PHYSICS 2: FLUID MECHANICS AND THERMODYNAMICS

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- No of credits: 02 (30 teaching hours)
- Textbook: Halliday/Resnick/Walker (2018) entitled Principles of Physics, 11th edition, John Willey & Sons, Inc.

Course Requirements

- In-class activities: attendance (5%), homework (10%), quiz (15%), discussion (5%)
- Mid-term exam: 30%
- Final exam: 40%
- Absence more than 20% → not allowed to attend the Final exam

Preparation for each class

- Read text ahead of time
- Finish homework

Questions, Discussion

- Via email and/or make an appointment to meet at A1.503

Content

Chapter 1 Fluid Mechanics

Chapter 2 Heat, Temperature and the First Law of Thermodynamics

Chapter 3 The Kinetic Theory of Gases

Chapter 4 Entropy and the Second Law of Thermodynamics

(Chapters 14, 18, 19, 20 of Principles of Physics, Halliday et al.)

CHAPTER 1 FLUID MECHANICS

1.1. Fluids at Rest

1.2. Ideal Fluids in Motion

1.3. Bernoulli's Equation

Question: What is a fluid?

A fluid is a substance that can flow (liquids, gases)

Physical parameters:

Density: (the ratio of mass to volume for a material)

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

- Δm and ΔV are the mass and volume of the element, respectively.
- Density has no directional properties (a scalar property)

Unit: kg/m^3 or g/cm^3; 1 g/cm^3=1000 kg/m^3

Uniform density:

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

Fluid Pressure:

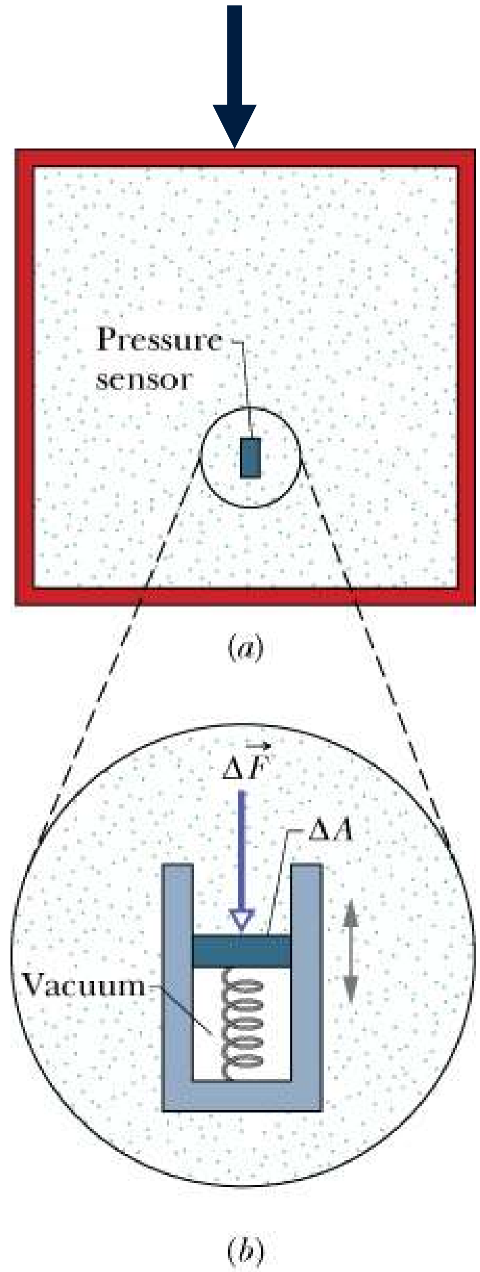
- Pressure is the ratio of normal force to area
  - Pressure is a scalar property
  - Unit:
    - SI: N/m^2 = Pa (Pascal)
    - Non-SI: atm = 1.01×10^5 Pa
- Fluid pressure is the pressure at some point within a fluid:

$$p = \frac{\Delta F}{\Delta A}$$

- Uniform force on flat area:

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

A fluid-filled vessel



Fluid Properties:

- Fluids conform to the boundaries of any container containing them.
- Gases are compressible but liquids are not, e.g., see Table 14-1:
  - Air at 20^0C and 1 atm pressure: density (kg/m^3)=1.21

    20^0C and 50 atm: density (kg/m^3)=60.5

  → The density significantly changes with pressure

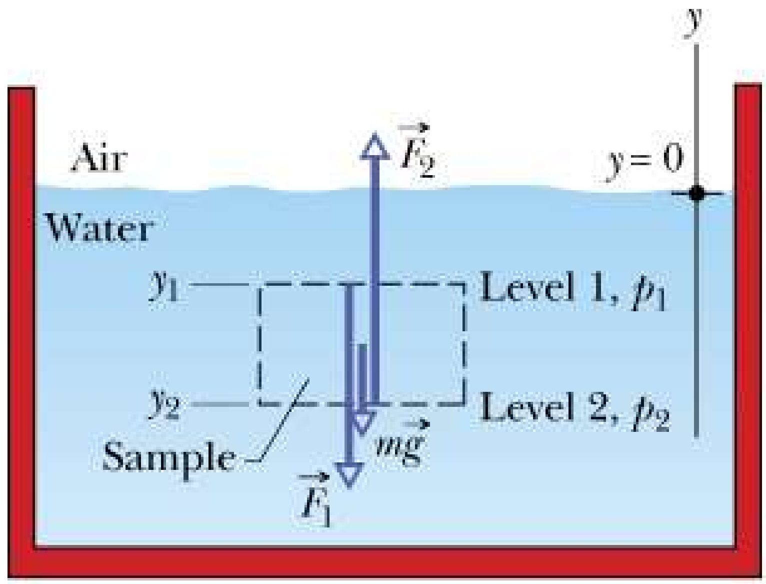
  - Water at 20^0C and 1 atm: density (kg/m^3)=0.998 x 10^3

    20^0C and 50 atm: density (kg/m^3)=1.000 x 10^3

  → The density does not considerably vary with pressure

1.1. Fluids at Rest

The pressure at a point in a non-moving (static) fluid is called the hydrostatic pressure, which only depends on the depth of that point.



