Kirkuk University

Science College

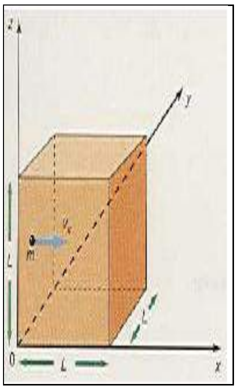
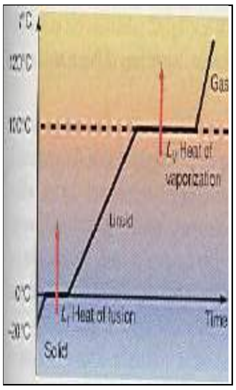
Physics Department

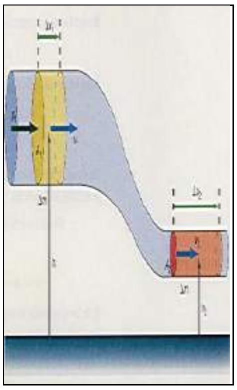
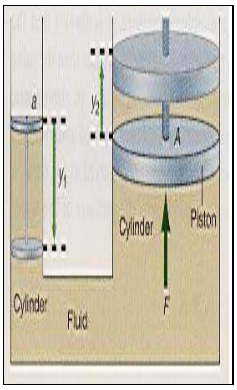
Lectures of

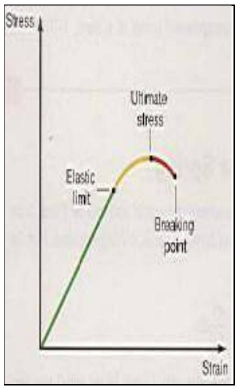
Properties of Matter

Lecture =2=

Static Fluids



Assistant professor Dr.Jawdet Hedayet Mohammed

Lecturer in Kirkuk University

Science College – Physics Department

2.1 Introduction

Matter is usually said to exist in three phases: solid, liquid, and gas.

Solids are hard bodies that resist deformations, whereas liquids and gases have the characteristic of being able to flow.

A liquid flows and takes the shape of whatever container in which it is placed.

A gas also flows into a container and spreads out until it occupies the entire volume of the container.

A fluid is defined as any substance that can flow, and hence liquids and gases are both considered to be ***fluids*****.**

Liquids and gases are made up of billions upon billions of molecules in motion and to properly describe their behavior, Newton's second law should be applied to each of these molecules.

However, this would be a formidable task, if not outright impossible, even with the use of modern high-speed computers.

Also, the actual motion of a particular molecule is sometimes not as important as the overall effect of all those molecules when they are combined into the substance that is called the fluid.

Hence, instead of using the microscopic approach of dealing with each molecule, we will treat the fluid from a macroscopic approach.

That is, we will analyze the fluid in terms of its large-scale characteristics, such as its mass, density, pressure, and its distribution in space.

The study of fluids will be treated from two different approaches.

First, we will consider only fluids that are at rest.

This portion of the study of fluids is called **fluid statics or hydrostatics.**

Second, we will study the behavior of fluids when they are in motion.

This part of the study is called **fluid dynamics or hydrodynamics.**

Let us start the study of fluids by defining and analyzing the macroscopic variables.

2.2 Density

*The **density** of a substance is defined as the amount of mass in a unit volume of that substance.*

We use the symbol **(ρ)** (the lower case Greek letter rho) to designate the density and write it as:

$$\boxed{\rho = \frac{m}{V} \quad ...(2-1)}$$

A substance that has a large density has a great deal of mass in a unit volume, whereas a substance of low density has a small amount of mass in a unit volume.

Density is expressed in SI units as **(kg/m^3),** and occasionally in the laboratory as **(g/cm^3)**.

Densities of solids and most liquids are very nearly constant but the densities of gases vary greatly with temperature and pressure.

Table (2.1) is a list of densities for various materials.

Table : (2-1)

Densities of Various Materials

Substance	kg/m³
Air (0 ºC, 1 atm pressure)	1.29
Aluminum	2,700
Benzene	879
Blood	1.05×10^3
Bone	1.7×10^3
Brass	8,600
Copper	8,920
Critical density for universe to collapse under gravitation	5×10^{-27}
Planet Earth	5,520
Ethyl alcohol	810
Glycerine	1,260
Gold	19,300
Hydrogen atom	2,680
Ice	920
Interstellar space	10^{-18}-10^{-21}
Iron	7,860
Lead	11,340
Mercury	13,630
Nucleus	1×10^{17}
Proton	1.5×10^{17}
Silver	10,500
Sun (avg)	1,400
Water (pure)	1,000
(sea)	1,030
Wood (maple)	620-750

We observe from the table that in interstellar space the densities are extremely small, of the order of **10^{-18}** to **10^{-21} kg/m³**.

