## TEACHING SCIENCE BY OCEAN INQUIRY <br> Pressure

Nine activities are described below. Explanations are provided after the instructions.
Goals: The activities below address different aspects of pressure. Activity $\mathbf{1}$ is a simple activity that can help students understand the concept and definition of pressure. Pressure is not a force but a force per unit area. Activity 2 deals with how our body perceives pressure and can be used to address some misconceptions about it. It can also be used as a discrepant event. Activities 3-4 both deal with the concept of hydrostatic pressure, [i.e., the force that is exerted on a unit area by the weight of a fluid column (air or water) above it]. It is related to the pressure changes that you feel in your ears when diving or during take off and landing when flying. Both activities help students relate the relationship between pressure, the height of a fluid column, and its density.

Activities 5-6 address the effect of pressure on compressible and incompressible fluids (air and water, respectively). Both activities can be taught in the context of the physiology of diving and deep sea creatures. In Activity 5 students quantify the compressibility of gases when subjected to pressure that is higher than atmospheric pressure, while Activity 6 is a qualitative demonstration of the effect of low/high pressure on fluids. Activity 7 provides several examples for demonstrating the Bernoulli's effect, that is, pressure changes associated with moving fluids (all previous activities deal with fluids at rest, that is, 'hydrostatic').

Two optional activities are included (if time allows). Activity 8 demonstrates the Pascal principle. In other words, how hydraulic lifts work. Activity 9 addresses the relationship between air volume and pressure and can be used as a discrepant event.

## 1. Bed of Nails



## Materials:

- Two square wooden boards (same size). One board with a single nail in the center; the other board with a grid of nails (15 X 15 nails)
- Ring stand
- A ring serving as a weight (fitted with a clear piece of tubing to make it easy to slide along the stand-pole) or another weight
- Balloons


## Instructions:

1. Why can you get injured stepping on one nail while a person lying on a bed of nails does not get injured?
2. Fill a balloon with air (this experiment will not work well if the balloon is only partially full).
3. Place the balloon on the bed of nails (board with 15 X 15 nails). What do you think will happen to the balloon when you place the weight (ring) on it and push against it?
4. Test your prediction.
5. Take the board with one nail and hold the balloon gently above the nail so it barely touches it. What do you think will happen to the balloon when you place the weight (ring) on it?
6. Test your prediction
7. How would you explain your observations?

## 2. Perception of Weight



## Materials:

- Large hollow steel ball
- Small hollow steel ball
- Two large funnels
- A scale
- Caliper(s) (large enough to measure the diameter of the large ball)


## Instructions:

You have two steel balls (a big and a small one).

1. Hold each ball in one palm of your hand. Which one is heavier?
2. Choose a volunteer and cover his/her eyes. Place each ball in a funnel and ask the volunteer to hold each funnel at its collar. Ask the volunteer which ball is heavier and record his/her answer. Repeat this experiment with another volunteer(s).
3. Was the perception of weight in the "blind" test different from the original one from (1)? Why?
4. Weigh the balls to determine which one is heavier. Explain your observations.

## 3. Hydrostatic Pressure



## Materials:

- One pipe with one small exit hole near the bottom and seven large holes plugged with rubber stoppers
- One pipe with three different size holes drilled in it (around the tube's perimeter, all at the same height)
- A large tub
- Ruler
- A jug with water
- Paper towels


## Instructions:

Part A. You have a pipe with one small exit hole near the bottom and several large holes plugged with rubber stoppers. By removing a stopper and letting water flow through one of the large holes, you can fix the height of the water column above the exit hole.

1. What do you expect will happen when you fill the tube with water and open the exit hole? Explain your expectations in terms of the forces acting on the fluid.
2. What do you expect will happen when the water height above the exit hole is increased? Why?

