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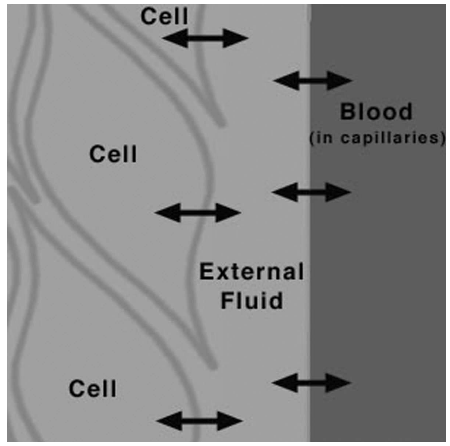
LAB 13:
FLUIDS



Fluids are an important part of our body

OBJECTIVES

- To learn how some fundamental physical principles apply to fluids.
- To understand the difference between force and pressure.
- To confirm that the static pressure in a fluid is proportional to depth.
- To verify the equation of continuity for fluid flow.
- To verify energy conservation in fluid flow.

OVERVIEW

Fluid Properties

When most people think of the word fluid, they imagine a liquid like water. In physics, the term fluid refers to any substance that adjusts its shape in response to its container. Fluid can be either liquids or gases. It is hard to imagine a topic in physics with which we have more personal experience to draw upon than the physics of fluids. Whether it be breathing, drinking, swimming, walking etc, we spend our days immersed in and interacting with various types of fluids. Ironically, given such a depth of experience, we know less about how to describe many aspects of fluids than we do about several other areas of physics. In some ways, the ability of fluids to change shape, to flow, and to separate makes it difficult to study.

In order to study an object, we need to define some quantitative properties of that object. Because a fluid is free to change its shape or breakup into smaller pieces, the density of a fluid is an important property. The density of a fluid is defined as its mass divided by its volume and is represented by the symbol ρ:

$$\text{Density} \qquad \rho = \frac{M}{V} \tag{1}$$

where M is the mass of a fluid with volume V. The SI units of density are kg/m^3. In this lab, we will be working with two fluids, water and air whose densities are 1000 kg/m^3 and 1.20 kg/m^3 respectively. The air density is for our altitude and room temperature.

Force and Pressure

When dealing with fluids, it is generally more convenient to talk about pressure rather than forces. Pressure is a measure of the amount of force F acting on an object per area A:

$$\text{Pressure} \qquad P = \frac{F}{A} \tag{2}$$

(Pressure has the SI units N/m^2; 1 Pascal = 1 Pa = 1 N/m^2. We will often use kilopascal (kPa) in this lab.) We prefer to talk about pressure rather than force when dealing with fluids because when a fluid interacts with an object, it flows around the object and applies a force on the object which is everywhere normal to the objects surface. One example of this is the pressure exerted on us by the air around us, called atmospheric pressure or P_{atm}. This pressure, a result of the weight of the air above us is equal to about 14.7 pounds per square inch or 101.326 kPa (kilo Pascals). For a person of average height, with a front surface area of 1,550 in^2, this corresponds to a total force of about 22,700 pounds! Of course the net force we feel is zero since the air pushes on us equally from all directions.

In many real life situations, we are interested in the difference between a given pressure P and atmospheric pressure. This quantity is called the gauge pressure P_g and is defined as

$$\text{Gauge Pressure} \qquad P_g = P - P_{atm} \tag{3}$$

The pressure sensors you will be using in this lab measure gauge pressure rather than absolute pressure. They are calibrated to measure zero when the pressure is 101.326 kPa, which is normal atmospheric pressure.

Pressure and Depth

If you have ever tried to swim under water or flown in an airplane, you will have experienced the fact that the pressure in a fluid under the influence of gravity changes with depth. This change in pressure is due to the weight of the fluid above the point in question. As you swim under the water, there is more water above you the deeper you go. Imagine a cylindrical swimming pool of area A. The force on the top layer of water is down and is due to atmospheric pressure. It has the value

$$F_{top} = P_{atm} A \tag{4}$$

where A is the area of the pool.