That is, interstellar space is almost empty space.

The density of the proton and neutron is of the order of **10^{17} kg/m³**, which is an extremely large density.

Hence, the nucleus of a chemical element is extremely dense.

Because an atom of hydrogen has an approximate density of **2680 kg/m³**, whereas the proton in the nucleus of that hydrogen atom has a density of about **1.5×10^{17} kg/m³**, we see that the density of the nucleus is about **10^{13}** times as great as the density of the atom.

Hence, an atom consists almost entirely of empty space with the greatest portion of its mass residing in a very small nucleus.

2.3 Pressure

Pressure *is defined as the magnitude of the normal force acting per unit surface area.*

The pressure is thus a scalar quantity.

We write this mathematically as:

$$\boxed{P = \frac{F}{A} \ldots (2-2)}$$

The SI unit for pressure is newton/meter^2, which is given the special name Pascal, in honor of the French mathematician, physicist, and philosopher, Blaise Pascal (1623-1662) and is abbreviated **(Pa)**.

Hence, **1 Pa = 1 N/m^2**.

Pressure exerted by a fluid is easily determined with the aid of figure **(2.1)**, which represents a pool of water.

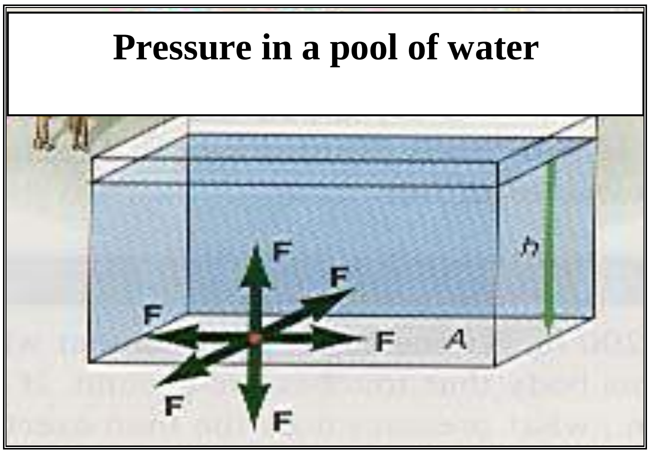


Figure (2.1) **: Pressure in a pool of water.**

We want to determine the pressure**(*p*)** at the bottom of the pool caused by the water in the pool.

By our definition, equation **(2.2)**, the pressure at the bottom of the pool is the magnitude of the force acting on a unit area of the bottom of the pool.

But the force acting on the bottom of the pool is caused by the weight of all the water above it.

Thus:

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

$$\boxed{P = \frac{w}{A} = \frac{mg}{A} \ldots (2-3)}$$

We have set the weight ***w*** of the water equal to ***(mg)*** in equation **(2.3)**.

The mass of the water in the pool :

$$\boxed{m = \rho.V \ldots (2-4)}$$

The volume of all the water in the pool is just equal to the area ***(A)*** of the bottom of the pool times the depth (***h)*** of the water in the pool, that is:

$$\boxed{V = A.h \ldots (2-5)}$$

Substituting equations **(2.4)** and (**2.5)** into equation **(2.3)** gives for the pressure at the bottom of the pool:

$$P = \frac{mg}{A} = \frac{\rho Vg}{A} = \frac{\rho Ahg}{A}$$

Thus:

$$\boxed{P = \rho gh \ldots (2-6)}$$

(Although we derived equation **(2.6)** to determine the water pressure at the bottom of a pool of water, it is completely general and gives the water pressure at any depth ***(h)*** in the pool.)

Equation **(2.6)** says that the water pressure at any depth ***(h)*** in any pool is given by the product of the density of the water in the pool, the acceleration due to gravity **(*g*),** and the depth ***(h)*** in the pool.

*Equation **(2.6)** is sometimes called **the hydrostatic equation.***

Just as there is a water pressure at the bottom of a swimming pool caused by the weight of all the water above the bottom, there is also an air pressure exerted on every object at the surface of the earth caused by the weight of all the air that is above us in the atmosphere.