Begin by removing the lowest rubber stopper. Hold your finger over the small exit hole, and fill the pipe with water until it runs out the hole the stopper was in. Measure the height of the water column above the exit hole. Then let the water run out the small exit hole while you keep filling the pipe with water to maintain the same height of water column above the exit hole. Note how far the water travels (when it first strikes the ruler). Plug the stopper back and repeat the steps for the four lowest holes.
3. Plot the distance at which the water hit the ruler as a function of the height of the water column for each of the holes. Do the data match your expectations?
4. Would the results change if you have a bigger hole in the middle? If so, how? Why?

Part B. Take the second pipe (with three holes of different sizes). Cover all three holes with your fingers and fill the pipe with water until it reaches the marked line. Uncover one hole at a time and measure the distance at which the water first strikes the ruler. Does your observation agree with your prediction at 4 ?

4. Manometer


## Materials:

- A U-shaped manometer (made of supplies that can be found at any hardware store: clear plastic tube, cut into three pieces and two elbows to connect the pieces of tube)
- Water
- Oil
- Equilibrium tube \#1- tubes of different shapes (Sciencekit.com)
- Equilibrium tube\#2- tubes of different diameters (Sciencekit.com)


## Instructions:

A manometer is a device that measures pressure. What is the principle of operation?

## Part A

1. Predict what will happen when you fill the U-shaped manometer with water? Will the water level be equal in both arms? Why? (Hint: if the water is at rest (no flow along the tube), what can you say about the pressure at the bottom of each arm? Draw a diagram.
2. Test your prediction.
3. What do you think will happen if you add oil into one arm? Will the fluid height in both arms remain the same? Why? If you predict a change draw a diagram of the new equilibrium.
4. Add oil to test you prediction.

## Part B

5. Look at equilibrium tube \#1 (with different shaped arms): what will happen when you fill the large arm with water? Predict the water level in each arm (relative to each other). Draw a diagram of your prediction and explain your reasoning to your team mates.
6. Test your prediction.
7. Does your observation agree with your prediction? If not, how would you revise your explanation?

## Part C

8. Now use equilibrium tube \#2 (different arm diameters).
9. Predict what will happen when you fill the large arm with water. Draw a diagram of your prediction and explain your reasoning to your team mates.
10. Test your prediction. Does it behave as expected? If not, how would you revise your explanation?

## 5. Compressibility of Gases



## Materials:

- Compressibility of gases apparatus (Arbor Scientific)
- Weights


## Instructions:

1. Record the volume of air in the syringe under conditions of atmospheric pressure.
2. Place a weight on the top of the syringe ( 2.5 lbs ). How do you think the weight will affect the volume of the air in the syringe? What is the pressure within the syringe?
3. Record the volume of air.
4. Place additional weights on the block of wood ( $5 \mathrm{lbs}, 10 \mathrm{lbs}$ and 15 lbs ). What do you observe?
5. Record the weight and the corresponding volumes of air and plot the weight vs. volume. How does the volume depend on pressure?
6. By what percentage did the pressure increase in the syringe compared to the atmospheric pressure (when the 15 lb mass is loaded, and noting that the cross-section of the syringe is $\sim 1 \mathrm{in}^{2}$ ). Under normal atmospheric conditions pressure $\left.=14.7 \mathrm{lb} / \mathrm{in}^{2}\right)$ ? By what percentage did the volume of the syringe change when the 15 lbs of weight were added (assuming no change in temperature) ? Is it consistent with the ideal gas law ( $\mathrm{P} \sim 1 / \mathrm{V}$, where P is pressure and V is the volume of the gas)?
7. Using your data, how do you expect the volume of the lungs of a free diver to change when diving to 10 m ? (Pressure increases by one atmosphere ( $\sim 14.7 \mathrm{lb} / \mathrm{in}^{2}$ ) for every 10 $\mathrm{m})$.
8. Vacuum


## Materials:

- A kitchen vacuum container
- Pressure apparatus (soda bottle)
- Balloon filled with air
- Balloon filled with water
- Marshmallow (or shaving cream)

Note: you can add any other items to be tested (e.g., tangerine, cherry tomato, cork, etc.)

