Physics 2: Fluid Mechanics and Thermodynamics

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- No of credits: 02 (30 teaching hours)
- Textbook: Halliday/Resnick/Walker (2011) entitled Principles of Physics, 9th edition, John Willey & Sons, Inc.

Course Requirements

- Attendance + Discussion + Homework: 15%
- Assignment: 15%
- Mid-term exam: 30%
- Final: 40%

Preparation for each class

- Read text ahead of time
- Finish homework

Questions, Discussion

- Wednesday's morning and afternoon: see the secretary of the department (room A1.413) for appointments

Chapter 1 Fluid Mechanics

Chapter 2 Heat, Temperature and the First Law of Thermodynamics

Chapter 3 The Kinetic Theory of Gases

- ✓ Midterm exam after Lecture 6

Chapter 4 Entropy and the Second Law of Thermodynamics

- ✓ Assignment given in Lecture 11
- ✓ Final exam after Lecture 12

(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:

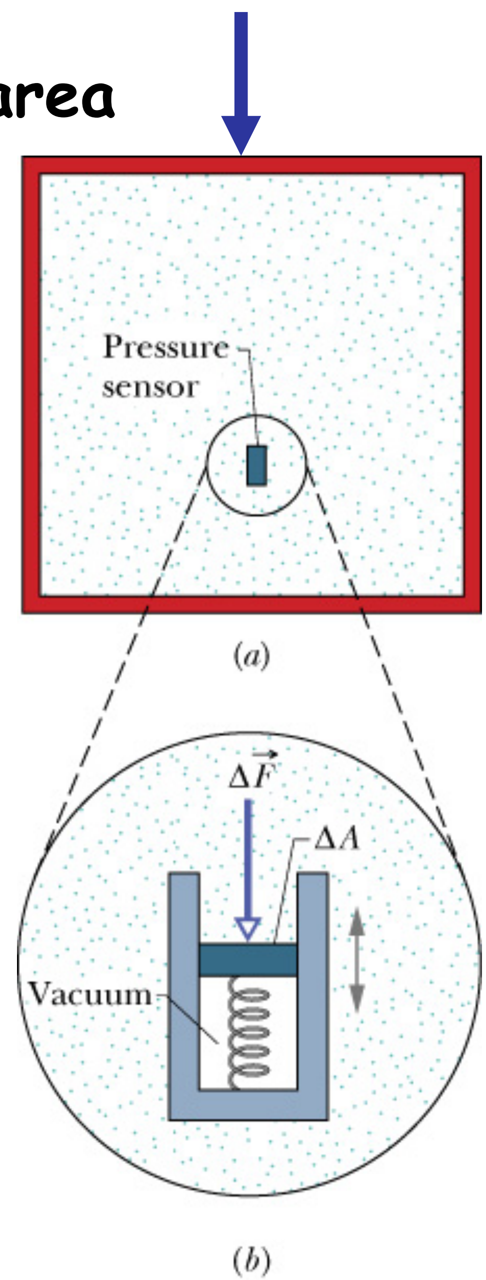
A fluid-filled vessel

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

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

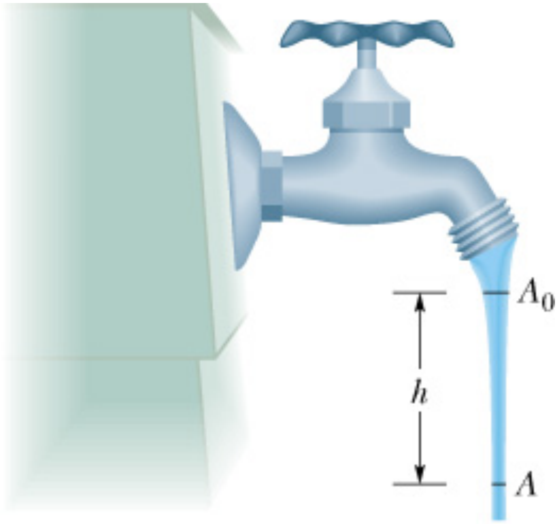
- Uniform force on flat area:

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



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)=0.998×10^3

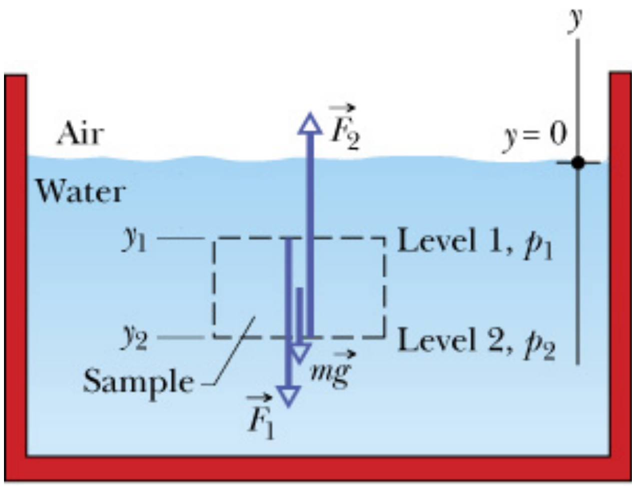
20^0C and 50 atm: density (kg/m^3)=1.000×10^3