That is, there is an atmospheric pressure exerted on us, given by equation **(2.2)** as:

$$\boxed{P = \frac{F}{A} = \frac{weight of air}{area} \quad ...(2.7)}$$

However we cannot use the same result obtained for the pressure in the pool of water, the hydrostatic equation (**2.6)**, because air is compressible and hence its density **(ρ)** is not constant with height throughout the vertical portion of the atmosphere.

The pressure of air at any height in the atmosphere can be found if we know the density variation in the atmosphere.

However, the variation in density is also a function of the temperature of the air and can be found by use of the ideal gas equation which we will cover in Lecture **5**.

Until then we will revert to the use of experimentation to determine the pressure of the atmosphere.

The pressure of the air in the atmosphere was first measured by Evangelista Torricelli (**1608-1647**), a student of Galileo, by the use of a mercury **barometer.**

A long narrow tube is filled to the top with mercury, chemical symbol **Hg**.

It is then placed upside down into a reservoir filled with mercury, as shown in figure **(2.2)** .

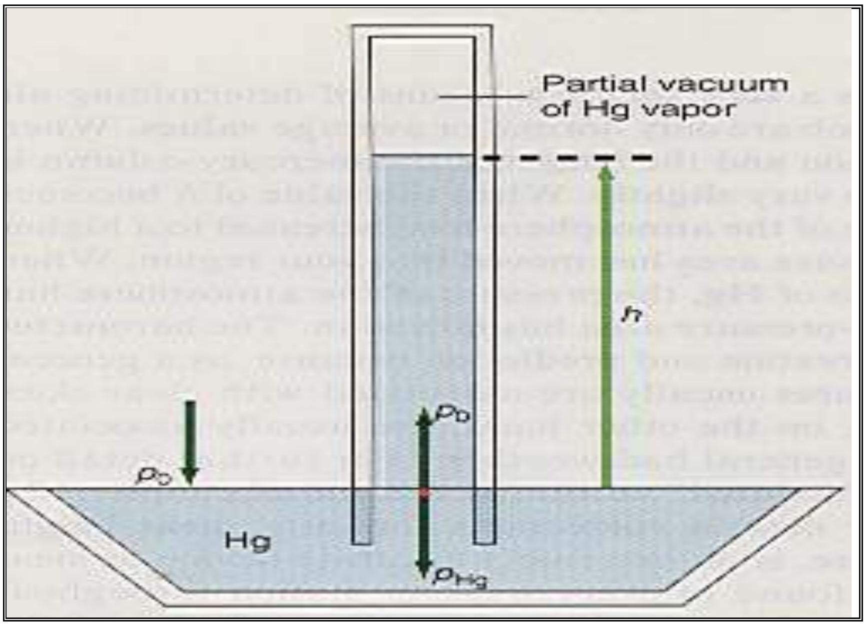


Figure (2.2) **: A mercury barometer.**

The mercury in the tube starts to flow out into the reservoir, but it comes to a stop when the top of the mercury column is at a height ***(h)*** above the top of the mercury reservoir, as also shown in figure **(2.2)**.

The mercury does not empty completely because the normal pressure of the atmosphere **(p_0)** pushes downward on the mercury reservoir.

Because the force caused by the pressure of a fluid is the same in all directions, there is also a force acting upward inside the tube at the height of the mercury reservoir, and hence there is also a pressure p_0 acting upward as shown in figure **(2.2)**.

This force upward is capable of holding the weight of the mercury in the tube up to a height **(*h*).**

Thus, the pressure exerted by the mercury in the tube is exactly balanced by the normal atmospheric pressure on the reservoir, that is:

$$\boxed{P_o = P_{Hg} \ldots (2-8)}$$

But the pressure of the mercury in the tube (**p_{Hg}**), given by equation **(2.6)**, is:

$$\boxed{P_{Hg} = \rho_{Hg} gh \ldots (2-9)}$$

Substituting equation **(2.9)** back into equation **(2.8)**, gives:

$$\boxed{P_o = P_{Hg} gh \ldots (2-10)}$$

Equation **(2.10)** says that normal atmospheric pressure can be determined by measuring the height **(h)** of the column of mercury in the tube.

It is found experimentally, that on the average, normal atmospheric pressure can support a column of mercury **(76.0 cm**) high, or **(760 mm**) high.