Problem: We consider an imaginary cylinder of horizontal base area A

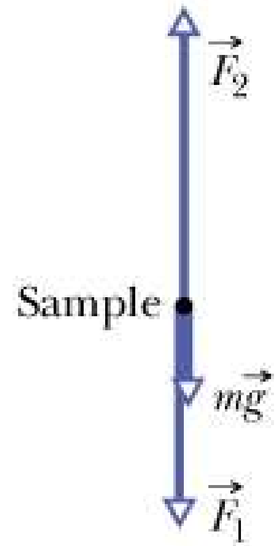
$$F_2 = F_1 + mg$$

$$F_1 = p_1 A$$

$$F_2 = p_2 A$$

$$\longrightarrow \quad p_2 A = p_1 A + \rho A (y_1 - y_2) g$$

$$\boxed{p_2 = p_1 + \rho (y_1 - y_2) g}$$



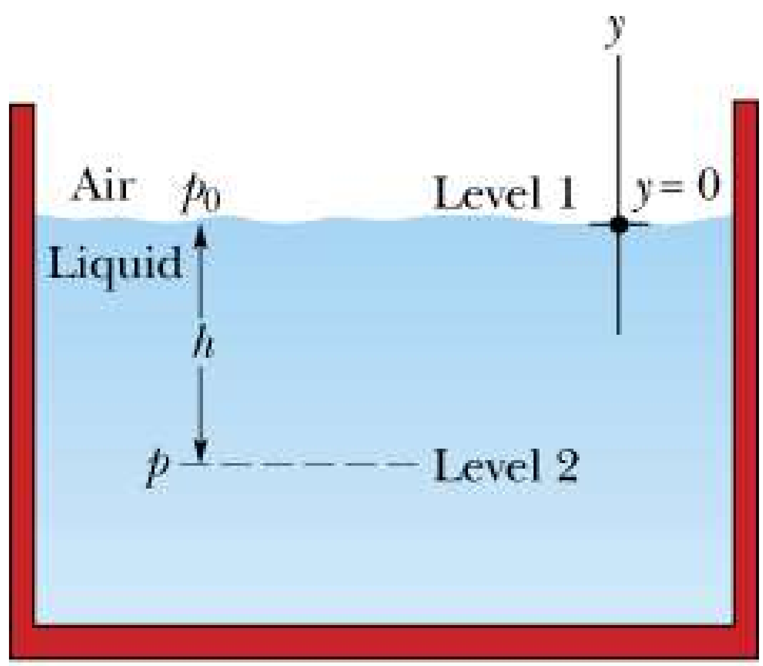
- If $y_1 = 0$, $p_1 = p_0$ (on the surface) and $y_2 = -h$, $p_2 = p$:

$$p = p_0 + \rho g h$$

absolute pressure: p

atmospheric pressure: p_0

gauge pressure: $\rho g h$

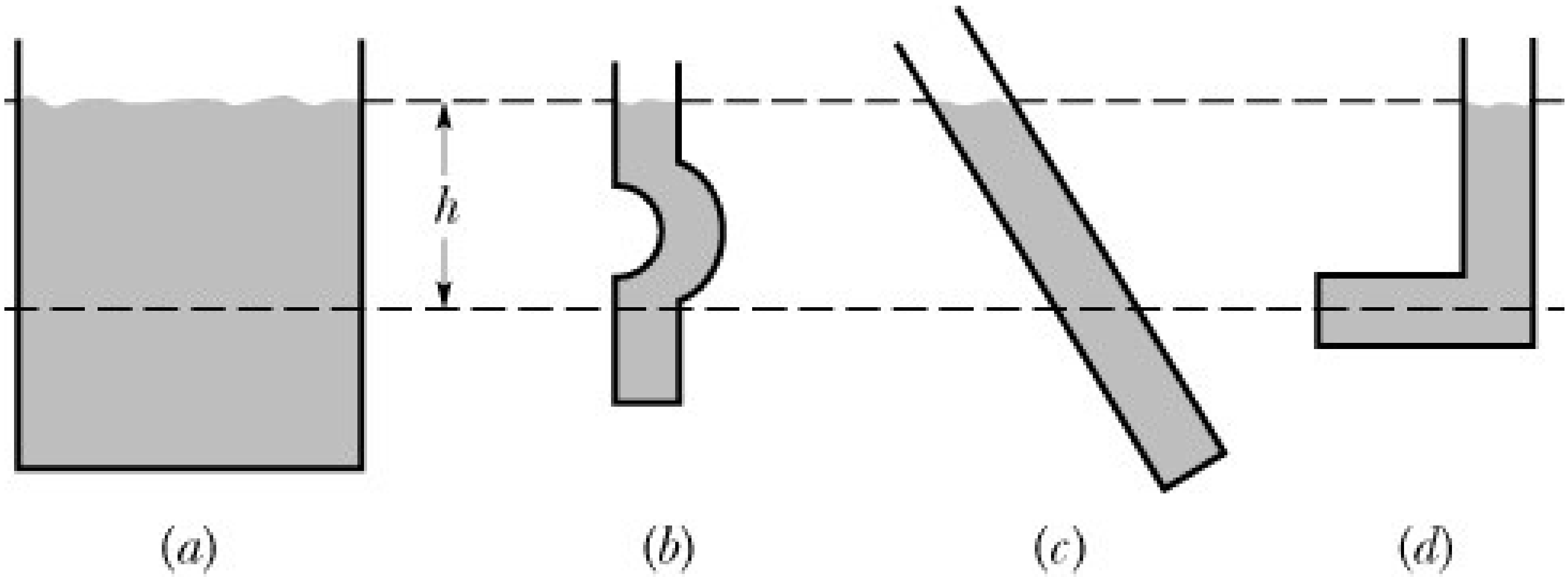


- Calculate the atmospheric pressure at d above level 1:

$$p = p_0 - \rho_{air} g d$$

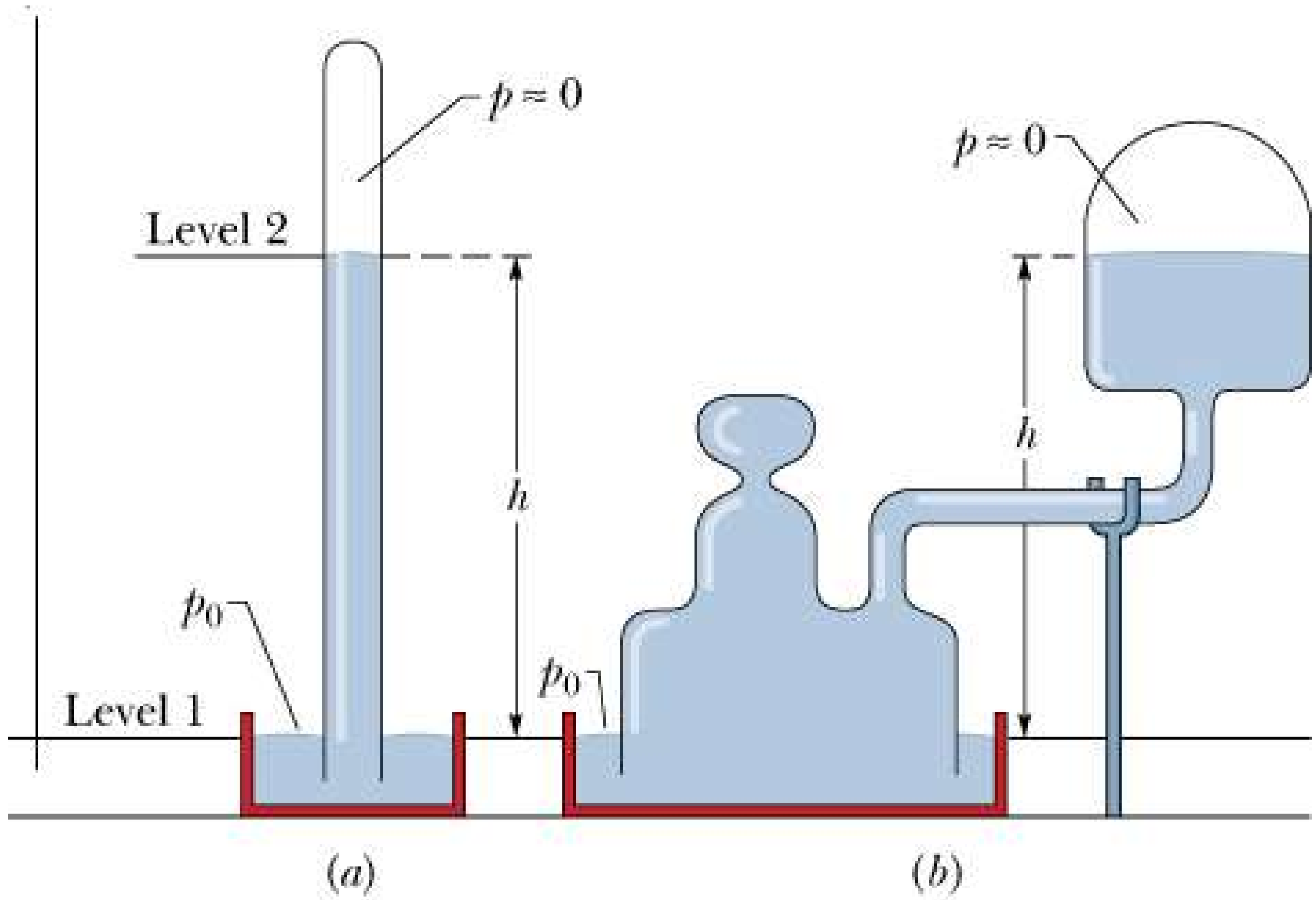
Question:

There are four containers of water. Rank them according to the pressure at depth h, greatest first.



A. Measuring pressure:

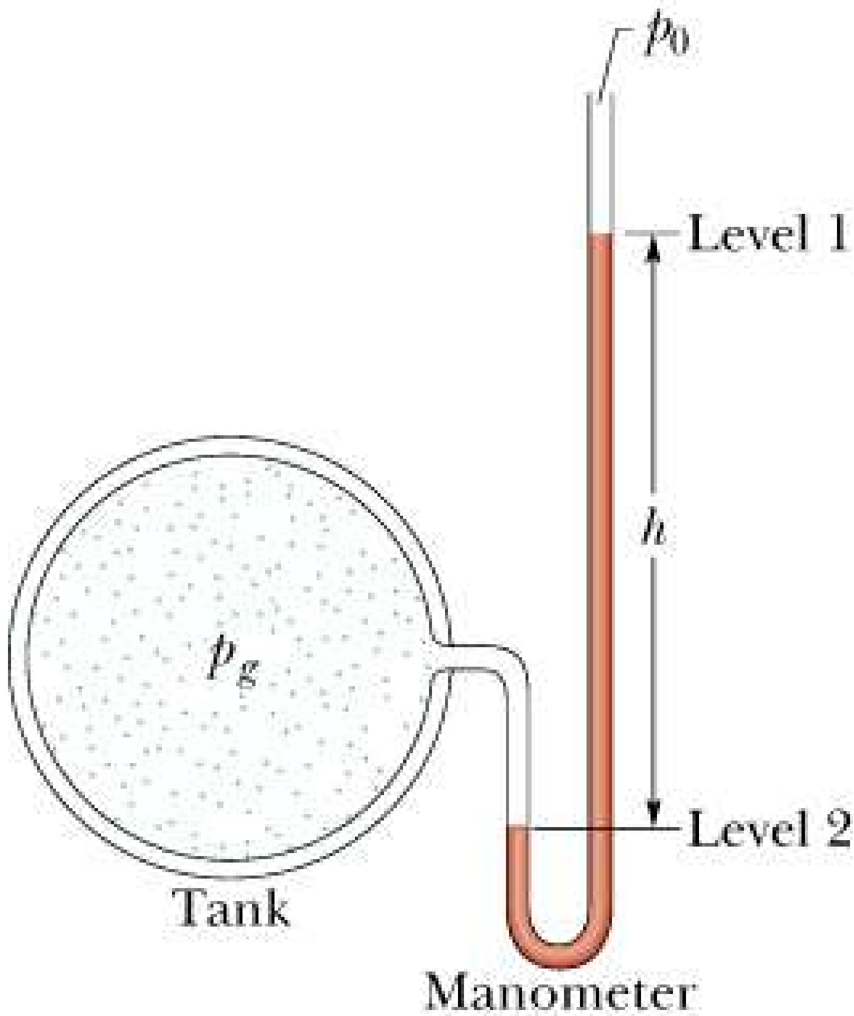
Mercury barometers (atmospheric pressure)



$$p_0 = \rho g h$$

ρ is the density of the mercury

An open-tube manometer (gauge pressure)

