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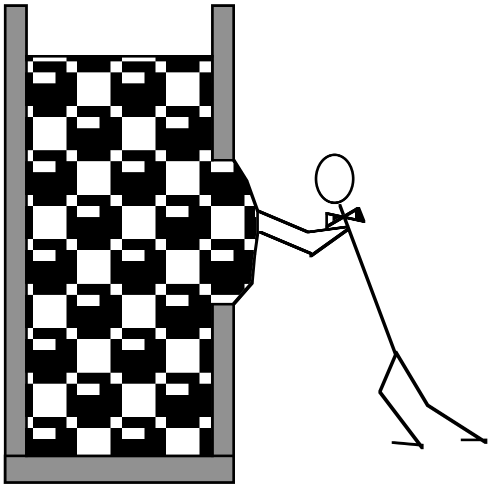
Unit I: Fluids and Pressure

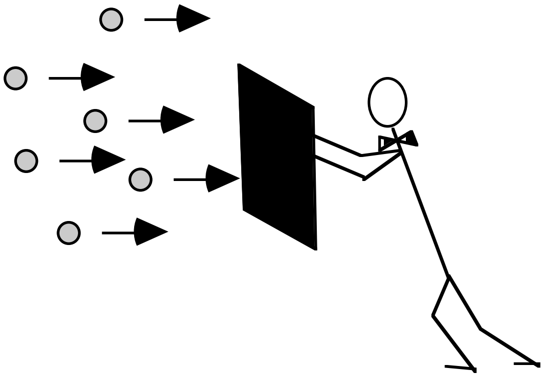
In this unit and the next, we will investigate the relationship between the pressure of a fluid and the flow of the fluid. To understand this, however, we first have to know a bit more about pressure. With that in hand, we will first look at how pressure in a fluid depends on the depth of the fluid. We will then use these concepts to investigate how pressure varies in a flowing fluid, and relate that to conservation of energy.

Session 1: Pressure and the Static Bernoulli Principle

Pressure has the qualitative relationship to flow that force has to motion for particle motion that we learned about in General Physics I. However, we have to understand some of the subtle differences between force and pressure. We can measure the pressure of the fluid by placing a flexible test window on the wall of the vessel holding the fluid, and seeing how much force is necessary to hold the window in place.



The pressure, on a microscopic level, arises from atoms bouncing against the surfaces inside the vessel, in particular, against the test window. In order to bounce the atoms backward, we need to apply a force. The force we apply against this window causes a change in momentum of the atoms (recall that $F = ma = dp/dt$). If you imagine how it might feel if you held up a big shield, and allow a group of people to throw balls against it, you have a good picture of what is going on. Every ball that hits the shield gives a little recoil to us; we have to plant our feet firmly and lean into the shield a bit (apply a force) to keep from being knocked over.



Now, you might ask why we can't feel the individual bumps like we would in the shield and ball example. For example, if we press against the side of a balloon, we feel just a constant force, with no bumping. The answer is that the bumps come much too frequently for us to discern one from the next. You will work out later in a problem what the typical time is between these bumps.

If we again consider the shield example, it makes sense that we will feel more bumps if we hold up a larger shield. A larger shield is a bigger target, so it will intercept more of the balls. If we accept the notion that the ball throwers are not very accurate, then it is plausible that the number of balls that bounce off the shield is simply proportional to the area of the shield. The same is true of the test window that we are using to measure the pressure. A large window requires a large force to hold it in; a small window a proportionately small force.

If we want the pressure to be a quantity that describes a property of the fluid, and not a combination of properties of the fluid and of the test window, we want to divide out this area factor. That is why pressure has the units of force per unit area. It is the force we have to exert on the window divided by the area of the window. And while the force exerted on the window has a definite direction, pressure has no direction. It causes forces to be exerted on walls or surfaces, but the direction of the force is determined by the shape of the surface, not by the fluid. That is, the force always pushes out against the wall. This makes some sense when one thinks of a microscopic picture in which the atoms are bouncing about randomly. The random directions average one another out, except for the fact that the surface is only hit from one side. This leaves a force in the only unique direction; perpendicular to the surface.

Guidebook Entry I.1: Pressure, Vacuum, and Gauges.

To help you investigate the pressure within a fluid, we have a number of Bourdon gauges (sometimes just called spring gauges) that give a coarse measurement of pressure. Start with one of the gauges that is labeled Absolute Pressure. What does the gauge read? Why does it not read zero?

