Physics Notes Chapter 9 – Fluid Mechanics

Fluids

- ***Fluids*** are materials that flow, which include both *liquids* and *gases*. Liquids have a definite volume but gases do not. In our analysis of fluids it is necessary to understand the concepts of density and pressure. With solids it is often convenient to speak in terms of *mass* and *force*, whereas with fluids we often speak of *density* and *pressure*.
    - ***Mass density (ρ)*** of any substance is its mass (m) divided by its volume (V). The units of density are **kg/m³**. ***The density of water is 1000 kg/m³***. Density is an intrinsic property of matter. Equal volumes of different substances generally have different masses, so density depends on the nature of the material.

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

$$\boxed{\rho_{water} = 1000\ kg/m^3}$$

a. Is a piece of lead necessarily heavier than a piece of wood?

b. When we say lead is heavier than wood…what are we really meaning?

c. Which would have more volume, a kg of lead or a kg of wood?

d. Which would be more massive?

- **Density of solids and liquids will not change measurably under pressure…but the density of gases change when pressure changes.** Just because aluminum is less dense than lead does NOT mean that aluminum will compress when lead will not…it just tells us that in solids and liquids the atoms or molecules are already touching and do not compress much while gas molecules are not touching unless they are compressed into a solid.

    - ***Pressure*** is defined as *force per unit area*. Any fluid can exert a force perpendicular to its surface on the walls of its container. The force is described in terms of the pressure it exerts, or force per unit area. The units of pressure are **N/m² = Pa (Pascal)**. One atmosphere (1 atm) of pressure is equal to 101,000 Pa.

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

$$\boxed{1\ atm = 101{,}000\ Pa}$$

[Demo of Cartesian diver]

<u>Questions:</u>

h. A 95 lb. (mass = ~42 kg) woman exerts how much force (in N) on the floor?

i. Explain why the Cartesian diver works the way it does.

Example 1: If the woman mentioned in "question h" above has bare feet with each having a surface area of 0.025 m², what pressure would she exert on the floor?

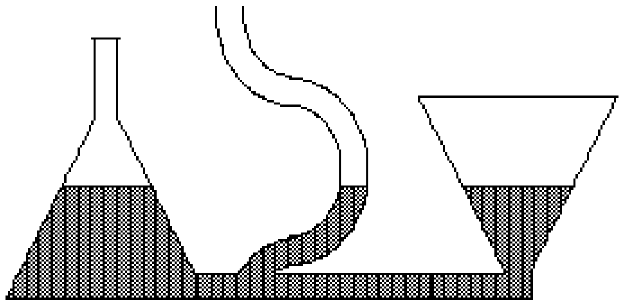
j. That would probably feel fairly good for her to walk on your tired, aching back to massage it…maybe? What if she was wearing high heels?

k. How much force would she exert on your back?

l. If the total surface area of the shoes was 0.0083 m^2, how much pressure would be exerted on your back?

Pressure in a fluid

- In the presence of gravity, the upper layers of a fluid push downward on the layers beneath it producing pressure within the fluid due to its own weight. The *pressure in a fluid increases with depth* because of the additional weight of the fluid above it. But strange as it might first seem, the increase in pressure only *depends upon depth and not volume*. Look at the diagrams below. The height of the fluid is the same in all three cases because the pressure is the same at equivalent heights even though they have different shapes and volumes.



- In an incompressible static fluid whose density **is ρ, the increase in pressure is calculated by ρgh ($\Delta P=\rho g\Delta h$) with *h* being the height below the reference point or $P=P_o+\rho gh$ where P_o is the pressure at one level and *P* is the pressure at a level that is *h* meters deeper.** P_o typically refers to the pressure at the surface of the fluid which would be 1atm or 101 kPa. ***Gauge pressure*** is the change in pressure relative to atmospheric pressure (calculated by $\Delta P=\rho g\Delta h$). ***Absolute pressure*** is the total pressure in a fluid which must include atmospheric pressure ($P=P_{atm}+\rho gh$).