➔ 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***



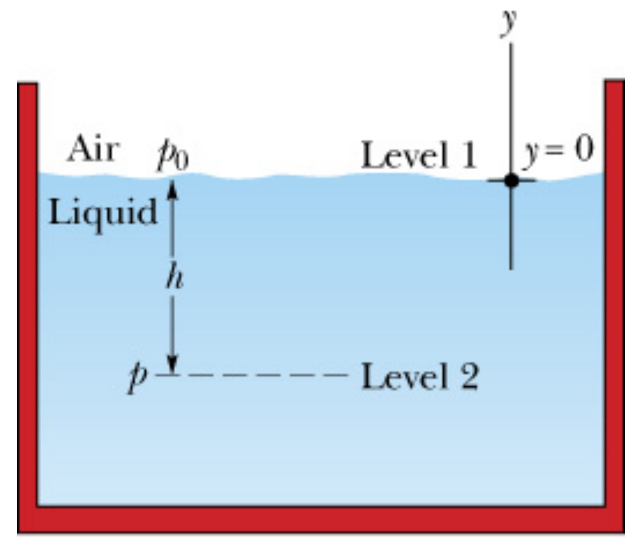
$$F_2 = F_1 + mg$$

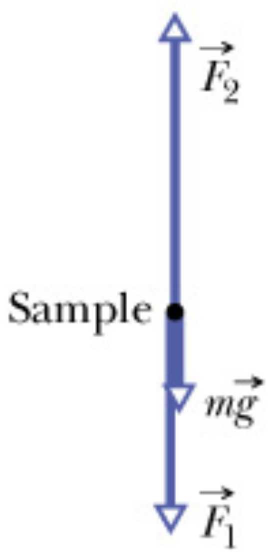
$$F_1 = p_1 A$$

$$F_2 = p_2 A$$

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

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





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

$$\boxed{p = p_0 + \rho g h}$$

gauge pressure ($\rho g h$)

absolute pressure (p)

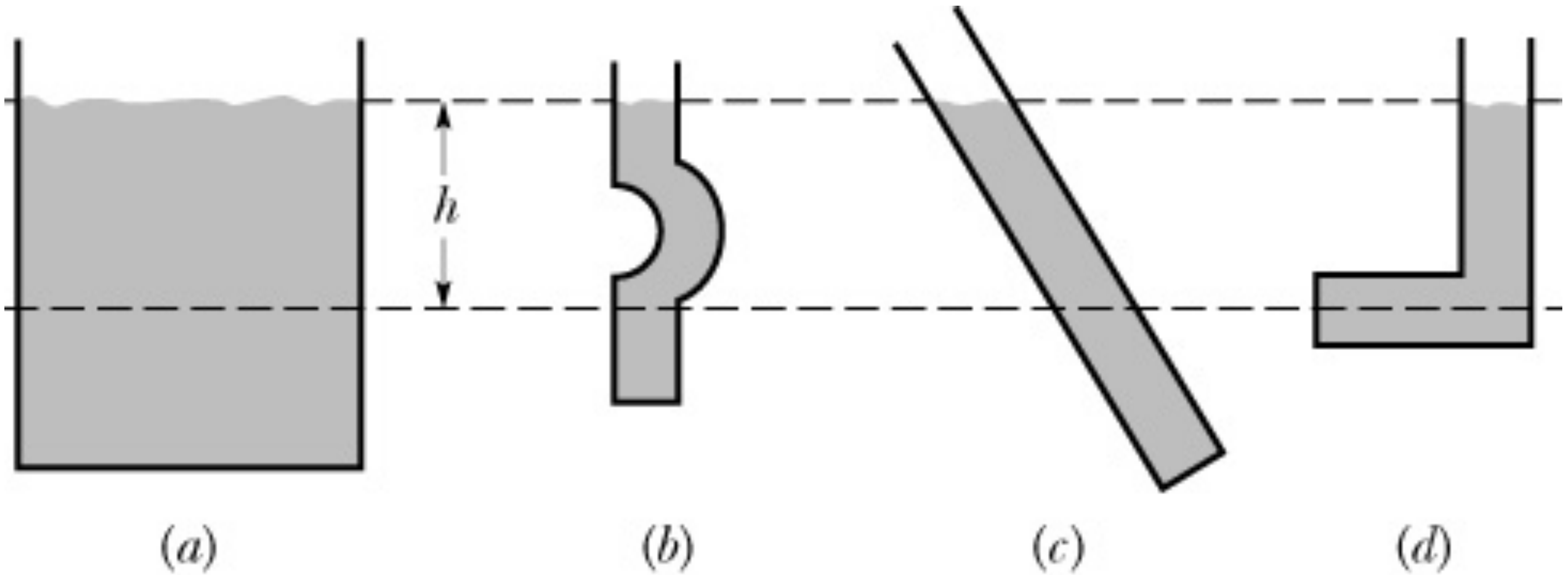
atmospheric pressure (p_0)