## Instructions:

1. Explore the effect of pressure on the two balloons. Place the balloon filled with air in the container and evacuate the air from the container by using the hand pump. What happens to the balloon? Now release the valve, allowing air to get back into the container. What happens to the balloon now?
2. Repeat this experiment with the balloon that is filled with water. How does the effect of pressure differ between the two balloons? Why?
3. Based on your observations what do you think will happen to the marshmallow when you evacuate the container?
4. Draw a face on a marshmallow and test your prediction. Now, release the valve and observe the marshmallow. Explain your observations.
5. Explore the second pressure apparatus. Compare/contrast your observations on the behavior of the balloon in this apparatus to the behavior of the balloon in the vacuum container. What is the difference between this apparatus and the vacuum chamber?

## Challenge:

1. How would you get a balloon full of air into the soda bottle?
2. How could you use this apparatus to demonstrate that air has weight?

## 7. Bernoulli



## Materials:

- Bernoulli Bag (Arbor Scientific)
- A candle
- A straw
- A piece of paper
- Bernoulli apparatus: includes glass manometer (3 arms) fitted with a Bernoulli device and a piece of tubing
- Vacuum pump
- Food coloring


## Instructions:

Part A. Fill the glass manometer with dyed water so that the water level is at about $1 / 3$ of the arms length. Connect the piece of tubing to the outflow port of the vacuum pump.

1. What do you predict will happen to the water level at each of the arms when you turn on the pump? Draw a diagram and discuss your reasoning with your group.
2. Turn on the pump and observe the water level at each arm. Does it meet your prediction and explanation? If not, how would you revise your explanation?
Part B. Below are three challenges. Experiment and explain them using what you have learned from your observations in Part A.
3. Can you fill the bag in one breath? Have a friend hold the bag at the knotted end so the bag is horizontal.
4. Can you tilt the flame of a candle to the left side/right side using a straw? (Be careful not to touch the flame or the candle)
5. Hold a piece of paper just under your bottom lip. Can you lift horizontally without touching it with your other hand?

What is the common physical principle in all these experiments? Discuss it with your group. Hint: draw the pressure distribution in each of these experiments.

OPTIONAL ACTIVITIES

## 8. Pascal Press



## Materials:

- Pascal demonstrator (Hydraulic jack) (sciencekit.com)


## Instructions:

1. You have a large and a small syringe. If you have to push liquid from one syringe to another which will be harder to push, the large or the small one? Why?
2. Push each side and determine which one requires more force?
3. Given that work = force X distance, and that the same work is done in both cases, how much more force is required to push one syringe the same distance relative to the other?
(Hint: what relevant parameter varies between the two syringes? By how much?)

## 9. Balloon in a Glass



## Materials:

- Differential pressure bottle demonstration kit (obtained from Arbor Scientific or sciencekit.com, but you can make your own using a soda bottle, see example).
- Balloons


## Instructions:

1. Remove the stopper and place a balloon in the lipped opening of the glass ball (or bottle). Fill the balloon with air until it fills the entire volume. Let go. What happens?
2. Blow into the balloon again and insert the stopper in the hole of the glass globe (or plastic bottle) while still blowing. Remove your mouth from the balloon. What is happening now?
3. Release the stopper and empty the balloon. Put the stopper back in and fill the balloon. What is happening now?
4. Explain your observations in terms of forces, pressure, elasticity of balloon, and fluid expansion.

## PRESSURE: EXPLANATIONS FOR LAB ACTIVITIES

## 1. Pressure

Pressure ( P ) is defined as force ( F ) per unit area (A): $\mathrm{P}=\mathrm{F} / \mathrm{A}$. The ring applies a force on the balloon. When you place the balloon on the single nail this force is distributed on a small area and the pressure is high enough to pop the balloon. When you place the balloon on the bed of nails the same force is now distributed over a larger area. The pressure is therefore smaller and you need to apply a larger force to pop the balloon. For that same reason lying on a bed of nails can feel prickly but will not hurt you while stepping on one nail may poke a hole in your foot.