At the bottom of the pool, the downward force is F_{top} plus the weight of the water above it. If the water has density ρ_w and the depth of the pool is h, the weight W of this water is

$$W = Mg = \rho_w Vg = \rho_w (Ah)g \quad (5)$$

where g is the acceleration due to gravity. The force F_{bottom} at the bottom of the pool is due to F_{top} and the weight of the water above. We have

$$F_{bottom} = F_{top} + W = P_{atm} A + \rho_w (Ah)g$$

(6)

The pressure P_{bottom} at the bottom is simply F_{bottom}/A and has the value

$$P_{bottom} = \frac{F_{bottom}}{A} = \frac{P_{atm} A + \rho_w (Ah)g}{A} = P_{atm} + \rho_w gh \quad (7)$$

We could just as well have done this calculation for a general depth h, so this result holds in general for the pressure P in a fluid at depth h:

$$P = P_{atm} + \rho_w gh \quad (8)$$

This is an important result that we will verify in Investigation 1.

Pascal's Principle

We can see from Equation (8) that, if the atmospheric pressure were to change, this change would be felt at all depths in the fluid. This property is referred to as Pascal's principle, which states that any external pressure applied to a fluid is transmitted undiminished throughout the liquid and onto the walls of the containing vessel. We will explore a common application of Pascal's principle namely the hydraulic lift in Investigation 2.

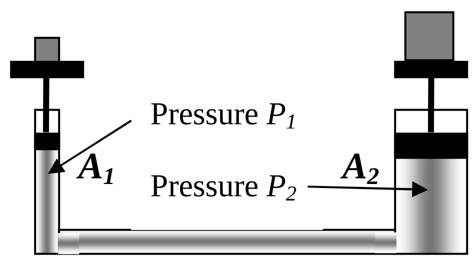


Figure 1: Hydraulic Lift

Suppose you have two connected pipes with different cross-sectional areas A_1 and A_2 which have pistons in them as in Figure 1. If the system is in equilibrium, the pressure in the fluid connecting the two pistons is the same so that

$$P_1 = P_2 \quad \text{or} \quad \frac{F_1}{A_1} = \frac{F_2}{A_2} \qquad \Rightarrow \qquad F_2 = F_1 \frac{A_2}{A_1} \quad (9)$$

Because the pressure of the liquid under both pistons is the same, the forces acting on each piston differ depending upon the area over which the pressure is acting. If the ratio of the two areas is large, large forces can be generated on one side by applying a small force to the other. We observe from Eq. (9) that, if A_2 is much larger than A_1, then F_2 is much larger than F_1.

Fluid in Motion

In Investigation 3, we will study fluid dynamics. We will explore Bernoulli's equation through the use of a Venturi tube. A Venturi tube is a pipe with a narrow constriction in it. The pressure of the fluid in the tube can be measured by attaching sensors at different places along the tube as shown in Figure 2.

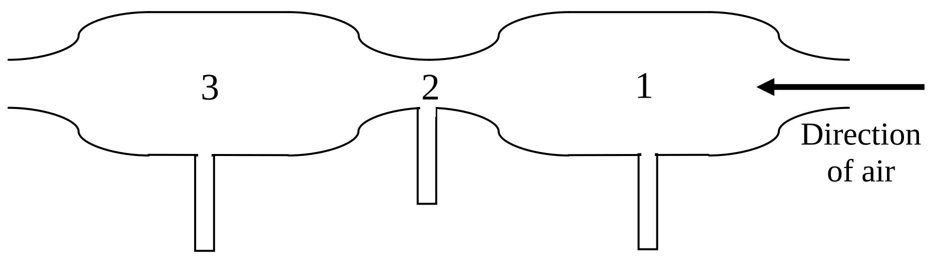


Figure 2: Venturi Tube: The pressure in the tube at points 1, 2 or 3 can be measured by connecting the pressure sensor to the tube openings.