The unit of **(1.00 mm)** of **Hg** is sometimes called a torr in honor of Torricelli.

Hence, normal atmospheric pressure can also be given as **(760** torr).

Using the value of the density of mercury of **1.360×10^4 kg/m^3**, found in table **(2.1)**, normal atmospheric pressure, determined from equation **(2.10)**, is:

$$p_0 = \rho_{Hg} g h = \left(1.360 \times 10^4 \frac{kg}{m^3}\right)\left(9.80 \frac{m}{s^2}\right)(0.760\ m)$$

$$= 1.013 \times 10^5\ N/m^2 = 1.013 \times 10^5\ Pa$$

Now that we have discussed atmospheric pressure, it is obvious that the total pressure exerted at a depth ***(h)*** in a pool of water must be greater than the value determined previously, because the air above the pool is exerting an atmospheric pressure on the top of the pool.

This additional pressure is transmitted undiminished throughout the pool.

Hence, the total or *absolute pressure* observed at the depth ***(h)*** in the pool is the sum of the atmospheric pressure plus the pressure of the water itself, that is:

$$\boxed{P_{abs} = P_o + P_w ...(2-11)}$$

Using equation **(2.6),** this becomes

$$\boxed{P_{abs} = P_o + \rho g h ...(2-12)}$$

2.4 Pascal's Principle

The pressure exerted on the bottom of a pool of water by the water itself is given by **(ρgh).**

However, there is also an atmosphere over the pool, and, as we saw in section **(2.3)**, there is thus an additional pressure, normal atmospheric pressure **(p_0)**, exerted on the top of the pool.

This pressure on the top of the pool is transmitted through the pool waters so that the total pressure at the bottom of the pool is the sum of the pressure of the water plus the pressure of the atmosphere, equations **(2.11)** and **(2.12)**.

The addition of both pressures is a special case of a principle, called ***Pascal's principle*** *and it states that if the pressure at any point in an enclosed fluid at rest is changed* **(Δp)**, *the pressure changes by an equal amount* **(Δp)**, *at all points in the fluid.*

As an example of the use of Pascal's principle, let us consider the hydraulic lift shown in figure **(2.3)**.

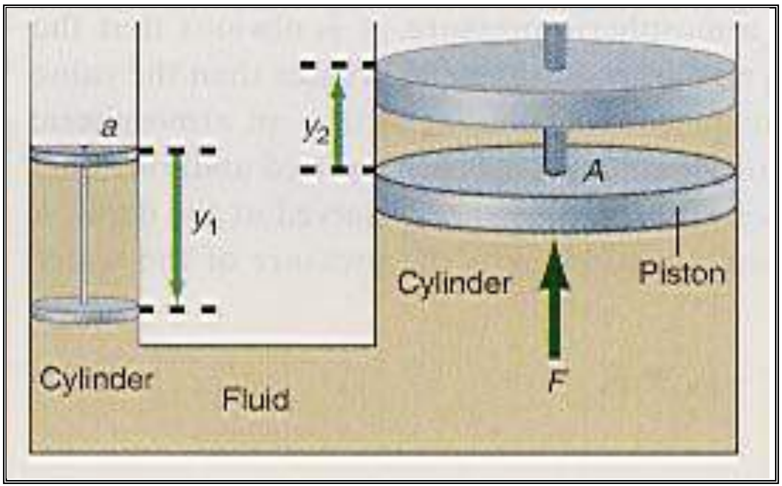


Figure (2.3) **: The hydraulic lift.**

A noncompressible fluid fills both cylinders and the connecting pipe.

The smaller cylinder has a piston of cross-sectional area ***(a)*,** whereas the larger cylinder has a cross-sectional area ***(A)***.

As we can see in the figure, the cross-sectional area ***(A)*** of the larger cylinder is greater than the cross-sectional area ***(a)*** of the smaller cylinder.

If a small force ***(f)*** is applied to the piston of the small cylinder, this creates a change in the pressure of the fluid given by:

$$\boxed{\Delta p = \frac{f}{a} \quad ...(2.13)}$$

But by Pascal's principle, this pressure change occurs at all points in the fluid, and in particular at the large piston on the right.