## 2. Perception of Weight

This is an activity that stresses the difference between force (i.e., weight) and pressure (force per unit area).The mass of the large ball is 144 g and the small ball is 128.7 g .

When you hold the balls in your hands the smaller ball exerts more pressure on your hand (smaller surface area; $\mathrm{P}=\mathrm{F} / \mathrm{A}$, where P is pressure, F is force and A is surface area) making it feel heavier. When you hold the balls in the funnels, the surface area to which the force applies is similar for both balls and they appear to be of equal mass (or the more sensitive of you may say the larger ball is slightly heavier).

## 3. Hydrostatic Pressure

The weight of the water column exerts pressure on the water at the level of the hole (imagine a cross-sectional area of the tube at the level of the hole). This pressure is higher compared to the pressure outside the hole, causing water to shoot out once the stopper has been removed.

As the height of the water column above the exit hole increases, the pressure difference (between the inside and the outside of the exit hole) increases causing the water to shoot to a larger
distance. Recall, hydrostatic pressure is given by $\mathrm{P}=\rho \mathrm{gh}$, where P is pressure, $\rho$ is the density of water, $g$ is the gravitational acceleration and $h$ is the height of the water column above the hole. Since $\rho$ and $g$ are constant in this case, if $h$ increases $P$ increases (the contribution of air pressure is the same on both sides of the hole).

Except for very small holes (where friction becomes important), the size of the hole will not change the distance at which the water travels. One way to look at this problem is to consider pressure ( $\rho g h$ ) as the potential energy ( PE ) per unit volume ( $\mathrm{PE}=\mathrm{mgh}$, where m is mass, thus, $\mathrm{PE} / \mathrm{V}=\mathrm{mgh} / \mathrm{V}=\rho \mathrm{gh}$, where V is volume). As a parcel of water squirts out of the column most of this energy is transformed to kinetic energy ( $\mathrm{KE}=\rho v^{2} / 2$, where $v$ is the velocity perpendicular to the hole). Thus, the velocity and hence the distance a given fluid travels does not depend on the size of the hole and is only a function of $h$ (conservation of energy: $P E=K E ; \rho g h=\rho v^{2} / 2$ and thus $v=\sqrt{2 g h}$. When the hole is very small, some energy is lost to friction on the side of the hole, and thus the velocity is reduced compared to larger holes.

## 4. Manometer

A manometer is a pressure-measuring device. The simplest form of a manometer is a U-shaped tube, filled with a fluid. When both arms of the manometer are open, the fluid will be at the same height at each arm (if the height is not equal in both arms, the pressure at the bottom of the arm with the higher column of fluid will be higher compared to the pressure at the bottom of the other arm and fluid will flow from high to low pressure). When pressure is applied to one arm, the fluid will be pushed down in that arm and up in the other arm. The difference in height of fluid between the two arms indicates the pressure difference.

Part A. The level of the water in each arm of the manometer is determined by the pressure that the air column + the water column exert on the bottom of the arm. When you fill the arm of the manometer with water and let the system reach an equilibrium there is no flow in the system, meaning that the pressure at the bottom of both tubes is hydrostatic and must be equal ( $\mathrm{P}_{1}=\mathrm{P}_{2}$ and $\mathrm{P}_{1}=g \rho_{\text {water }} \mathrm{h}_{1}+\mathrm{P}_{\text {air }} \quad \mathrm{P}_{2}=g \rho_{\text {water }} \mathrm{h}_{2}+\mathrm{P}_{\text {air }}$ ). When oil is added into one arm then the system is allowed to reach an equilibrium, $\mathrm{P}_{1}=\mathrm{P}_{2}$ and $\mathrm{P}_{1}=\mathrm{g}\left(\rho_{\text {water }} \mathrm{h}_{\text {water }}+\rho_{\text {oil }} \mathrm{h}_{\text {oil }}\right)$ and $\mathrm{P}_{2}=\mathrm{g} \rho_{\text {water }} \mathrm{h}_{\text {water }}$. Since $\rho_{\text {oil }}<\rho_{\text {water }}, \mathrm{h}_{\text {oil }}$ must be $>\mathrm{h}_{\text {water }}$ and the fluid column in the arm with water + oil will be higher than that in the arm with water only.