The equation of continuity for fluids states that for fluid flow in two regions 1 and 2, we must have the relation

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2 \tag{10}$$

As air flows through the tube, it encounters the constriction at point 2. We will assume that the air is not compressed as it goes through the constriction so that $\rho_1 = \rho_2$. This assumption is valid as long as the absolute pressure difference between points 1 and 2 is less than 1%. It will be useful to define the flow rate *FR* of a fluid as the cross-sectional area of flow times the speed. The flow rate gives the volume of air passing a certain point per unit time and is a constant for incompressible fluids, which we are assuming air to be (not a good assumption).

The general form of Bernoulli's equation states that

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 . \tag{11}$$

where we have assumed an unchanging density ρ. If we consider a horizontal fluid flow, we have $h_1 = h_2$, and Eq. (11) simplifies to

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \tag{12}$$

We use Equations (10) and (12) to solve for the pressure difference between points 1 and 2 in terms of the flow rate of the air in the tube:

$$\Delta P = P_2 - P_1 = C(FR)^2 \tag{13}$$

where

$$FR = \text{ flow rate } = A_1 v_1 = A_2 v_2 \tag{14}$$

and the constant C is

$$C = \frac{1}{2}\rho \frac{1}{A_1^2}\left(\frac{A_1^2}{A_2^2} - 1\right) \tag{15}$$

We will verify these results in Activity 3-2.

INVESTIGATION 1: STATIC EQUILIBRIUM IN FLUIDS

In this investigation we will verify that the pressure at any point in a fluid depends on the external pressure acting on the fluid and the weight of fluid above the point in question as given by Equation (8). The sensors used in this investigation actually measure the gauge pressure P_g. The pressure measured by the sensor P_{sensor} will then be, according to Eqs. (3) and (8),

$$P_{sensor} = P_g = P - P_{atm} = \rho g h \tag{16}$$

You will need the following:

- 500 ml cylinder
- stand with clamps for sensor and tube
- low pressure sensor
- tubing with stopper
- graduated glass tube

ACTIVITY 1-1: PRESSURE DEPENDENCE ON DEPTH

Be careful that no water enters the pressure sensor. This could ruin it.

1. Set up the apparatus as shown in Figure 3. The pressure sensor is connected to the small diameter glass tube by a small tube with a black rubber stopper on the end. Make sure the stopper is inserted into the flared end of the small glass tube so that air cannot escape through that end. Notice the markings on the glass tube. These markings represent a volume measurement in units of milliliters but you will use them to measure depth.

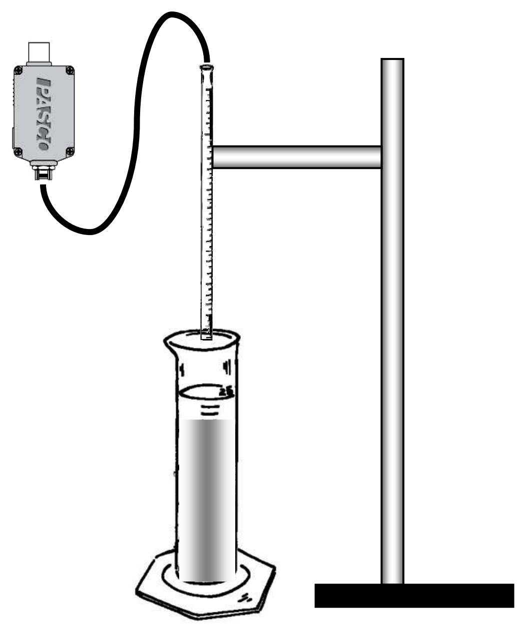


Figure 3: Apparatus for Pressure vs. Depth

2. Pour about 450-500 mL of water into the 500 mL cylinder. The exact amount is not important.

3. Open the experimental file **L11.A1-1 Pressure vs. Depth**. This file will record pressure measurements when the keep button is clicked. Each time you click on keep, you will be asked to input a volume. This volume should be the difference between the volume measured at the large graduated cylinder water surface and at the water level in the small glass tube. For instance, if the tube is partially submerged such that the water surface is at the 19 ml mark and the water has entered the tube up to the 10.9 ml mark, you would enter a value of 8.1 into *Data Studio*. **Important:** The markings on the tube begin at 10 ml. Keep

this in mind while you are making measurements. After entering the volume, the program will use the value you entered to calculate a depth and a point will be added to the table.