- **Calculate the atmospheric pressure at d above level 1:**

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

Question:

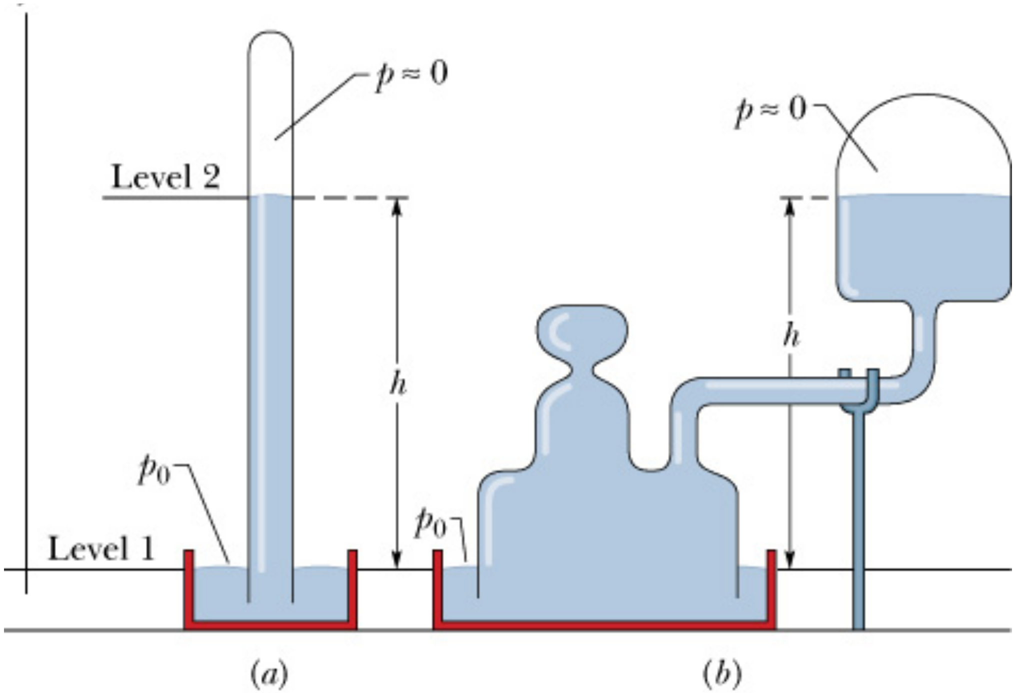
There are four containers of water. Rank them according to the pressure at depth h, greatest first.



Answer: All four have the same value of pressure.

A. Measuring pressure:

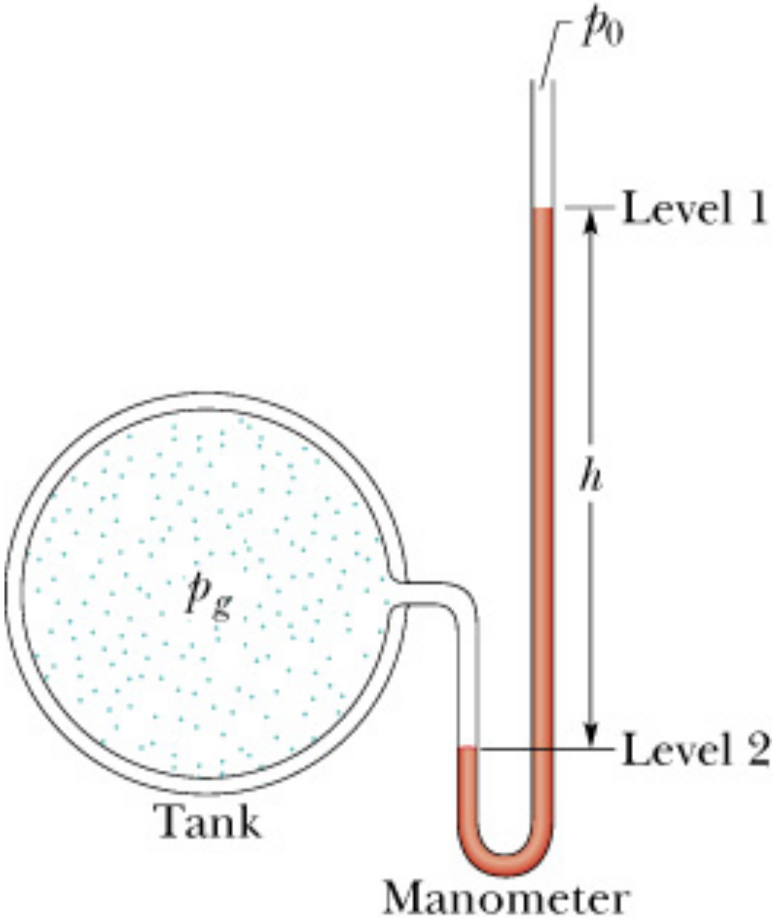
Mercury barometers
(atmospheric pressure)



$$p_0 = \rho g h$$

ρ is the density of the mercury

An open-tube manometer
(gauge pressure)