This same pressure change applied to the right piston gives:

$$\boxed{\Delta P = \frac{F}{A} \quad ...(2.14)}$$

where ***(F)*** is the force that the fluid now exerts on the large piston of area **(*A*).**

Because these two pressure changes are equal by Pascal's principle, we can set equation **(2.14)** equal to equation **(2.13)**. Thus:

$$\Delta P = \Delta p$$

$$\frac{F}{A} = \frac{f}{a}$$

The force ***(F)*** on the large piston is therefore:

$$\boxed{F = \frac{A}{a} f \ldots(2-15)}$$

Since the area ***(A)*** is greater than the area ***(a)*****,** the force ***(F)*** will be greater than ***(f)*****.**

Thus, the hydraulic lift is a device that is capable of multiplying forces.

It is interesting to compute the work that is done when the force ***(f)*** is applied to the small piston in figure **(2.3)**.

When the force ***(f)*** is applied, the piston moves through a displacement **(**y_1**),** such that the work done is given by:

$$W_1 = f y_1$$

But from equation **(2.13)** :

$$f = a\Delta p$$

Hence, the work done is :

$$\boxed{W_1 = a(\Delta p) y_1 \ldots(2-16)}$$

When the change in pressure is transmitted through the fluid, the force ***(F)*** is exerted against the large piston and the work done by the fluid on the large piston is:

$$W_2 = F y_2$$

where **(**y_2**)** is the distance that the large piston moves and is shown in figure **(2.3)**.

But the force **(*F*),** found from equation **(2.14)**, is:

$$F = A\Delta P$$

The work done on the large piston by the fluid becomes:

$$\boxed{W_2 = A(\Delta p) y_2 \ldots(2-17)}$$

Applying the law of conservation of energy to a frictionless hydraulic lift, the work done to the fluid at the small piston must equal the work done by the fluid at the large piston, hence:

$$\boxed{W_1 = W_2 ...(2-18)}$$

Substituting equations **(2.16)** and **(2.17)** into equation **(2 .18)**, gives:

$$\boxed{a(\Delta p)y_1 = A(\Delta P)y_2 ...(2-19)}$$

Because the pressure change **(Δ*p*)** is the same throughout the fluid, it cancels out of equation **(2.18),** leaving:

$$ay_1 = Ay_2$$

Solving for the distance **(y_1)** that the small piston moves

$$\boxed{y_1 = \frac{Ay_2}{a} ...(2-20)}$$

Since ***(A)*** is much greater than **(*a*),** it follows that **(y_1)** must be much greater than **(y_2).**

2.5 Archimedes' Principle

The variation of pressure with depth has a surprising consequence, it allows the fluid to exert buoyant forces on bodies immersed in the fluid.

If this buoyant force is equal to the weight of the body, the body floats in the fluid.

This result was first enunciated by Archimedes (**287-212** BC) and is now called Archimedes' principle.

Archimedes' principle *states that a body immersed in a fluid is buoyed up by a force that is equal to the weight of the fluid displaced.*

This principle can be verified with the help of figure **(2.4)**.

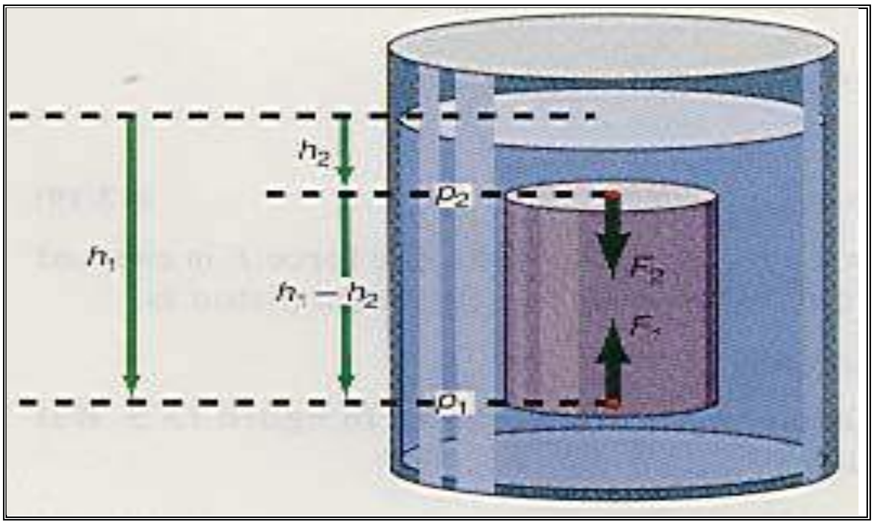


Figure 2.4 **: Archimedes' principle.**

If we submerge a cylindrical body into a fluid, such as water, then the bottom of the body is at some depth **(h_1)** below the surface of the water and experiences a water pressure **(p_1)** given by :

$$P_1 = \rho g h_1 \ldots (2-21)$$

where **(ρ)** is the density of the water.