  $P=P_o+\rho gh$

Demo of Pressure increasing with depth: 2 liter bottle with holes
http://paer.rutgers.edu/pt3/experiment.php?topicid=9&exptid=67

Questions:

m. Would the pressure on you be greater when swimming 3 meters deep in the middle of the ocean than when swimming 3 meters deep in an ocean tide pool?

n. Would the pressure on you be greater when swimming 3 meters deep in the middle of the ocean than when swimming 3 meters deep in a pond?

o. Why do you think that the tall grain silos have more closely spaced metal bands around it at the bottom than near the top?

p. What part of a dam across a river should be thickest…the bottom or the top? Or should it be the same thickness all the way from top to bottom?

q. If the pressure of our atmosphere can support a 0.760 meter column of Mercury and the density of Mercury is 13.6 times the density of water - How high could a column of water get if supported by that same pressure?

Atmospheric pressure

A glass is filled to the top with water. A piece of cardboard is placed over the top of the glass. The glass is then inverted
http://paer.rutgers.edu/pt3/experiment.php?topicid=9&exptid=75

Atmospheric Vs. Water pressure 1: A soda bottle is filled with water and a small space with air is left at the top. The cap is then put on. A hole is made in the side with a pin.
The hole is first plugged with the pin, then the pin is removed
http://paer.rutgers.edu/pt3/experiment.php?topicid=9&exptid=76

Atmospheric Vs. Water pressure 2: A soda bottle is filled with water and a small space with air is left at the top. The cap is then put on. Two holes at different heights are made in the side with a pin.
The holes are first plugged with the pin, then the two pins are removed.
http://paer.rutgers.edu/pt3/experiment.php?topicid=9&exptid=77

r. Could you drink soda through a straw that is 11 meters tall?

s. Could you drink soda through a straw if the soda container had an airtight lid?

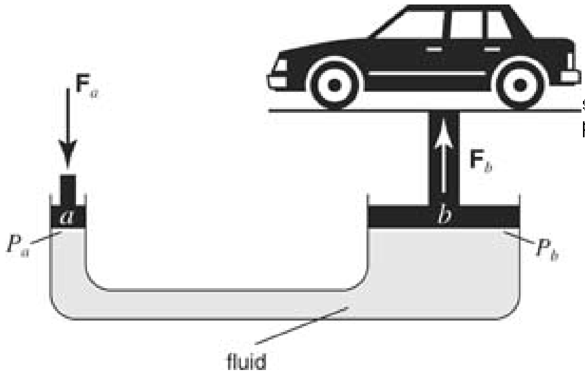
Atmosphere Crushing a 55 Gallon drum:
http://www.science.tv/watch/616d874afad0f44ba338/Crushing-a-Steel-Drum

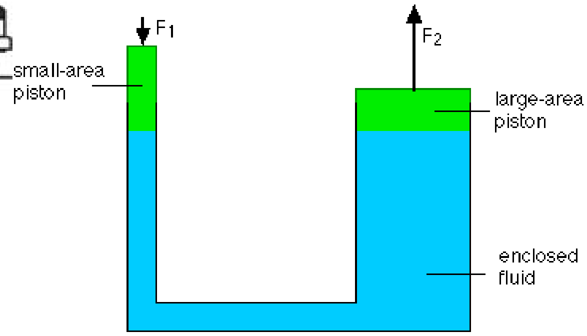
http://littleshop.physics.colostate.edu/Videos/Pressure/GallonDrum/GallonDrum.html

- ***Example 2.*** Calculate the absolute pressure and gauge pressure at an ocean depth of 1000 m.

Pascal's principle

- ***Pascal's principle*** states that if the pressure at one point in an incompressible fluid is changed, the pressure at every other point in the fluid changes by the same amount. Pascal's principle explains why only a small force is required to lift a massive object with a *hydraulic* lift. Look at the diagrams below. A small force applied to the small piston causes an equivalent increase in pressure at all points in the fluid. Since the pressure increases by the same amount at the large piston and $F=PA$, a larger area produces a larger force. Consequently, the entire weight of the car is supported by a much smaller force.



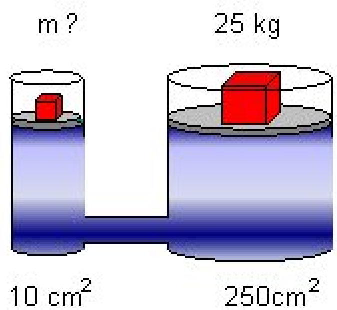


- Because the pressure is equal at equivalent heights, the forces exerted on the pistons are related by $F_1/A_1 = F_2/A_2$. The previous equation can be rearranged to show *that the force at the large piston is greater than the force at the small piston by a factor equal to the ratio of the areas of the two pistons.*

  $P_1 = P_2$ **at equivalent heights**

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

- ***Example 3.*** Determine the unknown mass in the diagram below.