What do you predict will happen if you blow into the gauge? What if you suck on it?

With a clean length of plastic tube, suck and blow into the gauge. What happens?

Make sure to look at all the different gauges that we have. Some are absolute pressure gauges, as you used in GE I.1. Some are vacuum only gauges, where increasing numbers mean lower pressure (greater vacuum). Some are pressure/vacuum gauges, where zero is at atmospheric pressure. There are also a variety of different units for pressure and vacuum. The SI metric unit is Newtons per square meter, otherwise known as Pascal. Also in very common use for pressure is the English unit of pounds per square inch. Many vacuum gauges use the unit of torr (or millimeters of mercury or Hg--more about that later). This is sometimes also expressed as either centimeters or inches of mercury. To get an idea of these units (and to have the conversion factors from on unit system to another), here is one atmosphere of pressure (roughly) in each unit system:

1 atm = 101,300 Pa = 14.7 PSI (pounds per square inch) = 760 torr = 760 mm Hg = 76 cm Hg = 29.9 in. Hg.

To make it a bit more confusing, many combined vacuum/pressure gauges use PSI for pressure and inches of mercury for vacuum! Fortunately, these gauges are usually easy to identify, since the scale gradation makes a big jump between above- and below-atmosphere ranges.

Guidebook Entry I.2: Pressure and Height.

The pressure of a fluid depends on the height within the fluid. To see this, we have some long clear plastic tubing that you can attach to one of the gauges. But before you investigate this we want you to predict what happens to the pressure in a vessel of fluid as you go below the surface of the fluid. Explain your reasoning.

Our pressure gauges don't work well if you submerge them, but we can simulate this by having just a thin column of water above the gauge in the clear plastic tubing. To make this easier, fill a long tube by siphoning water from a bucket up to the gauge (you will probably need help with this). Then, see qualitatively how the pressure read on the gauge depends on:

height of the gauge relative to the bucket:

absolute height of the gauge (if height relative to the bucket is constant):

height of the tube running between the bucket and the gauge:

Summarize in a few words how the pressure in a fluid depends on height (specify heights of what!) from what you observed.

Discuss this within your group, and then with at least one other group, and an instructor or TA.

Now we want you to be more quantitative about the behavior of pressure as a function of height. To do this, you'll need to move your bucket and gauge assembly to a tall stairwell.

Guidebook Entry I.3: Pressure Dependence on Height.

Measure the pressure on the gauge as a function of the height of the water in the tube above the surface. Height marks have been placed along the banister. It measures 4.39 meters from the basement floor to the top of the open metal railing on the first floor, and 8.28 meters from the basement floor to the top of the railing on the second floor. It is important to match the height of the water in the tube to these marks, not the height of the gauge.

Height	Pressure

Graph this data using Excel, and attach the graph. Can you find a simple mathematical relationship between height and pressure? Check your result with an instructor

Before you leave the stairwell, make sure to see what happens to the water column when you try to make it exceed 34 feet in height. What you have then is a water barometer. Atmospheric pressure on an average day in Grinnell is sufficient to support a column of water about 34 feet high. Since pressure is force per unit area, atmospheric pressure exerted on an equal diameter tube will support a height of any fluid with the same weight (gravitational force) as the water. (It is easy to show, as you may do in a homework problem, that the pressure in the fluid varies with the change in height by $-rgh$, where r is the density of the fluid. In other words, changing your height in the fluid by h changes the pressure exerted by the fluid by $-rgh$.) If it is on display, you can compare the 34 feet of water to the column of mercury in the mercury barometer that is in the museum. [It is about 3/4 of a meter high, in case there isn't one for you to see.] Why would one choose to use mercury instead of water? Do the pressure units of lengths of mercury make some sense now? Make sure to discuss this within your group and with an instructor or TA.

