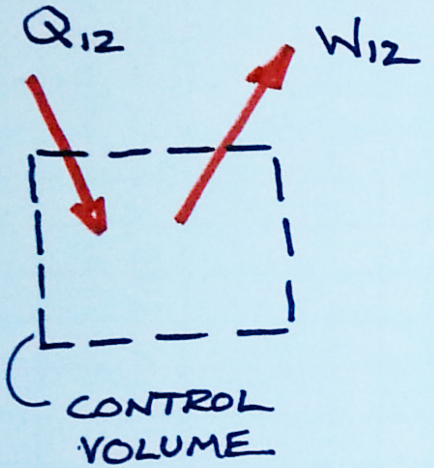
$$J \equiv \frac{kg\,m}{s^2}\,m \equiv \frac{kg\,m^2}{s^2}$$ Dimensions: $\left\{\frac{M\,L^2}{T^2}\right\}$

- Thus, energy/work/heat have dimensions $\{ML^2T^{-2}\}$

Dimensional Homogeneity

- All terms in equations must be homogeneous in both dimensions and units

- For example, the first law of thermodynamics for a closed system:



All terms have units of energy: $J \equiv \frac{kgm^2}{s^2}$

$$Q_{12} - W_{12} = \Delta U + \frac{1}{2} m (V_2^2 - V_1^2) + mg(Z_2 - Z_1)$$

$$kg\frac{m^2}{s^2} \quad kg\frac{m^2}{s^2} \quad kg\frac{m^2}{s^2} \quad kg\left(\frac{m}{s}\right)^2 \quad kg\frac{m}{s^2}\,m$$

$$\left\{\frac{ML^2}{T^2}\right\} \quad \left\{\frac{ML^2}{T^2}\right\} \quad \left\{\frac{ML^2}{T^2}\right\} \quad \left\{\frac{ML^2}{T^2}\right\} \quad \left\{\frac{ML^2}{T^2}\right\}$$

- Useful for detecting errors. Needed for *Dimensional Analysis* (Chapter 5)

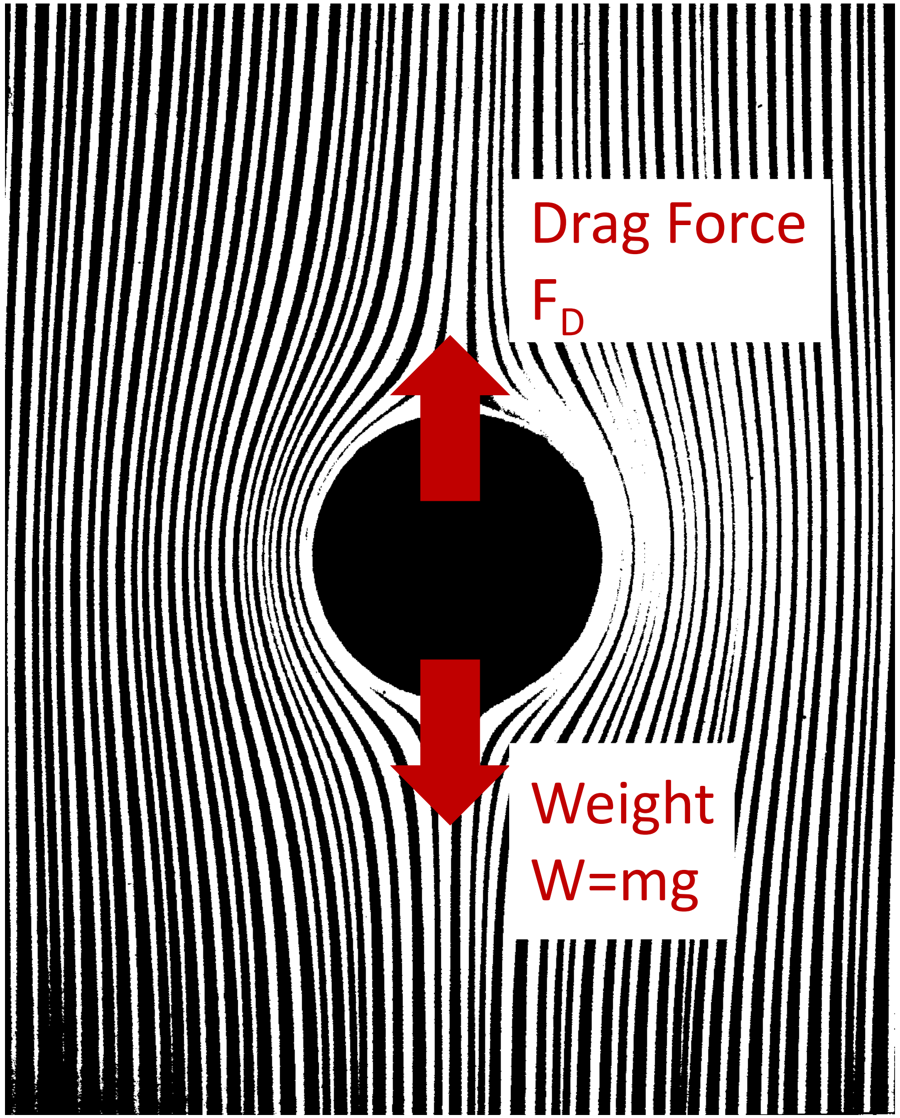
Example: Dimensional Consistency

- The dynamic viscosity (μ) of an oil is calculated by measuring the terminal velocity (V) of small spheres falling under the action of gravity (g)

- For very slow flow ("Stokes Flow"):

$$\mu = \frac{D^2 g\,(\rho_{sphere} - \rho_{oil})}{18\,V}$$

Confirm the dimensional consistency of this equation



Streamlines for Laminar Flow Over a Sphere


What are the units of mass in the British Gravitational System?

END NOTES