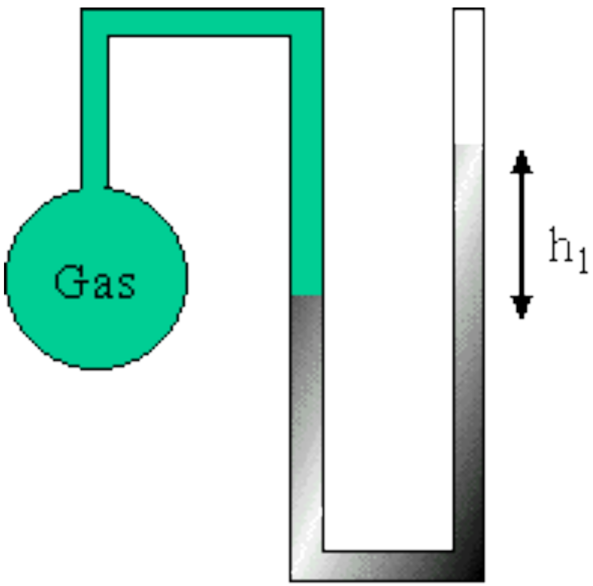


$$p_g = \rho g h$$

ρ is the density of the liquid

The gauge pressure can be positive or negative:

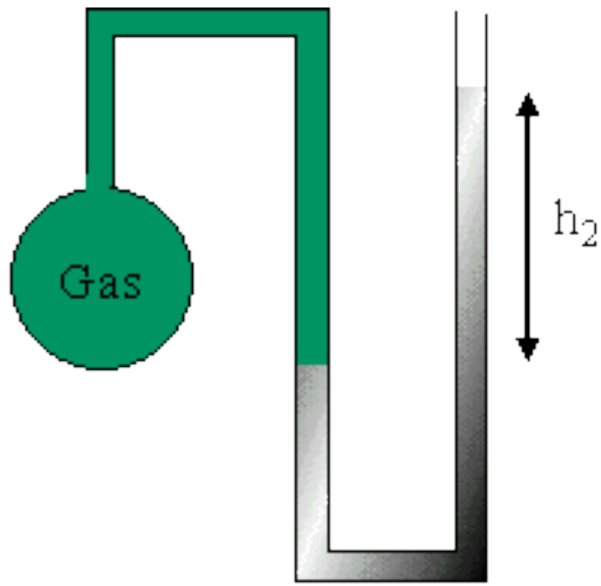
closed tube



$$p_{gas} = \rho g h_1$$

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

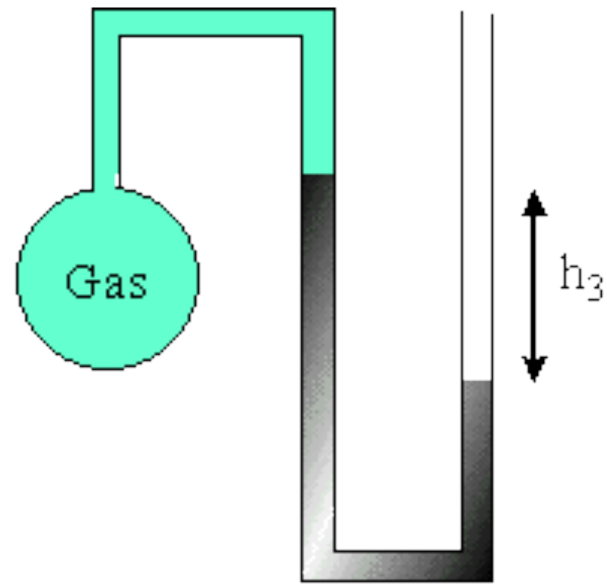
open tube



$$p_{gas} = \rho g h_2 + p_0$$

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

open tube



$$p_{gas} + \rho g h_3 = p_0$$