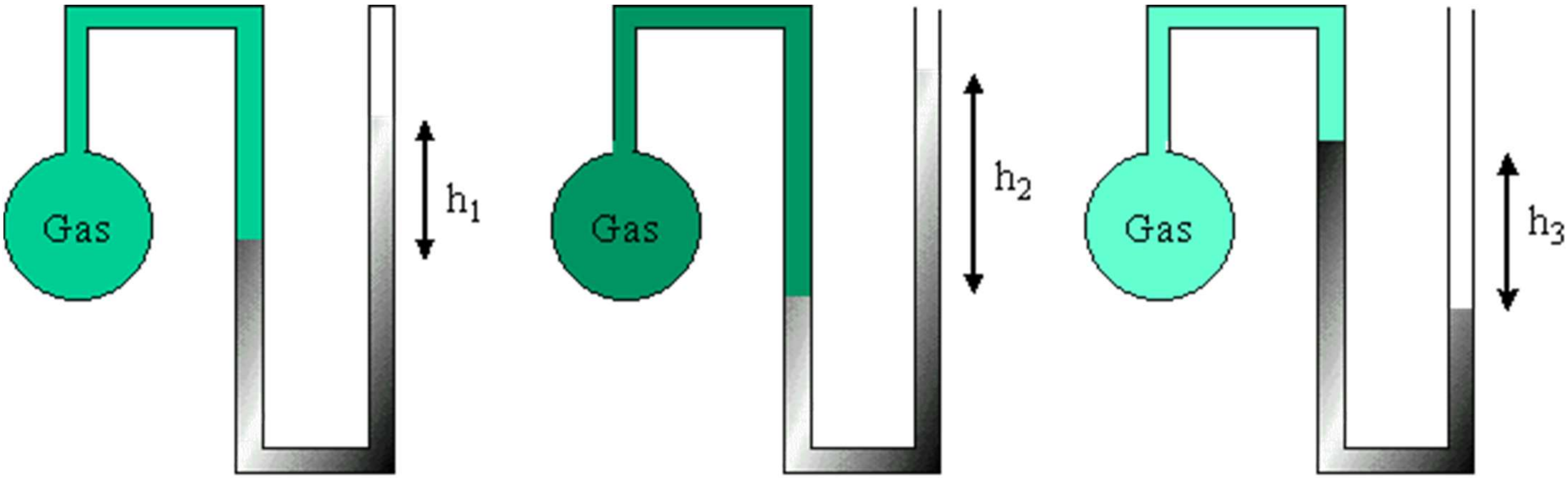


$$p_g = \rho g h$$

ρ is the density of the liquid

The gauge pressure can be positive or negative:

closed tube | open tube | open tube



closed tube

$$p_{gas} = \rho g h_1$$
$$p_{gauge} = p_{gas} - p_0 = \rho g h_1 - p_0$$

open tube

$$p_{gas} = \rho g h_2 + p_0$$
$$p_{gauge} = p_{gas} - p_0 = \rho g h_2 > 0$$

open tube

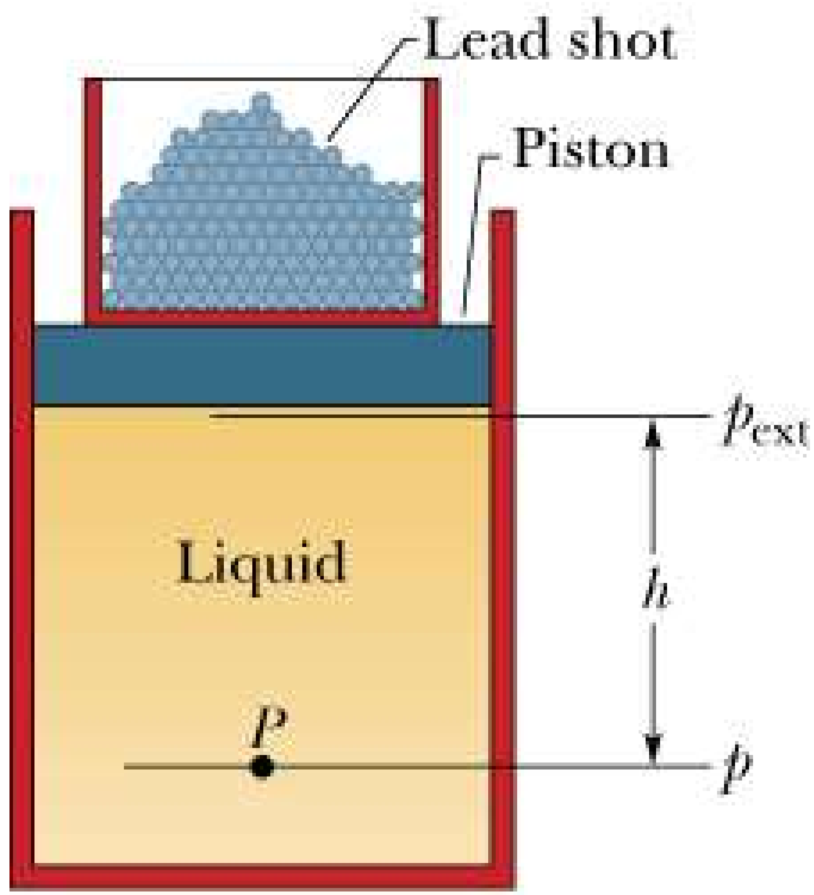
$$p_{gas} + \rho g h_3 = p_0$$
$$p_{gauge} = p_{gas} - p_0 = -\rho g h_3 < 0$$

B. Pascal's Principle:

A change in the pressure applied to an enclosed incompressible fluid is transmitted undiminished to every part of the fluid, as well as to the walls of its container.