Prediction 1-1: If you were to lower the small glass tube into the water in the larger cylinder, how would you expect the pressure of the air in the small glass tube to change? Write down a formula expressing the pressure measured by the sensor (connected to the glass tube) in terms of the depth of the liquid in the tube, i.e. the distance from the water surface to the water level in the tube.

Question 1-1: Why don't we have to worry about how high the actual sensor is compared to the water level?

4. Bring up Table 1 in *Data Studio* if not already visible. This will show the pressure, depth and volume measurements as you enter them. You begin with the small tube positioned above the water level of the larger cylinder. Click the Start icon and note the pressure reading in the table. It should measure zero pressure within plus or minus about 0.2 kPa. If this is not the case, either there is something wrong with your setup or there is a tornado nearby and you should take cover. Ask your TA to check your setup before taking cover.
5. Lower the glass tube about 2 cm into the water. Placing white paper behind the water cylinder may help you read the numbers more easily. Record your measurements of the water levels in Table 1-1 below and enter the calculated Difference value into *Data Studio* when prompted. Then click Keep. Make a total of four measurements equally spaced throughout the depth of the graduated cylinder in the same manner.
6. Once you have made all four measurements, click on the red Stop icon next to the Keep icon. Bring up Graph 1, which is a plot of Pressure vs Depth using the values you just entered.

Table 1-1. Volume (depth) Measurements

Volume at Water Surface (mL)	Volume in Tube (mL)	Difference (mL)

7. We found in Eq. (16) that $P_{sensor} = \rho gh$, where h is the depth of the level in the tube below the water surface. This equation has the form $y = mx$ where the slope $m = \rho_w g$. Given that $\rho_w = 1000$ kg/m^3 and $g = 9.8$ m/s^2, calculate the predicted value of the slope of a graph of P vs h in units of kPa/mm. Show your work. (Hint: You can more easily calculate kPa/m, than kPa/mm.)

Predicted slope: ____________________kPa/mm

8. Use the fit routine and try a linear fit to your data. Record the slope of the line given in the Linear Fit window.

Measured slope: ____________________kPa/mm

Question 1-2: How well does the predicted slope compare to the measured one? If the disagreement is more than about 5%, try to explain why.

Note that the linear fit may not go quite through the origin. This might be partially explained by the fact that the calibration of your pressure sensor may not be quite accurate for your location.

ACTIVITY 1-2: PRESSURE DEPENDENCE ON HEIGHT

You will now repeat the measurements of the previous activity except that this time, you will start with the tube fully submersed in the water.

1. Remove the rubber stopper from the small glass tube and lower the glass tube so that the bottom of the tube is about 1 cm above the bottom of the larger cylinder. At this point, the water in the tube should be at the same level as the water in the cylinder. Place the rubber stopper back into the glass tube.
2. Lift the bottom of the glass tube about 2 cm above its current position.

Question 1-3: Why does the water level in the tube rise as you lift the tube?

Prediction 1-2: If you were to continue to raise the glass tube out of the cylinder, how would you expect the pressure of the air in the tube to change? Write down a formula expressing your prediction of the pressure measured by the sensor connected to the glass tube in terms of the height of the liquid in the tube, i.e. the distance from the water surface to the water level in the tube.

3. Open the experimental file **L11.A1-2 Pressure vs Height**. This file has the same format as the previous one.
4. Click the Start icon and perform the same series of measurements as in the previous activity but this time start with the water level in its current position about 2 cm above where you first placed it mostly immersed in the larger cylinder. In this measurement, you will raise the glass tube and take four measurements over the length of the cylinder. Use Table 1-2 below to calculate the volume values you enter when prompted. Note that this time the level of the Volume in the Tube is highest, instead of the level of the Water Surface.

Table 1-2. Volume (height) Measurements

Volume in Tube (mL)	Volume at Water Surface (mL)	Difference (mL)

5. As before, write down your predicted and measured slopes below:

Predicted slope: ______________________kPa/mm

Measured slope: ______________________kPa/mm

6. **Print** out your graph with the fit showing.