Part B. The same principle applies to the equilibrium tubes. The height of the water (or any other fluid) column in each arm is only a function of the pressure and the density of the fluid ( $\mathrm{h}=$ $\mathrm{P} / \mathrm{\rho g}$ ) and is not affected by the shape or cross-sectional area of the tube. Since the pressure at the bottom of each arm of equilibrium tube $\# 1$ is equal (no flow), the height of the water will be the same for each arm, regardless of its shape.

Part C. The same principle applies to equilibrium tube \#2, where the height of the water is NOT a function of the diameter of the tube's arm, except when the diameter becomes small enough that surface tension becomes important. Therefore, the height of the water column will be the same for each arm. The only exception to this statement involves the thinnest arm, for which surface tension at the rim of the glass acts to pull the water to a higher level.

## 5. Compressibility of Gases

Under normal atmospheric pressure ( $14.7 \mathrm{lb} / \mathrm{in}^{2}$ ), the volume of air in the syringe is 46 ml . For any gas at constant temperature ( T ), the volume $(\mathrm{V})$ of the gas varies inversely to the pressure applied to the gas (Boyles' Law: under constant mass and temperature the product of the pressure ( P ) and volume of a gas ( V ) is constant $\rightarrow \mathrm{PV}=\mathrm{c} ; \mathrm{P} \propto 1 / \mathrm{V}$ where $\propto$ means "is proportional to"). Thus the addition of weight (increase in pressure) will reduce the volume of air in the syringe.

| Weight added (lbs) | Volume of air in the syringe (ml) |
| :---: | :---: |
| 0 | 46 |
| 2.5 | 40 |
| 5 | 35 |
| 7.5 | 31.5 |
| 10 | 28 |
| 12.5 | 26 |
| 15 | 23.5 |

Adding 15 lbs of weight to the syringe doubles the pressure (compared to normal atmospheric pressure) and the volume of air in the syringe decreases by half, as expected from Boyle's Law.

When a free diver descends to a depth of 10 m the pressure he/she experiences doubles. As a result, the volume of his/her lungs will be reduced by half.

## 6. Vacuum

When you pump air out of the container, the pressure in the container decreases. Objects that contain air cavities (e.g., balloon with air, marshmallow) are now able to expand compared to their size under atmospheric pressure. Since water is to a large extent an incompressible fluid, the size of the balloon containing water will be the same under low pressure and under atmospheric pressure. A marshmallow contains air pockets and will expand when you create a vacuum in the container. When you release the valve, air rushes back into the container, increasing the pressure (until it reaches atmospheric pressure) and the marshmallow will shrink.

In the second apparatus (soda bottle), the hand pump pumps air into the bottle, increasing the pressure within the bottle, causing the balloon with the air to shrink. When you open the cap of the bottle, pressure is released and the balloon expands back to its original size.

You can use this apparatus to demonstrate that air has weight by weighing the apparatus, then pumping air inside, and weighing the apparatus again.

## 7. Bernoulli

Please refer to the pressure review handout for background about Bernoulli principle. The handout contains a diagram showing the pressure changes in a Bernoulli apparatus.

When you turn on the pump air is moving in the Bernoulli apparatus. When the moving air approaching the constriction (narrow part of the apparatus) it accelerates and the total pressure at the constriction drops, resulting in a lower local pressure above the middle arm of the manometer. Because pressure is lower at the middle arm water will flow from the two end arms into the middle arm (from high pressure to low pressure) and once the system reaches an equilibrium the water level in the middle arm will be higher compared to the water level at the two end arms.