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Session 2: Pressure and Fluid Flow

In the last session, you discovered that the pressure in a fluid that was not moving depended on the height in the fluid. In other words, as we go deeper into a body of fluid, the fluid pressure increases. This is sometimes referred to as the static Bernoulli principle:

$$P_{reference} = P(h) + \rho g h$$

where $P_{reference}$ gives the pressure at one point in the fluid, and h is the height measured from that point (e.g. for Session 1, above the surface of the water, and $P_{reference}$ is 1 atm), P(h) is the pressure as a function of height, r is the fluid density, and g is the acceleration due to gravity. **Given this, we will use height differences as indicative of pressure differences, and use this indicator to help understand the relation between pressure [difference] and fluid flow.**

Analysis of fluid flow is messy, and difficult to analyze precisely. As is common in physics, when faced with a difficult problem, we study the extreme, or so-called "limiting" cases, in which the physics is dominated by a single effect, and analysis becomes relatively simple. The two limiting cases we will consider are the following 1) cases in which friction (or as it is called for fluids, viscosity) is so large in a single element that it dominates the flow, and 2) cases in which viscosity is so small that the flow is governed by the dynamic Bernoulli equation, the equivalent of F=ma for fluids. Real fluids, naturally, contain both of these elements, and so the complete analysis is more complicated. As we go along, it is good to remind yourself frequently of what limiting case we are considering, and if you are not sure, ask an instructor. For those who took Workshop I, we are doing a further investigation today of the drag force we saw with the cylinders of corn syrup. Corn syrup has a lot of viscosity, but rather than use such messy stuff, we will take ordinary water and try to force it through a narrow tube, and thereby make the viscosity very important.

Before we can gain a quantitative understanding of the relationship between fluid flow and pressure in *either* extreme case, we have to make sure we know how to measure each of these quantities of flow and pressure difference. We have already made quantitative measurements of pressure (actually differences from atmospheric pressure) with the spring gauges, and from that learned that we can also get some indication of pressure differences by differences of fluid levels. In this session we will use fluid heights as a way to both control and measure pressure differences. Now we need to have a quantitative way of measuring fluid flow.

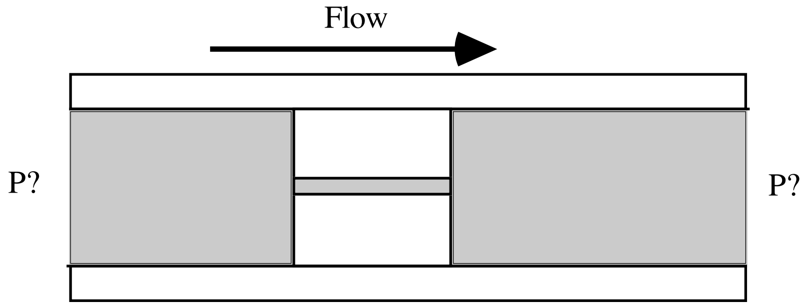
Guidebook Entry I.4: Measuring Fluid Flow.

We have built some devices to help us measure some of these fluid properties. So that you can see what is going on easily, they are made of clear materials whenever possible. There are several different building blocks, which you need to know about. There are clear cylinders, which can hold a column of water. They have both inlet and outlet connections, with barbed tubing connectors. To these, you can connect flexible tubing. Some of these tubes have had tiny pieces of glass capillary tube inserted as a method of restricting the flow to a slow dribble. This will allow us to make measurements more easily, but even more importantly, allows us to make the assumption of a static fluid everywhere but at that flow-restricting capillary. Some of you may use a tubing clamp to restrict the flow instead of a capillary--check with an instructor.

First, you need to observe flow of water through the capillary. In your own words, describe what fluid flow means, and how you would know that you have achieved it.

Now, figure out some way to do this, and demonstrate that you can make fluid flow through the capillary. Describe what you did, and what you observed.

Now, using the language of pressure, describe the pressure on



either side of the capillary. In other words, if the flow is going from left to right through the capillary as shown in the picture, what can you say about the pressure of the fluid on the left relative to that on the right?

Now, come up with your own way of measuring flow. This is a two part question. First you have to create a quantitative definition what you mean by flow:

and then you need a recipe for how to measure it. Write down a very clear technique for measuring how much flow you have. Talk with some of the other groups, and see if you have similar methods. Then check with the instructor to see how well your method will work in practice with our equipment.