Question 1-4: Is there any difference between the measured slopes of Activities 1-1 and 1-2? How about the *y*-offsets? Try to explain any differences or similarities.

INVESTIGATION 2: PASCAL'S PRINCIPLE

In this investigation you will explore the relationship between force and pressure and how pressure is transmitted through a fluid.

The materials you will need are:

- 2 force probes
- digital mass scale
- 50 cc glass syringe
- rubber bumper for force probes
- low pressure sensor with tubing and rubber stoppers
- 50 g mass
- digital calipers
- paper towels
- 2-10 cc glass syringes
- tubing and connectors to connect syringes
- distilled water with eyedropper at front of room

In order to perform the following activities, you will need to know the properties of the pistons in the syringes you will be using:

mass of 10 cc piston: 16 g

mass of 50 cc piston: 60.6 g

diameter of 10 cc piston: 14.7 mm

diameter of 50 cc piston: 28.0 mm

In this investigation, you will be using glass syringes. We need for the pistons to move freely inside the syringes. You need to do the following procedure with each of the two syringes. Hold the syringe in your hand vertically and lift up the piston almost to the top and release it. The piston should fall freely without sticking to the bottom of the syringe. If it does not, the piston must be cleaned, because someone before you was not careful. Pull out the piston and clean it off with a paper towel. Insert it back into the syringe and test it. You may need to do this two or three times before the piston falls freely. If it does not, contact your TA. It is important not to touch the sliding surface of the pistons during your lab. As you perform the following activities, you should check the syringes from time to time to make sure that they are operating smoothly. If they do not, clean the piston again with a paper towel. Before taking final measurements, it helps sometimes to tap on the side of the syringe to help the piston move to its final position. If you can't get the syringe to work properly, ask your TA for help.

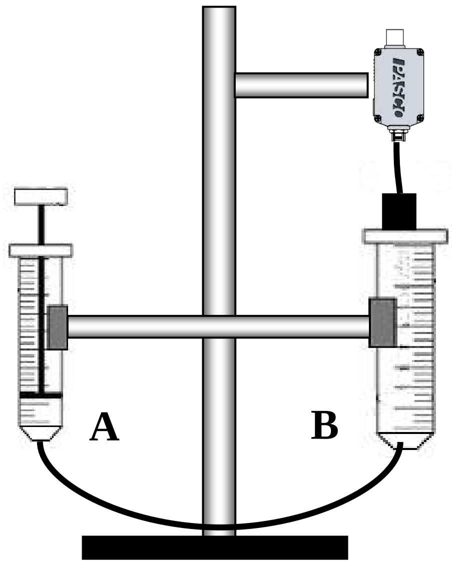


Figure 4: Measuring Pressure

Start off by connecting the two force probes to inputs A and B and the pressure sensor to input C of the PASCO interface.

ACTIVITY 2-1: FORCE AND PRESSURE

1. We will now lead you through setting up the apparatus shown in Figure 4. Place the 10 cc syringe on the left side and the 50 cc syringe on the right side. We have found that if we clamp the syringes, then the pistons do not slide easily in the syringe. It is best to rest the upper lip of the syringe on the clamp instead of clamping the syringe. **Do not clamp the syringe as shown in Fig. 4.** Rather the clamp should be placed under the upper lip of the syringe just snugly enough to not let the syringe fall through the clamp. For the remainder of this investigation, we will refer to the left side of the apparatus as A and the right side as B. For example, syringe B is the syringe connected to the pressure sensor in Figure 4. **Leave the large rubber stopper off the 50 cc syringe for now.**

2. Connect the bottom of the syringes with the clear plastic ¼" tubing with the white connectors on the end. Twist the connectors onto the bottom of the syringes.

3. The pressure sensor should be connected to input C of the interface.

4. Open the experimental file **L11.A2-1 Force and Pressure**. The graph Pressure vs. Time is displayed.

The offset pressure is the difference between the current atmospheric pressure and the average value of atmospheric pressure for which the sensor is calibrated. This also corresponds to the value of the *y*-offset from Investigation 1.