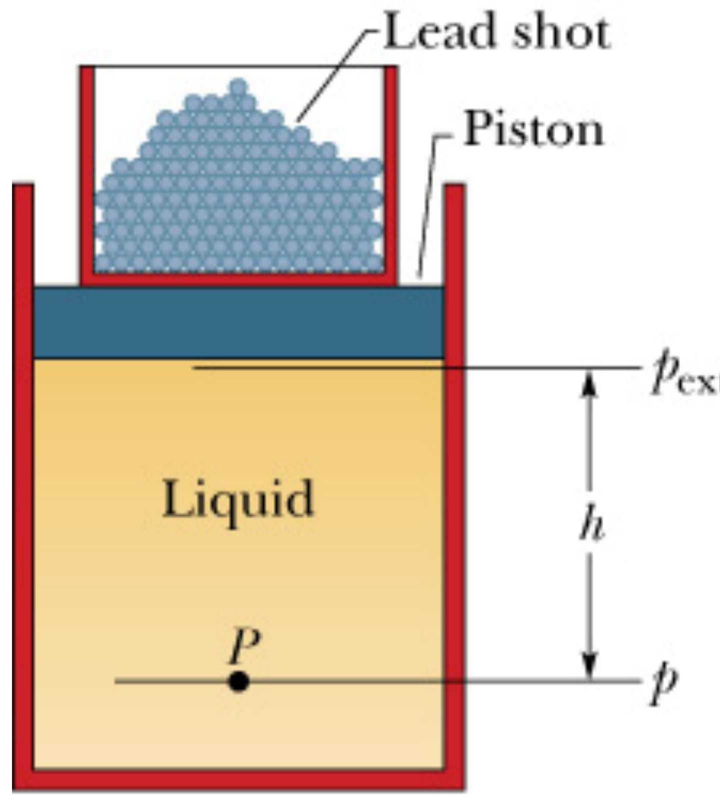
$$p_{gauge} = p_{gas} - p_0 = -\rho g h_3 < 0$$

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.

$$p = p_{ext} + \rho gh$$

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



- Application of Pascal's principle:

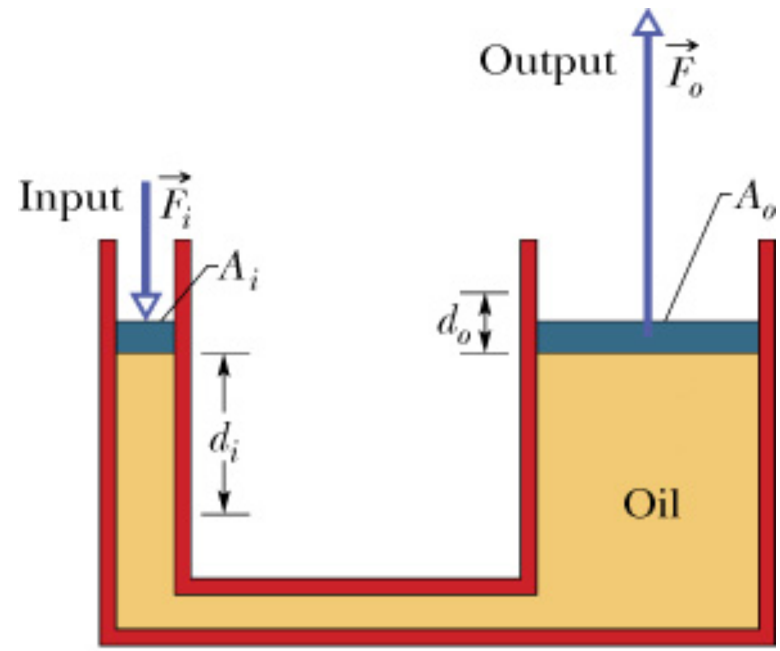
$$\Delta p = \frac{F_i}{A_i} = \frac{F_0}{A_0}$$

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

$A_0 > A_i \rightarrow F_0 > F_i$

The output work:

$$W = F_i d_i = F_0 d_0$$



A Hydraulic Lever

Pascal's Law

C. Archimede'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)

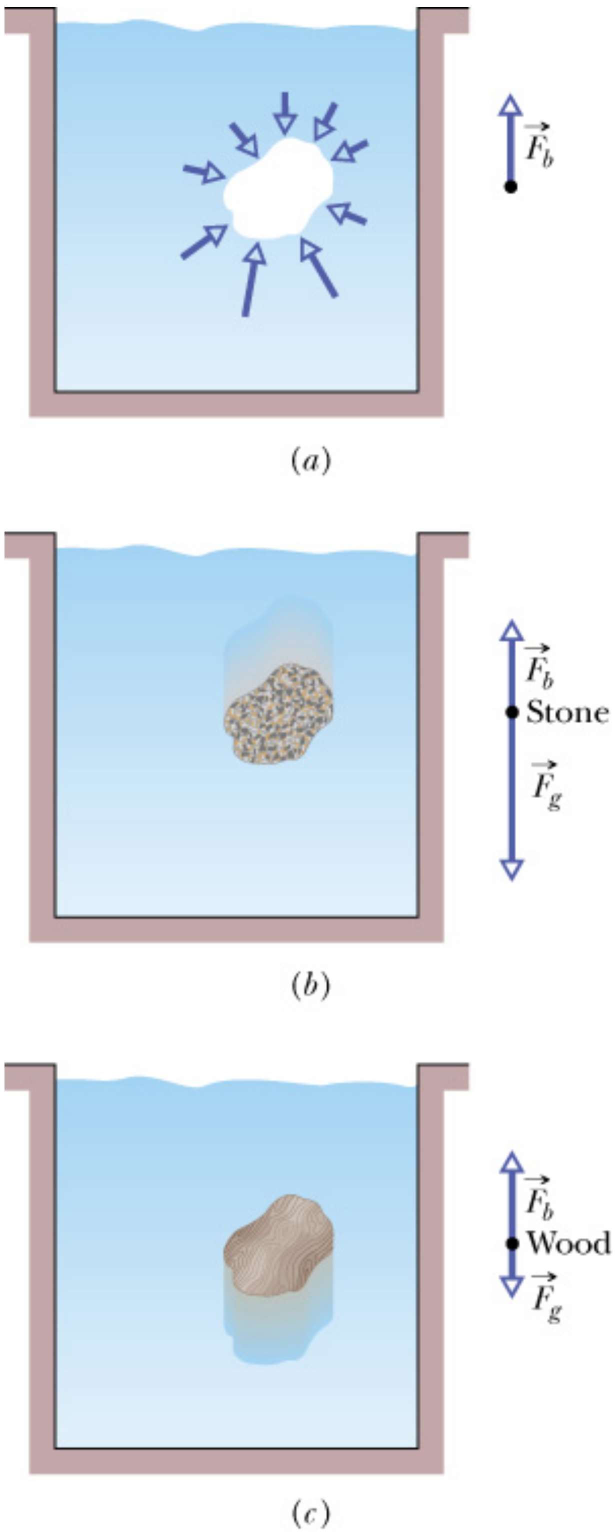
$$F_b = \rho_{fluid} g V$$

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):

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

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

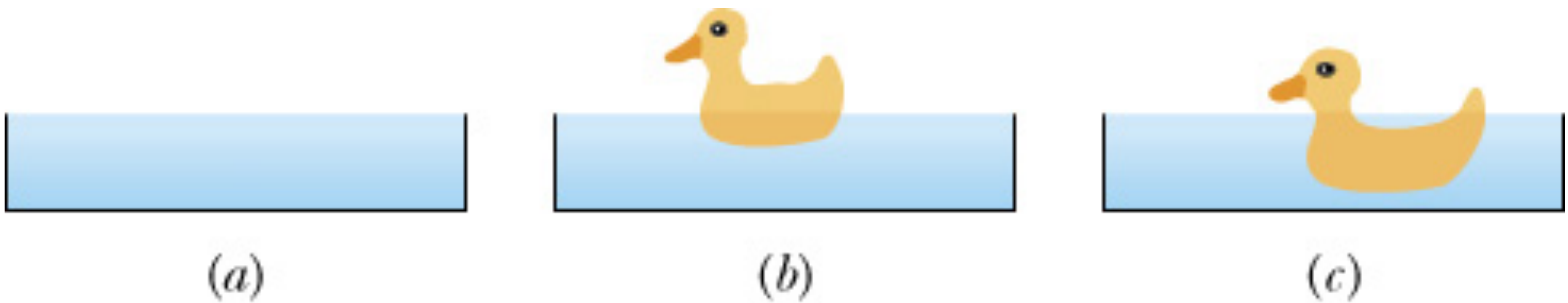


The buoyant force on a submerged object is equal to the weight of the fluid that is displaced by the object.

Apparent weight in a Fluid:

$$weight_{app} = weight_{actual} - F_b$$

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.



Answer: All have the same weight.