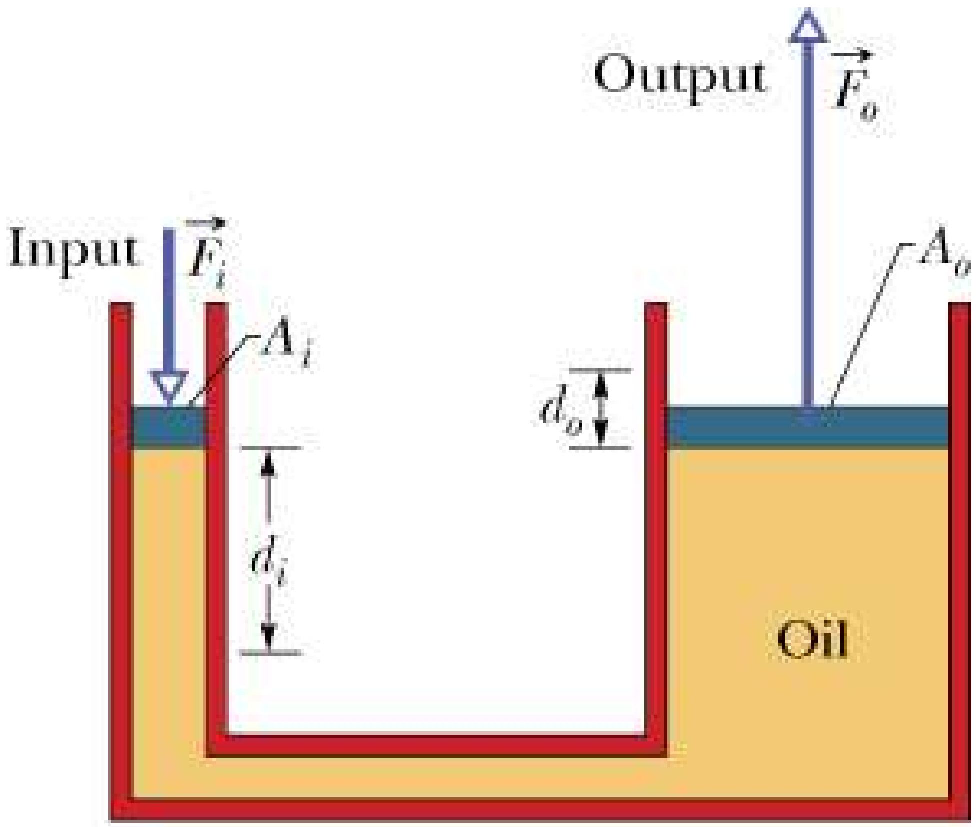
$$p = p_{ext} + \rho g h$$

$$\Delta p = \Delta p_{ext}$$



- Application of Pascal’s principle:

$$\boxed{\begin{aligned}\Delta p &= \frac{F_i}{A_i} = \frac{F_0}{A_0} \\ F_0 &= F_i\,\frac{A_0}{A_i}\end{aligned}}$$



A Hydraulic Lever

$A_0 > A_i \rightarrow F_0 > F_i$

The output work:

$$W = F_i d_i = F_0 d_0$$

https://www.youtube.com/watch?v=hV5IEooHqIw

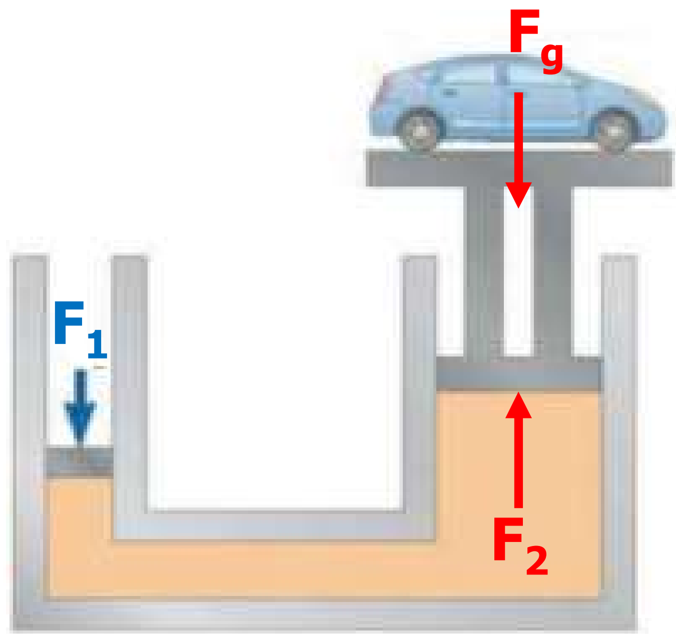
Sample: What force must be exerted on the master cylinder of a hydraulic lift to support the weight of a 2000 kg car (a large car) resting on the slave cylinder, see Figure? The master cylinder has a 2.0 cm diameter and the slave has a 24.0 cm diameter.

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$F_1 = F_2 \frac{A_1}{A_2} = m_2 g \frac{\pi r_1^2}{\pi r_2^2}$$

$$F_1 = (2000)(9.8) \frac{\left(\frac{0.02}{2}\right)^2}{\left(\frac{0.24}{2}\right)^2}$$

$$F_1 = 136.11 \text{ N}$$



C. Archimedes's Principle:

We consider a plastic sack of water in static equilibrium in a pool:

$$\vec{F}_g + \vec{F}_b = 0$$

The net upward force is a buoyant force $\vec{F}_b$
$F_b = F_g = m_f\, g$ (m_f is the mass of the sack)