5. We will first measure the offset pressure. The 50 cc syringe is open to atmospheric pressure, so the pressure is atmospheric in the 10 cc syringe as well. **Start** taking data. After about 10 s, click the Stop icon. Highlight a good portion of the data and determine the average pressure read by the sensor. This is the offset pressure, because according to Eq. (16), it should be zero. Write it down.

Offset pressure, P_0 = ____________________kPa

6. Now raise piston A so it reads about 7 cc and place the large rubber stopper into the top of syringe B. The piston is not in syringe B at this time. See Figure 4. Notice that the piston in the 10 cc syringe remains suspended near the 7 cc level, even though the force of gravity is pulling it down. The force of gravity is offset by the force due to the air trapped in the syringes. This force is equal to the pressure of the air in the piston times the cross-sectional area of the piston.

Prediction 2-1: Suppose you were to place a 50 g mass on piston A. You calculated in your pre-lab the predicted pressure measured by sensor B. Don't forget the mass of the piston. Write here the pressure you calculated:

Predicted pressure with only piston: ________________ kPa

Predicted pressure with piston and 50 g mass: ________________ kPa

7. Click on the Start icon, and place a 50 g mass on top of piston A as shown in Figure 5. Once you are convinced that the piston has reached equilibrium without friction, record the pressure below.

Measured Pressure: ________________kPa

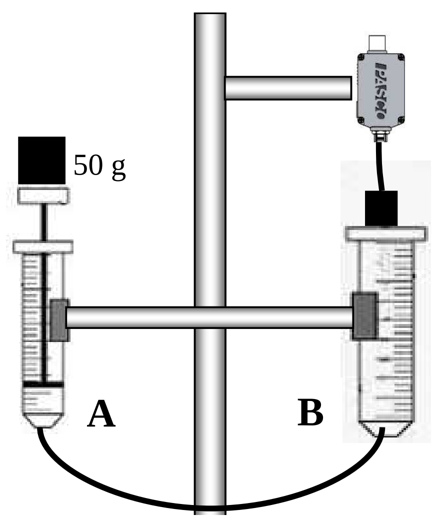


Figure 5: Adding a mass to syringe A.

Question 2-1: Did your prediction match the measured value? Explain any differences greater than about 5%.

We can see from the above results that the force of the piston on the air in the syringe is transmitted throughout the volume of air trapped in the syringes and tubes connected to the pressure sensor as predicted by Pascal's principle.

Prediction 2-2: If we repeated the above measurement by switching the pressure sensor to syringe A and placing the mass on top of piston B, do you think the measured and predicted measurements would still be equal? About what would you predict the pressure to be? **Do not do this second measurement, only predict!**

Pressure: __________________kPa

ACTIVITY 2-2: HYDRAULIC SYRINGE

A classic implementation of Pascal's principle is the hydraulic lift. In this activity you will perform measurements on a scaled down version of the same type of apparatus used in automotive repair shops to lift cars.

1. Disconnect the tubing from syringe B and replace it with the second 10 cc syringe. Set up the apparatus shown in Fig. 6. Syringe B now has a piston with a force probe above it. You will need the second force probe as well. The probes should be already be inserted into inputs A and B on the PASCO interface. Make sure that the probe above the right syringe is plugged into input B. Adjust force probe B so that as you lift piston B, it touches the force probe when the syringe reads about 2 cc. Before reconnecting the tubing between the syringes, make sure the two pistons are sliding freely. When

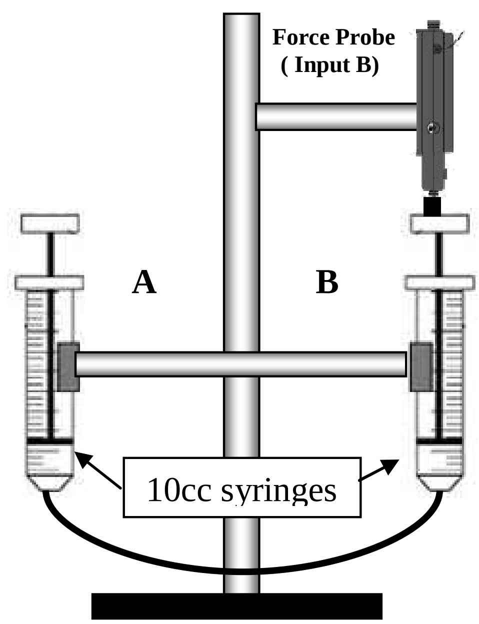


Fig. 6: Hydraulic Syringe Apparatus

this is done, lift piston A until it reads about 4 cc and reconnect the tubing to both syringes.