Because the force due to the pressure acts equally in all directions, there is an upward force on the bottom of the body.

The force upward on the body is given by :

$$\boxed{F_1 = P_1 A ...(2-22)}$$

where ***(A)*** is the cross-sectional area of the cylinder.

Similarly, the top of the body is at a depth **(h_2)** below the surface of the water, and experiences the water pressure **(p_2)** given by :

$$\boxed{P_2 = \rho g h_2 ...(2-23)}$$

However, in this case the force due to the water pressure is acting downward on the body causing a force downward given by :

$$\boxed{F_2 = P_2 A ...(2-24)}$$

Because of the difference in pressure at the two depths, **(h_1)** and **(h_2)**, there is a different force on the bottom of the body than on the top of the body.

Since the bottom of the submerged body is at the greater depth, it experiences the greater force.

Hence, there is a net force upward on the submerged body given by :

$$\text{Net force upward} = F_1 - F_2$$

Replacing the forces **(F_1)** and **(F_2)** by their values in equations **(2.22)** and **(2.24)**, this becomes :

$$\text{Net force upward} = p_1 A - p_2 A$$

Replacing the pressures **(p_1)** and (**p_2**) from equations **(2.21)** and **(2.23)**, this becomes :

$$Net force upward = \rho g h_1 A - \rho g h_2$$

$$\boxed{Net force upward = \rho g A(h_1 - h_2) ...(2-25)}$$

But :

$$A(h_1 - h_2) = V$$

the volume of the cylindrical body, and hence the volume of the water displaced.

Equation **(2.25)** thus becomes :

$$\boxed{Net force upward = \rho g V ...(2.26)}$$

But **(ρ)** is the density of the water and from the definition of the density :

$$\rho = \frac{m}{V} ...(2-1)$$

Substituting equation **(2.1)** back into equation **(2.26)** gives:

$$Net force upward = \frac{mgV}{V} = mg$$

But ***mg*** **=** ***w***, the weight of the water displaced.

Hence:

$$\boxed{Net force upward = Weight of water displaced ...(2.27)}$$

The net force upward on the body is called the *buoyant force* **(BF).**

When the buoyant force on the body is equal to the weight of the body, the body does not sink in the water but rather floats.

Since the buoyant force is equal to the weight of the water displaced, *a body floats when the weight of the body is equal to the weight of the fluid displaced.*

The Language of Physics

Lecture 2: (Static Fluids)

Fluids

A fluid is any substance that can flow.

Hence, liquids and gases are both considered to be fluids .

Fluid statics or hydrostatics

The study of fluids at rest .

Fluid dynamics or hydrodynamics

The study of fluids in motion .

Density

The amount of mass in a unit volume of a substance .

Pressure

The magnitude of the normal force acting per unit surface area .

The hydrostatic equation

An equation that gives the pressure of a fluid at a particular depth .

Barometer

An instrument that measures atmospheric pressure .

Pascal's principle

If the pressure at any point in an enclosed fluid at rest is changed, the pressure changes by an equal amount at all points in the fluid .

Archimedes' principle

A body immersed in a fluid is buoyed up by a force that is equal to the weight of the fluid displaced.

A body floats when the weight of the body is equal to the weight of the fluid displaced .

Summary of Important Equations

Lecture 2: (Static Fluids)

Density	$\rho = \dfrac{m}{V}$
Mass	$m = \rho V$
Pressure	$p = \dfrac{F}{A}$
Hydrostatic equation	$p = \rho g h$
Force	$F = pA$
Absolute and gauge pressure	$p_{abs} = p_{gauge} + p_0$
Hydraulic lift	$F = \dfrac{A}{a} f$ $y_1 = \dfrac{A}{a} y_2$
Archimedes' principle	Buoyant force = Weight of water displaced $BF = w_{water} = w_{wood}$ $w_{water} = m_{water}\, g = \rho_{water} V g = \rho_{water} A h g$ $\rho_{water} A h g = w_{wood}$ $h = \dfrac{w_{wood}}{\rho_{water} A g}$

Problems for Lecture

Lecture 2: (Static Fluids)

Problem 2.1

Your own water bed

A person would like to design a water bed for the home. If the size of the bed is to be **(2.20 m)** long, **(1.80 m)** wide, and **(0.300 m** deep), what mass of water is necessary to fill the bed? What is the weight of the water ?