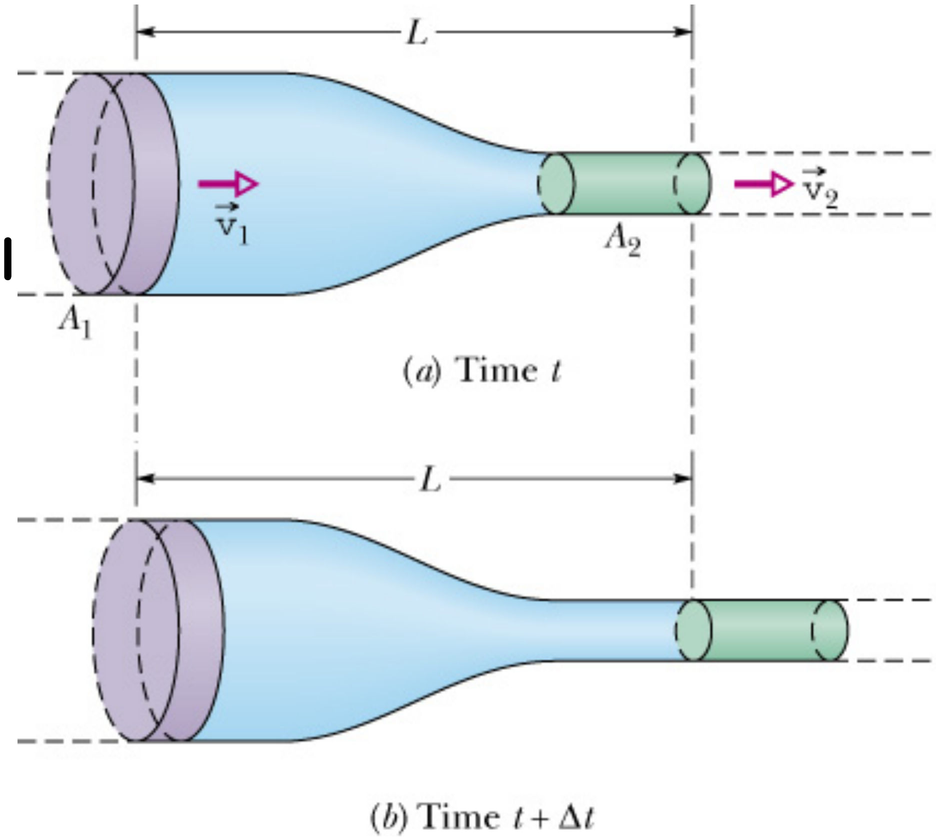
1.2. Ideal Fluids in Motion

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:

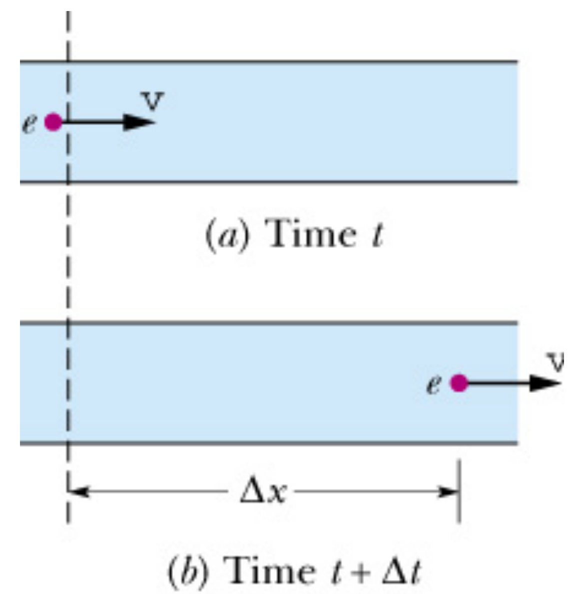
$$\Delta x = v\Delta t$$

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

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

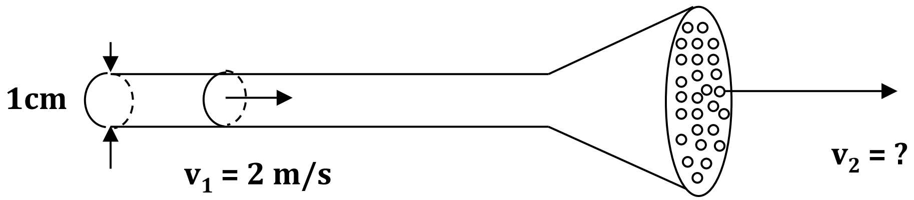
or

$$A_1 v_1 = A_2 v_2$$ (Equation of continuity)



- **Volume flow rate:** $R_V = A\,v$ = a constant
- **Mass flow rate:** $R_m = \rho\, R_V = \rho A v$ = a constant

Sample problem: 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? (Midterm 2014)



Using the equation of continuity, the speed v_2 is:

$$v_1 A_1 = v_2 A_2 = v_2 (40 a_0)$$

a_0 is the area of one hole

$$v_2 = \frac{v_1 A_1}{40 a_0} = \frac{2.0 \times \pi \left(\frac{1.0}{2}\right)^2}{40 \times \pi \left(\frac{0.05}{2}\right)^2} = 20 \text{ (m/s)}$$