2. The pistons in each syringe are now connected to each other by the air trapped in the syringes and tubing. If you move one piston, the other should respond. Check to make sure they respond freely; air leaks will cause errors.

Prediction 2-3: If you now place a 50 g mass on piston A as you did in the last activity, what do you expect will be the force measurement from force probe B? Explain your answer.

Predicted force: __________N

3. Verify your prediction using the same experimental file. Bring up the graph Force B vs Time. You may need to wet the piston again if it is not sliding freely. Tare force probe B to zero out the gravitational force on the rubber bumper. Make sure that the piston is not in contact with the force probe while taring. Click the **Start** icon. Place the 50 g mass on piston A and record the force measurement below, making sure that the pistons are not binding in the syringes.

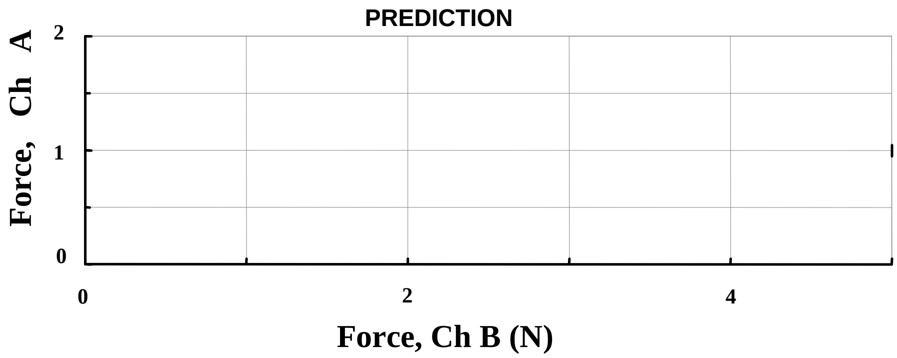
Measured force: ____________________N

If your measured force is not within 10% of your predicted value, compare with your calculation in Prediction 2-2 and check your apparatus before moving on to the next part.

4. Disconnect the tubing from the bottom of the 10 cc syringe B and remove syringe B. Replace it with the 50 cc syringe. Make sure the piston slides freely in the new syringe and adjust force probe B so that the piston hits the probe at the 1 cc mark. Lift up piston A to the 5 cc mark and reconnect the tubing to the bottom of syringe B.

Question 2-2: You may notice that even though the piston in the 50 cc syringe is almost four times as heavy as the 10 cc piston, the two pistons seem to be well balanced. Why is this?

Prediction 2-4: Suppose you were to push down on piston A with force probe A. On the graph below, force probe A is on the vertical axis and force probe B is on the horizontal axis. Sketch your prediction for the resulting curve as you push harder with force probe A. What is your prediction for the slope of this curve?



Predicted Slope: ___________

5. We will verify your prediction by pushing the second force probe down on piston A. Open experimental file **L11.A2-2 Hydraulic Syringe**. This file is set up to automatically stop taking data when the force measured by probe A reaches its maximum (so it will not be harmed). Make sure the pistons move freely. Tare both force probes (make sure both probes are vertical while taring) and click the Start icon. As slowly as you can, increase the force you apply to piston A until the program stops taking data or piston A is fully depressed. If syringe A becomes fully depressed before the program stops taking data, click the Stop icon, disconnect the tubing, lift up piston A to the 5 cc mark and reconnect the tubing (make sure piston B is fully depressed while you adjust piston A). Take the data again. Once the data has been taken, do a linear fit to your data, and record the slope in the space below. Print out the graph and include it in your group report.

Measured Slope: ________________

Question 2-3: Do your values agree? Explain any differences greater than 10% in your predicted and measured values.