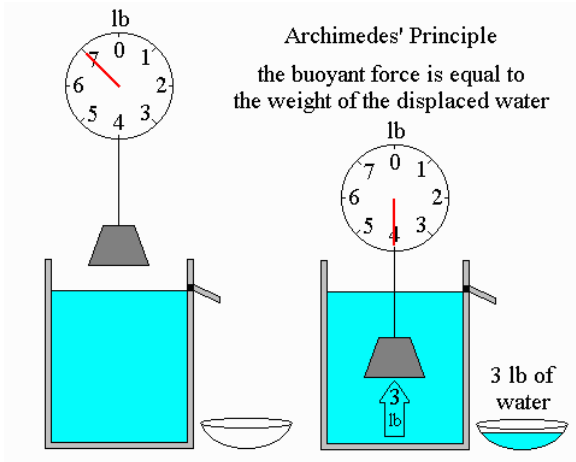
  - ***Example 4.*** The small piston of a hydraulic lift has an area of 0.20 m^2. A car weighing 12000 N sits on a rack mounted on the large piston. The large piston has an area of 0.90 m^2. How large a force must be applied to the small piston to support the car?

Archimedes' Principle

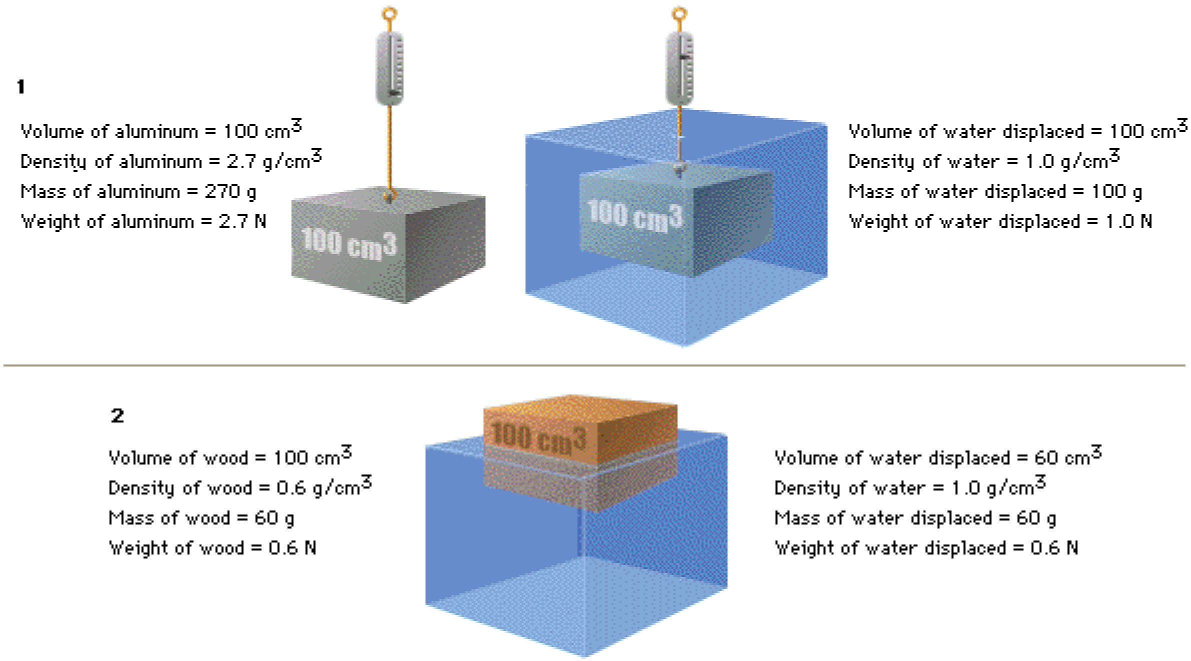
- Since pressure in a fluid increases with depth, an object immersed either partially or completely in a fluid will experience a greater pressure on the bottom than on the top. Because of this pressure difference, there is a net upward force that a fluid applies to an object in a fluid. We call this force the ***buoyant force.*** ***Archimedes' principle states that the magnitude of the buoyant force equals the weight (NOT just the mass) of the fluid that the immersed object displaces.***

  $\mathbf{F_{buoyant} = W_{displaced\ fluid}}$

$$F_{buoyant} = \rho g V_{fluid\ displaced}$$



- You should remember from chapter 4 that if an object remains at rest then the net force acting on the object is zero (Newton's 1st law). ***If an object floats*, the net force on the object must be zero and *the weight of the object must equal the buoyant force* which also must equal the weight of displaced fluid.** Diagram 2 below shows how the mass of the wood is equal to the mass of displaced water.