All these experiments can be explained using Bernoulli's Principle (see pressure review handout).

When you hold the bag close to your mouth and blow, air rushes into the bag. If you are blocking the passage of air from outside the bag into the bag (by holding the bag's opening around your mouth), the only air that fills the bag comes from your lungs. When you hold the bag a few inches away from your mouth and blow toward the bag, you create a stream of air with a higher velocity and hence lower pressure. The air around the opening of the bag is under higher pressure compared to the region of the blown air and therefore more air rushes into the bag and you can fill it in "one breath".


Similarly, you can move the flame to the left/right by using a straw to blow air on either side of the flame. By blowing air you create a region of low pressure (according to Bernoulli's Principle: higher velocity, lower pressure). Air will flow from the surrounding higher pressure to the region of low pressure causing the flame to tilt towards the location of lower pressure.


Lastly, when you place the piece of paper below your lower lip and blow, you create a region of higher velocity and low pressure above the paper. Below the paper, the pressure is higher causing it to lift.


## 8. Pascal Press

According to Pascal's law, pressure that is applied to any part of a confined fluid is transmitted equally in all directions to all parts of the fluid (i.e., as you push the syringe pressure will increase everywhere equally). Thus, both syringes experience the same pressure. Since the larger syringe has a larger surface area (cross sectional area) and F = AP, you have to apply a larger force in order to push the liquid. This is the principle behind any hydraulic system.

For a given amount of work and lifting distance, you need to apply less force on a smaller cross sectional area compared to a larger cross sectional area.

$$
\text { Work }=\mathrm{F} * \text { distance }(\mathrm{d}) \text { and } \mathrm{P}=\mathrm{F} / \mathrm{A}
$$

Since the cross sectional area of the larger syringe is four times that of the smaller syringe, in order to push it the same distance (d) as the small syringe, you need to apply four times the force that you would apply to the small syringe.

$$
\text { Work }=\mathrm{P}_{1} \mathrm{~A}_{1} \mathrm{~d}_{1}=\mathrm{P}_{2} \mathrm{~A}_{2} \mathrm{~d}_{2}
$$

Since $P_{1}=P_{2}$

$$
\mathrm{d}_{1} / \mathrm{d}_{2}=\mathrm{A}_{2} / \mathrm{A}_{1}
$$

## 9. Balloon in a Glass

When you blow into a balloon you exert a pressure on the rubber wall of the balloon. When the pressure exceeds that of the surrounding air plus the inward pressure that is exerted by the rubber wall (due to elastic force of the rubber resisting stretching), the balloon will expand. When the pressure of the air outside, combined with the elastic force of the rubber equals the force of the inner air pressure, the balloon stops expanding.

The air pressure inside the balloon is always higher than the air pressure of the surrounding air because the wall of the balloon pushes back as air inside pushes out. When you stop blowing and let go, air will flow out from the higher pressure area inside the balloon to the lower pressure area surrounding the balloon and the balloon will deflate. By inserting the stopper while still blowing the balloon you can control the air pressure around the balloon

After inserting the stopper, you have sealed the air inside the glass globe. The inward elastic forces of the rubber wall of the balloon act to shrink the balloon. That results in an increase in the volume of the air between the balloon and the glass wall and the air pressure outside the balloon decreases allowing the balloon to remain inflated (recall the law of ideal gas: $\mathrm{PV}=\mathrm{nRT}$; for a constant temperature $\mathrm{P} \sim 1 / \mathrm{V}$ ). The pressure of the air surrounding the balloon + the inward pressure exerted by the rubber wall now equal the pressure inside the balloon. When you try to blow the balloon with the stopper inserted in the hole, you will find it difficult. The reason for that is that when you attempt to blow into the balloon inside the sealed glass globe, the volume of air trapped between the wall of the balloon and the wall of the glass globe decreases and as a result its pressure increases, making it more difficult to blow.