INVESTIGATION 3: BERNOULLI'S EQUATION

In this investigation, you will be using Bernoulli's equation to predict the behavior of air as it passes through a Venturi tube. A Venturi tube is a device, which can be used to measure the speed of fluid flow as discussed in the introduction.

In the following activities you will be using a device called an air flow meter. It will allow you to send a known volume of air per unit time through the Venturi tube. The meter measures the flow rate in units of SCFH which stands for Standard Cubic Feet per Hour. The black knob on the front of the meter controls the amount of air flow, the faster the flow, the higher the float in the meter is pushed up by the air. The value is read off by looking at the top of the float. For example, if you want a flow rate of 50 SCFH, adjust the flow until the top of the float is even with the 50 SCFH line. Gently tapping the side of the meter can help to keep the float moving freely and provide more accurate measurements.

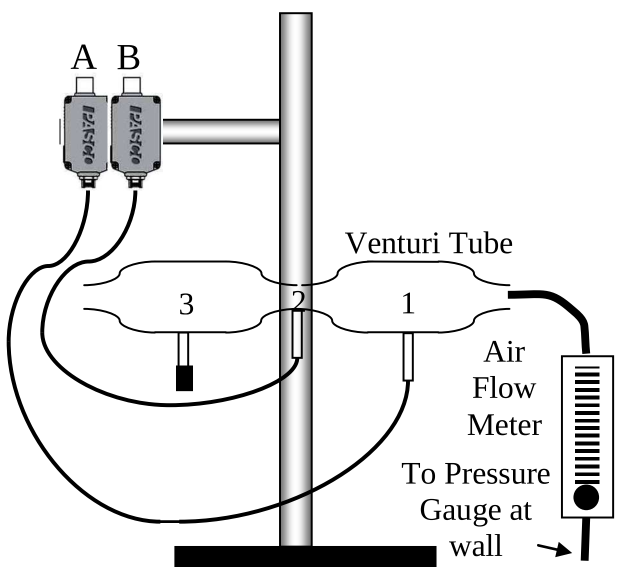
You will need the following materials:

- Venturi tube apparatus
- air flow meter
- tubing
- 2 – stoppers for Venturi tube
- 2 – low pressure sensors
- stand

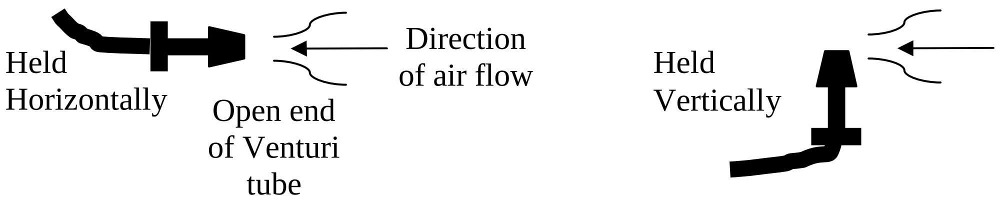
ACTIVITY 3-1: PRESSURE AND SPEED

1. Set up the apparatus as in Fig. 7. Make sure to connect the pressure sensors to the appropriate inputs on the interface as labeled in the figure (i.e., A and B inputs.)
2. Open the experimental file **L11.A3-1. Pressure and Speed**. Make sure the air flow meter is completely closed (turn knob clockwise to close) and adjust the pressure gauge at the wall to read approximately 13 psi. Disconnect the tube from sensor A from input 1 on the Venturi tube and put a stopper in its place.

Figure 7. Apparatus for measuring pressure and speed.



Prediction 3-1: Suppose you were to allow air to flow through the Venturi tube. Imagine placing the end of the tube connected to the pressure sensor near the open end of the Venturi tube in the two configurations shown below. What difference might you expect in the two cases? Explain your answer.



3. Adjust the air flow so that the meter reads 60 SCFH and click the Start icon. Perform the same series of measurement as in the previous prediction. When you are done, click the Stop icon and turn off the air flow at the air flow meter. Print out the graph and indicate on it when the different orientations of the sensor tube occurred.

Question 3-1: Did your prediction match your measurements? Explain any differences.