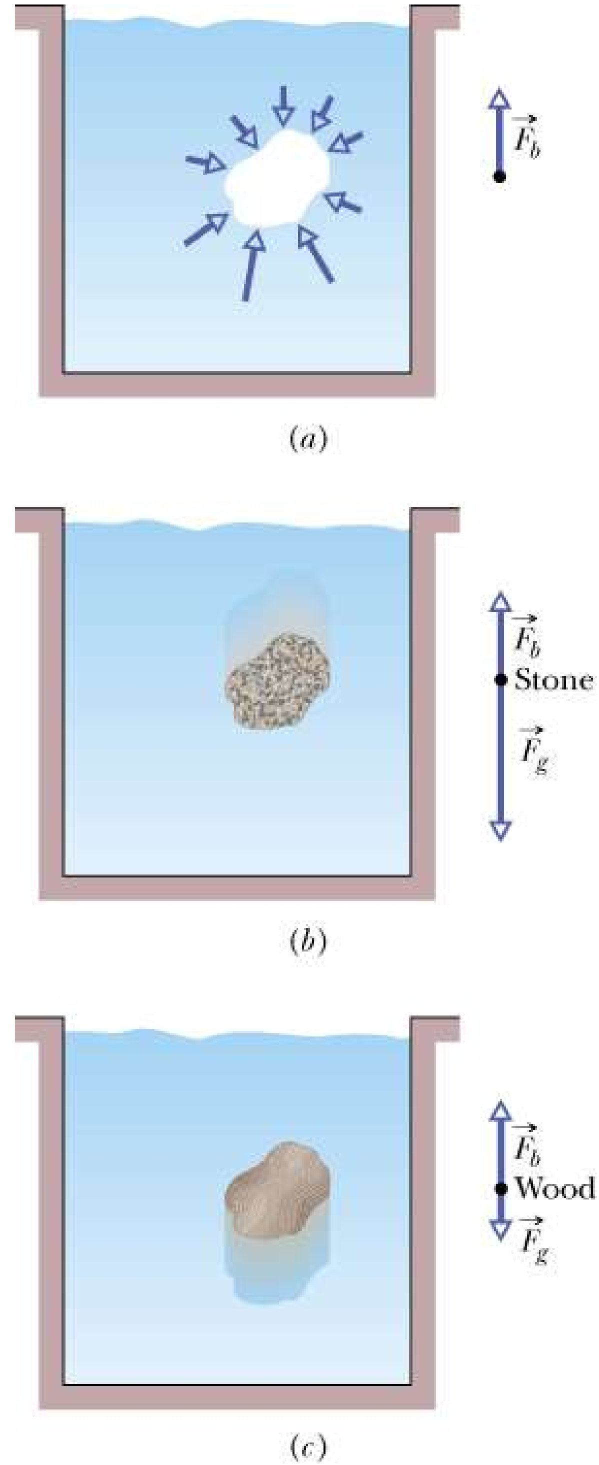
$$\boxed{F_b = \rho_{fluid}\, g V}$$

V: volume of water displaced by the object, if the object is fully submerged in water, $V = V_{object}$

If the object is not in static equilibrium, see figures (b) and (c):

$$F_b < F_g \text{ (case b: a stone)}$$

$$F_b > F_g \text{ (case c: a lump of wood)}$$

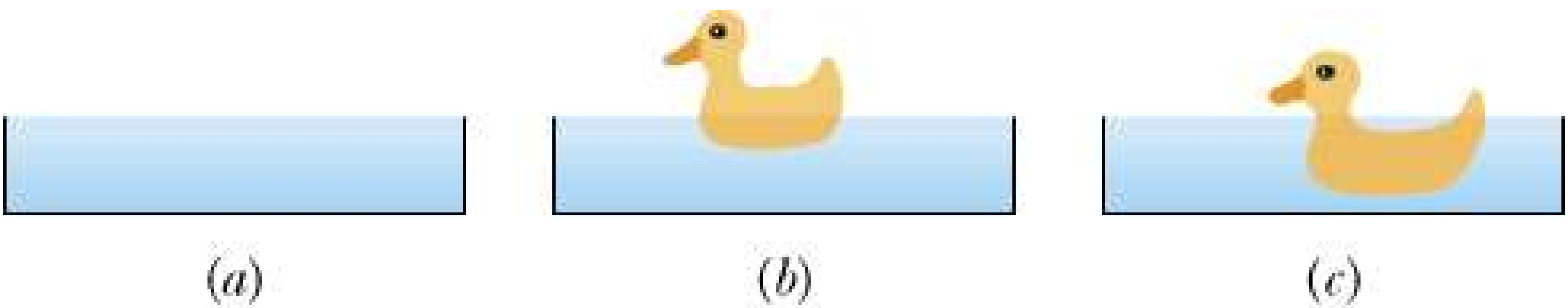


The buoyant force on a submerged object is equal to the weight of the fluid that is displaced by the object.

Apparent weight in a Fluid:

$$\textbf{weight}_{\textbf{app}} = \textbf{weight}_{\textbf{actual}} - \textbf{F}_{\textbf{b}}$$

Question: Three identical open-top containers filled to the brim with water; toy ducks float in 2 of them (b & c). Rank the containers and contents according to their weight, greatest first.



1.2. Ideal Fluids in Motion

We do only consider the motion of an ideal fluid that matches four criteria:

- Steady flow: the velocity of the moving fluid at any fixed point does not vary with time.
- Incompressible flow: the density of the fluid has a constant and uniform value.
- Non-viscous flow: no resistive force due to viscosity.
- Irrotational flow.

The Equation of Continuity

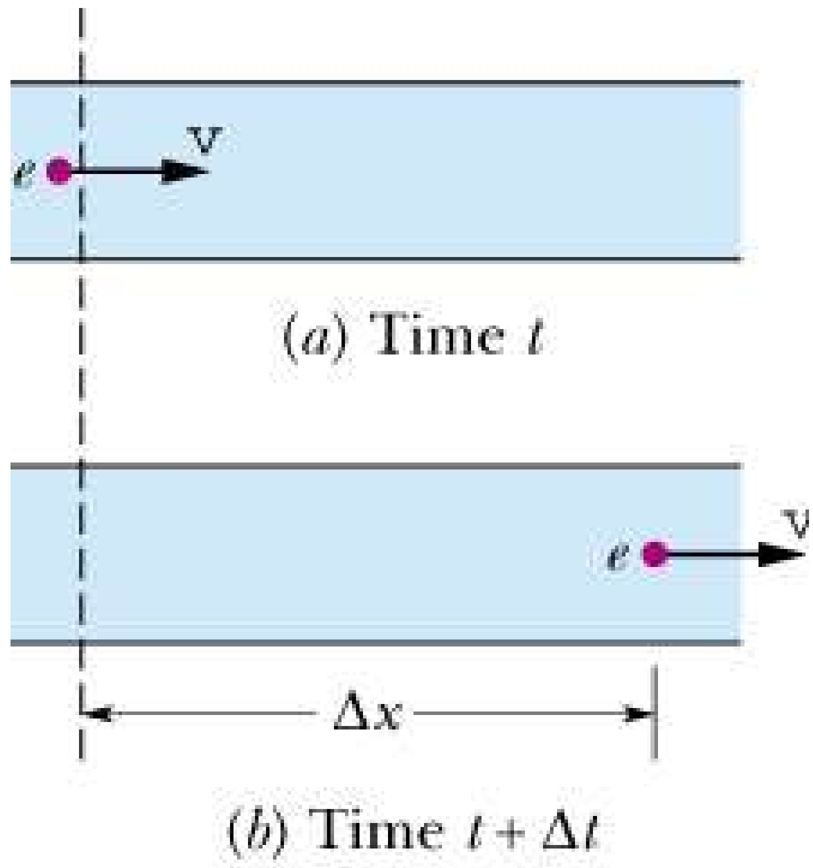
(the relationship between speed and cross-sectional area)