Answer : (1190 kg) , (11600 N)

Problem 2.2

Pressure exerted by a man

A man has a mass of **(90 kg)**. At one particular moment when he walks, his right heel is the only part of his body that touches the ground. If the heel of his shoe measures **(9 cm)** by **(8.30 cm)**, what pressure does the man exert on the ground?

Answer : (1.18×10^5 N/m^2)

Problem 2.3

Pressure exerted by a woman

A **(45.0-kg)** woman is wearing "high-heel" shoes. The cross section of her high-heel shoe measures **(1.27 cm)** by **(1.80 cm)**. At a particular moment when she is walking, only one heel of her shoe makes contact with the ground. What is the pressure exerted on the ground by the woman?

Answer : (1.93×10^6 N/m^2)

Problem 2.4

Pressure in a swimming pool

Find the water pressure at a depth of **(3 m)** in a swimming pool.

Answer : (2.94 x 10^4 N/m^2 (Pa))

Problem 2.5

Why you get tired by the end of the day

The top of a student's head is approximately circular with a radius of **(8.90 cm)**. What force is exerted on the top of the student's head by normal atmospheric pressure?

Answer : (2520 N)

Problem 2.6

Atmospheric pressure on the walls of your house

Find the force on the outside wall of a ranch house, **(3.05 m)** high and **(10.7 m)** long, caused by normal atmospheric pressure.

Answer : (3.30 x 10^6 N)

Problem 2.7

Absolute pressure

What is the absolute pressure at a depth of **(3 m)** in a swimming pool? **:**

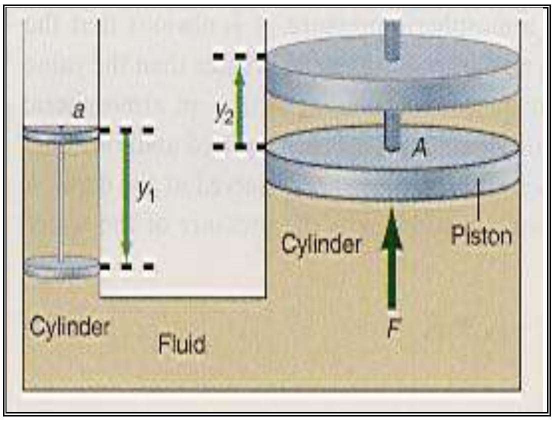
Answer : (1.31 x 10^5 N/m^2 (Pa))

Problem 2.8

Amplifying a force

The radius of the small piston in figure below is **(5 cm)**, whereas the radius of the large piston is **(30 cm)**. If a force of **(2 N)** is applied to the small piston, what force will occur at the large piston?

Answer : (72.1 N)



Problem 2.9

You can never get something for nothing

The large piston of problem **2.8** moves through a distance of **(0.200 cm)**. By how much must the small piston be moved**?**

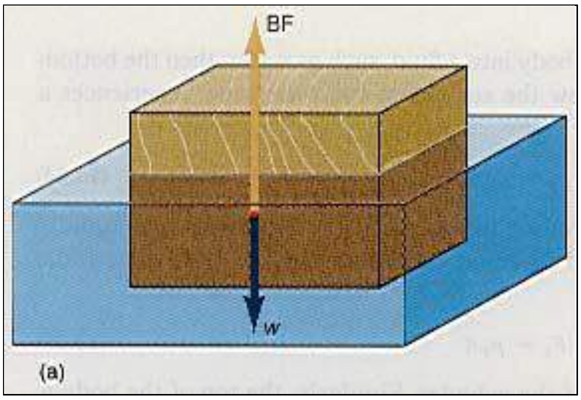
Answer : (7.21 cm)

Problem 2.10

Wood floats

A block of oak wood **(5 cm)** high, **(5 cm)** wide, and **(10 cm)** long is placed into a tub of water, figure below , the density of the wood is **(7.20×10^2 kg/m^3).** How far will the block of wood sink before it floats?

Answer : (0.0359 m)



Problem 2.11

Iron sinks

Repeat problem **2.10** for a block of iron of the same dimensions , then calculate the buoyant force on this piece of iron **?**

Answer : (0.394 m) , (2.45 N)