Archimedes Principle Observation experiment: Submerging objects attached to spring scales
http://paer.rutgers.edu/pt3/experiment.php?topicid=9&exptid=71

Questions:

t. Would a 1kg piece of lead sitting on the bottom of the ocean have more buoyant force on it than a 1kg piece of aluminum that also sank to the same depth?

u. Would the buoyant force be greater than the weight of the aluminum?

v. Which piece would have the greater pressure acting on its lowest part?

w. Would a 50cm^3 piece of lead have more buoyant force acting on it than a 50cm^3 piece of aluminum when they are both sitting as before?

F_{buoy} = Weight $_{displaced\ fluid}$ Since weight = mg and density is ρ = **m/V and m=ρV** the formula for buoyant force becomes:

$$\mathbf{F_{buoy} = (\rho V)g}$$

- ***SPECIAL CASE - If (<u>AND ONLY IF</u>) an object is floating … the buoyant force under those conditions then ALSO equals the <u>object's weight</u> (BUT <u>the buoyant force is ALWAYS equal to the weight of the FLUID displaced</u> – no special condition necessary for this one).***

Questions:

x. What is the buoyant force acting on a ten-ton ship floating in fresh water? In salt water? In a lake of mercury?

y. How would the volumes of the displaced liquids compare? Same? Smallest? Greatest?

z. Two solid blocks of identical size are released into a tank of water and sink to the bottom. One is made of lead and the other is aluminum. Which one has the greater buoyant force acting on it?

aa. Two solid blocks of identical size are released into a tank of water. One is made of lead and it sinks and the other is wood so it floats. Which one has the greater buoyant force acting on it?

Helium balloon and air
Predict what will happen when liquid nitrogen is poured over a balloon filled with helium.
http://paer.rutgers.edu/pt3/experiment.php?topicid=8&exptid=82

bb. Does the air exert a buoyant force on you?

cc. Does the air exert buoyant force on an air-filled balloon? Why does it fall down then?

dd. Does the air exert buoyant force on a helium-filled balloon? Why does it fly upward?

Balloon in a "car" with air inside at atmospheric pressure is given a sudden push. Car accelerates forward.
http://paer.rutgers.edu/pt3/experiment.php?topicid=8&exptid=79

ee. Would a helium filled balloon sink, rise, or just float if released on the moon?

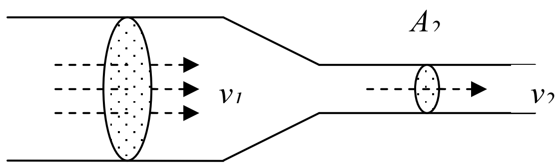
A partially inflated balloon is placed in a bell jar. A vacuum pump is then turned on and the air inside the bell jar is pumped out. Predict what will happen to the balloon.
http://paer.rutgers.edu/pt3/experiment.php?topicid=8&exptid=81

Helium balloon and air's buoyant force
Predict what will happen when liquid nitrogen is poured over a balloon filled with helium.
http://paer.rutgers.edu/pt3/experiment.php?topicid=8&exptid=82

- ***Example 4.*** A bargain hunter purchases a "gold" crown and wants to determine if the crown is made of pure gold. After she gets home, she hangs the crown from a scale and finds its weight to be 7.84 N. She then weighs the crown while it is immersed in water and the scale reads 6.86 N. Is the crown made of pure gold? (Hint – find the density of the crown and compare to the known density of gold.)