We consider the steady flow of an ideal fluid through a tube. In a time interval Δt, a fluid element e moves along the tube a distance:

$$\Delta x = v\Delta t$$

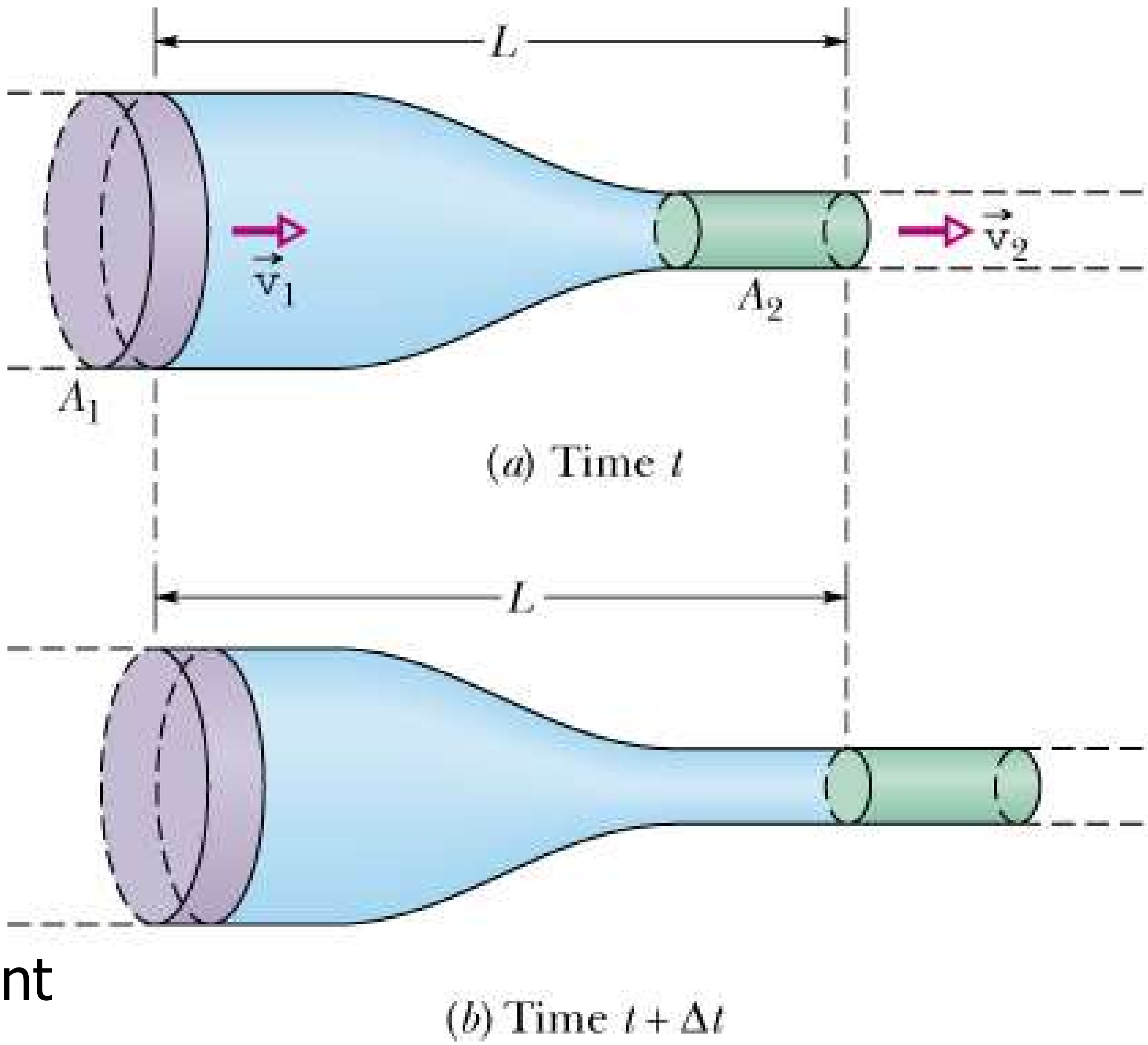
$$\Delta V = A\Delta x = Av\Delta t$$

$$\Delta V = A_1 v_1 \Delta t = A_2 v_2 \Delta t$$



The Equation of continuity

$$\boxed{A_1 v_1 = A_2 v_2}$$



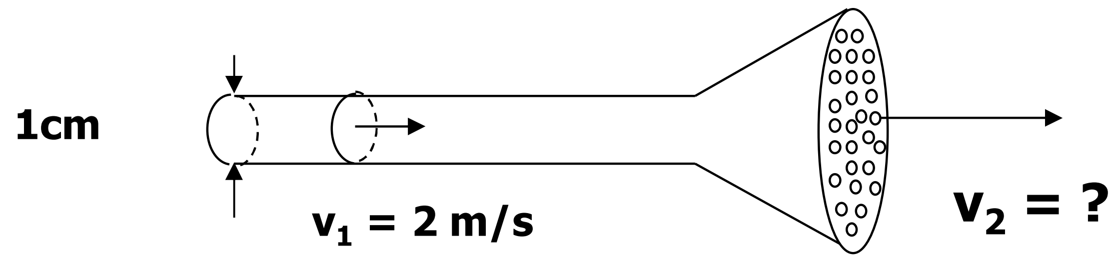
- Volume flow rate:

$$R_V = Av = \text{a constant}$$

- Mass flow rate:

$$R_m = \rho R_V = \rho Av = \text{a constant}$$

Sample: A sprinkler is made of a 1.0 cm diameter garden hose with one end closed and 40 holes, each with a diameter of 0.050 cm, cut near the closed end. If water flows at 2.0 m/s in the hose, what is the speed of the water leaving a hole?



Using the equation of continuity, the speed v_2 is:

$$v_1A_1 = v_2A_2 = v_2(40a_0)$$

a_0 is the area of one hole

$$v_2 = \frac{v_1A_1}{40a_0} = \frac{2.0\times\pi\left(\frac{1.0}{2}\right)^2}{40\times\pi\left(\frac{0.05}{2}\right)^2} = 20\ (\text{m/s})$$