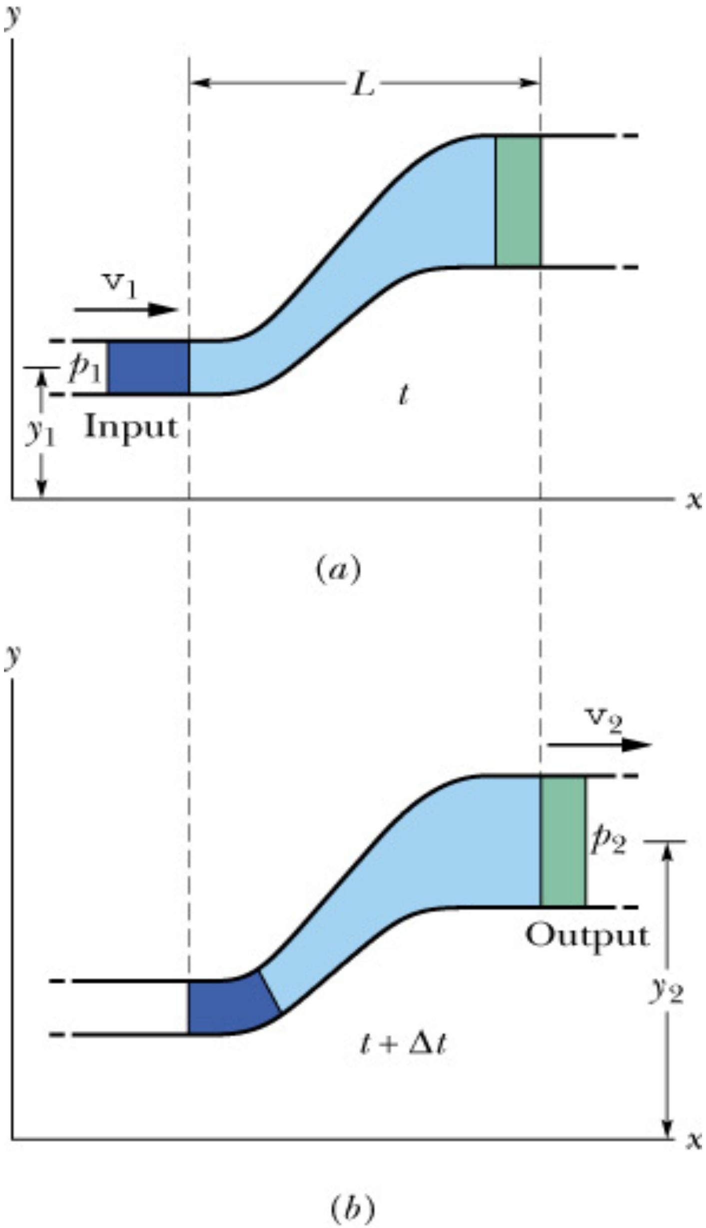
1.3. Bernoulli's Equation

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

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

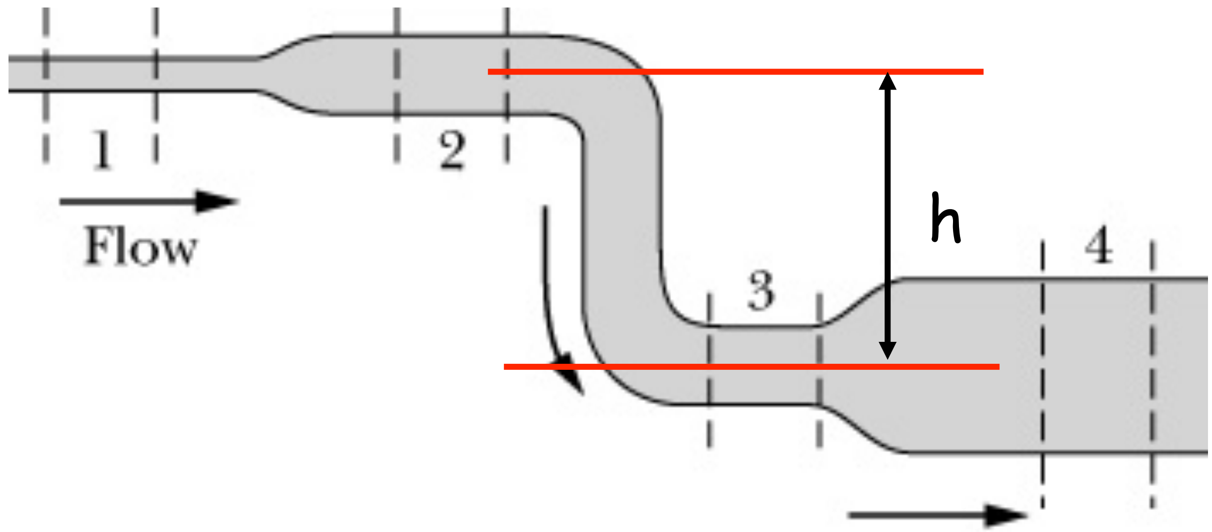
- If y=0: $p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$

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



Bernoulli's Principle

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.



$$R_V = A_1 v_1 = A_2 v_2 = A_3 v_3 = A_4 v_4$$

$$p_1 + \frac{1}{2}\rho {v_1}^2 + \rho g h = p_2 + \frac{1}{2}\rho {v_2}^2 + \rho g h = p_3 + \frac{1}{2}\rho {v_3}^2 = p_4 + \frac{1}{2}\rho {v_4}^2$$

(a) All tie; (b) 1, 2, 3, 4; (c) p_4, p_3, p_2, p_1

Keywords of the lecture:

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

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

2. *Gauge pressure* and *Absolute pressure*:

$$p_g = \rho g h$$

$$p = p_0 + p_g$$ (p_0: atmospheric pressure)

3. *Bouyant force* (Archimedes' principle):

$$F_b = \rho g V$$

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

$$R_V = Av$$

$$R_m = \rho R_V$$

Homework:

(1) Read "Proof of Bernoulli's Equation"

(2) Chapter 14: 1, 2, 5, 14, 17, 28, 38, 39, 48, 58, 64, 65, 71