Equation of continuity

- Note that in our analysis of fluid flow, we will consider each fluid as an *ideal fluid* and the flow to be *steady*. Ideal fluids are incompressible and non-viscous (lose no kinetic energy due to friction).
- The ***equation of continuity*** *is a result of conservation of mass*, **what flows into one end of a pipe must flow out the other end**, assuming there are no additional entry or exit points. Since mass is conserved, the speed of fluid flow must change if the cross-sectional area of the pipe changes. Look at the diagram below. A_2 is smaller than A_1 so v_2 must be larger than v_1.



- The ***mass flow rate*** **(in kg/s) of a fluid with a density ρ, flowing with a speed v in a pipe of cross-sectional area A, is the mass per second flowing past a point and is given by ρAv.** Since mass must be conserved, the mass of the fluid passing through A_1 must be the same as the mass of the fluid passing through A_2.

If the density of the fluid is ρ_1, and the density of the fluid at A_2 **is** ρ_2, the *mass flow rate* through A_1 **is** $\rho_1 A_1 v_1$, and the mass flow rate through A_2 is $\rho_2 A_2 v_2$. Thus, by conservation of mass,

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2$$

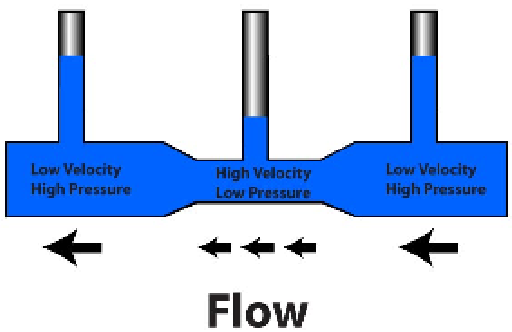
This relationship is the ***equation of continuity***. For an ideal fluid (incompressible) the density of the fluid is the same at all points in the pipe and the equation becomes

$A_1 v_1 = A_2 v_2$ *Av* is *volume flow rate* and has the units m^3/s.

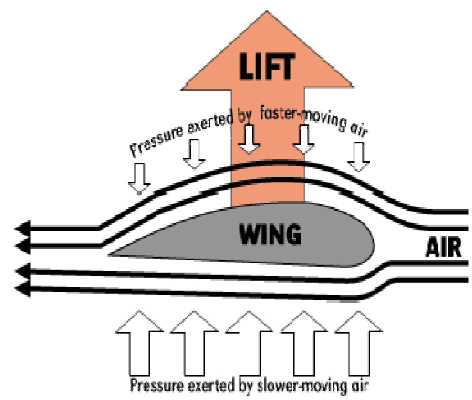
- ***Example 4.*** A horizontal pipe has a circular cross section where the diameter diminishes from 3.6 m to 1.2 m. If the velocity of water flow is 3.0 m/s in the larger part of the pipe, what is the velocity of flow in the smaller part of the pipe?

Bernoulli's principle

- ***Bernoulli's principle*** *is a result of conservation of energy in dynamic fluids and is used to find pressure changes in a fluid due to changes in fluid speed.* Conservation of energy shows that the energy per unit volume of a moving fluid must remain constant. As a result if there is no change in height and kinetic energy increases then pressure must decrease. Simply stated *if the speed of a fluid increases the pressure exerted by that fluid decreases and vice-versa.* Look at the diagram below. From the equation of continuity you know that the speed of the fluid is greater in the narrower portion of the pipe. Since the speed is larger in the narrower section the pressure is smaller resulting in a shorter column of fluid above it.



$$P_1+\frac{1}{2}\rho v_1{}^2=P_2+\frac{1}{2}\rho v_2{}^2$$



- Bernoulli's principle is used to explain many phenomena in nature, such as why a spinning ball curves and why you are pushed towards passing traffic. But probably the most often cited example of Bernoulli's principle is in relation to the design of airplane wings. As shown below, airplane wings are designed so that the speed of air above the wing is greater than at the bottom of the wing. Since the speed is greater, the pressure is less, producing a net upward force due to the difference in pressure.

[Demos of each of the following and then these questions.]

<u>Questions:</u>

ff. Why does the ping-pong ball stay in the airstream from the hair dryer?

gg. Why do the cans do what they do when you blow a stream of air between them?

hh. Why does the paper come up when you blow across the top?

ii. How does the "atomizer" work?

Physics I Practice Problems Ch. 9: p. 343-345. #'s 2, 3, 4, 5, 9, 10, 12, 13, 15, 16, 19, 22, 31, and 37a