1.3. Bernoulli's Equation

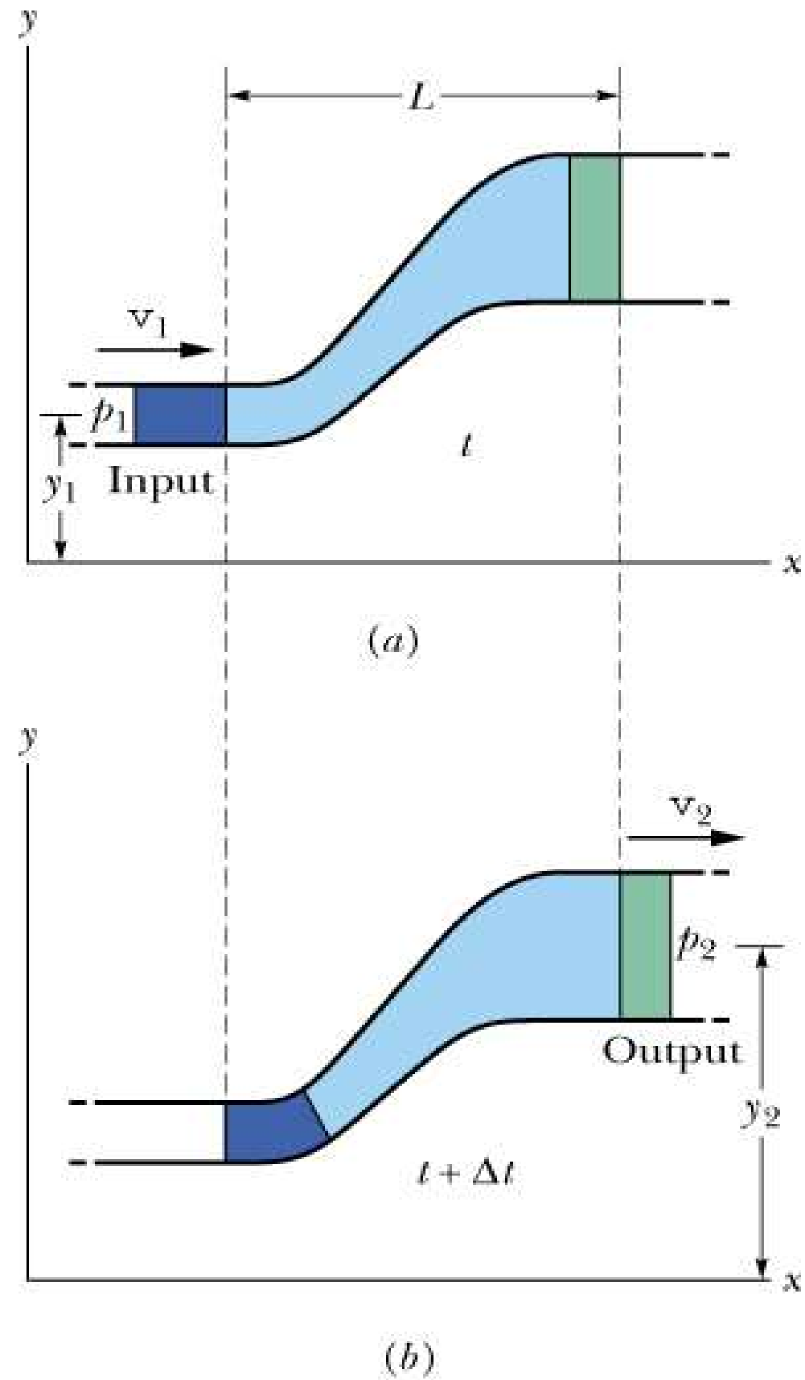
- An ideal fluid is flowing at a steady rate through a tube.
- Applying the principle of conservation of energy (work done = change in kinetic energy):

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2$$

$$\boxed{p + \frac{1}{2}\rho v^2 + \rho g y = \text{a constant}}$$

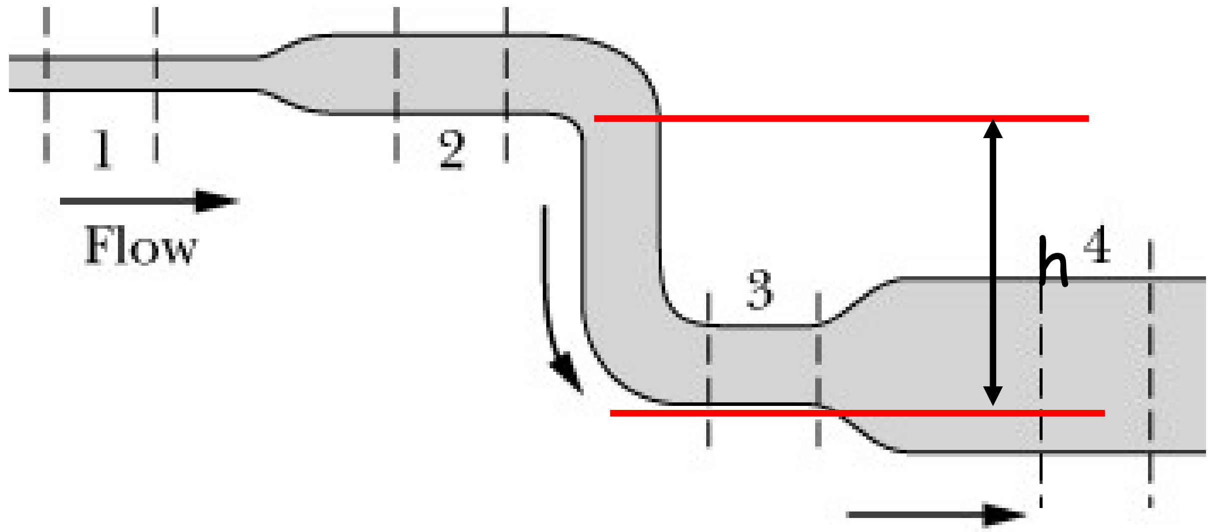
- If y=0: $$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$$

→ As the velocity of a horizontally flowing fluid increases, the pressure exerted by that fluid decreases, and conversely.



https://www.youtube.com/watch?v=UJ3-Zm1wbIQ

Question: Water flows smoothly through a pipe (see the figure below), descending in the process. Rank the four numbered sections of pipe according to (a) the volume flow rate R_V, (b) the flow speed v, and (c) the water pressure p, greatest first.



Conclusion:

1. Pressure (N/m^2 = Pa): the ratio of normal force to area

$$p = \Delta F/\Delta A$$

2. Gauge pressure and Absolute pressure:

$$p_g = \rho g h$$

$$p = p_0 + p_g \quad (p_0\text{: atmospheric pressure})$$

3. Pascal's principle

$$\Delta p = \frac{F_i}{A_i} = \frac{F_0}{A_0}$$

4. Bouyant force (Archimedes' principle):

$$F_b = \rho g V$$

5. Volume flow rate (m^3/s) and Mass flow rate (kg/s):

$$R_V = Av$$

$$R_m = \rho R_V$$

6. Bernoulli's Equation :

$$p + \frac{1}{2}\rho v^2 + \rho g y = \text{a constant}$$

Homework:

(1) Read “Proof of Bernoulli’s Equation”

(2) Problems 1, 2, 17, 28, 38, 39, 48, 58, 65, 71 in Chapter 14 Textbook