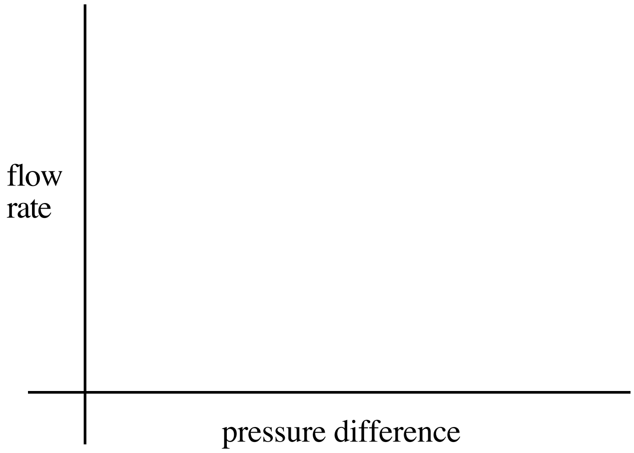
Now that we have some good ways of measuring flow, and some intuitive notion of how that relates to pressure differences, let's make some experimental measurements and see if we can relate them quantitatively. To do this, you will use one of the clear cylinders as a reservoir of fluid and a source of the pressure difference. You will need the inlet closed, and the outlet connected to tubing with the capillary inside it.

Guidebook Entry I.5: Flow Rate and Pressure Difference.

Hopefully in the last Guidebook Entry, you decided that flow rate had to do with the rate of transfer of fluid. To measure this, we then need to measure the amount of fluid transfered, and the amount of time it takes for that transfer. You can measure the amount of fluid transfered by measuring the amount of fluid that comes out, or the decrease in the amount of fluid in the original tube. We have stopwatches available for you to measure the time required for the transfer to take place.

With this in mind, describe how you can set up an experiment in which you look for the dependence of flow rate on pressure difference across a capillary or other narrow spot:

What do you predict you will see for the flow rate as a function of that pressure difference? Express your answer both in words, and in a graph:



Now, take some flow rate data for at least five different pressure differences.

Height (pressure diff)	Amount of fluid	Time	Rate

Graph this data, and compare to your predicted dependence.Make sure to attach your graph.

Ideally, if the flow through the capillary isn't *too* fast, the flow is nearly proportional to the pressure difference across the capillary. If this is true, we see a characteristic dependence to the draining of the tube. The behavior of this system is typical of many physical systems, so it will give us good practice to look at this in a little detail. Let's observed first what this looks like, and later we will try to make sense of this theoretically. Try to keep your capillary drain tube at the same height as the bottom of the cylinder

Guidebook Entry I.6: Draining a Tube.

To investigate the draining of a tube, we want to see what the flow rate is as a function of time. The easiest way to do this is to place marks on the outside of the clear tube with a washable marker every centimeter. Then, use the stop watch to record the times when the fluid level passes each mark.

Height	Time

Use Excel to make a graph of height versus time, and sketch below or attach a copy of that graph to your activity guide.

Now use Excel to calculate the approximate flow rate as a function of time. You can measure the amount of fluid in centimeters of tube height. Remember to turn this into a rate. Graph the rate versus time, and sketch below or attach. How does this compare to your original graph of height versus time? Talk about the significance of this with your partners and an instructor.

Session 3: The Bernoulli Equation

In the last session, we saw how differences caused flow through a tiny tube—the hole in a glass capillary. In this glass capillary, the hole is so small, that the flow is severely restricted by friction, which in the fluids world is usually referred to as viscosity, or more properly, viscous drag. This system was a limiting case where behavior was determined strictly by this fluid friction at one point in the system: the capillary (or perhaps a nearly clamped-shut section of tubing). Some fluids exhibit a great deal of viscosity (such as corn syrup, or thick oil), whereas water or alcohol exhibit only a very modest amount of viscosity. Some remarkable fluids, known as superfluids (which exist only at temperatures very close to absolute zero), exhibit no viscosity whatsoever.

One can treat viscosity quantitatively, but we will not deal with this a great deal. However, in this session, we will deal with another extreme case exhibiting **another source of pressure differences** that arises from simple Newtonian F=ma mechanics. It in fact is quite simple in origin, but gives rise to some surprising effects.

Guidebook Entry I.7: Some Bernoulli Demonstrations.

At this point, you all need to watch a few demonstrations of Bernoulli effects. First, you need to predict what you expect to happen when a ball is released in the stream of air (which is our fluid here).

Now write what you actually observed, and how it compares with what you expected.

The next demonstration involves placing a ball in a stream of air that is coming out of a funnel. Predict what you expect to happen:

Now watch the demonstration, and write down what you observed.

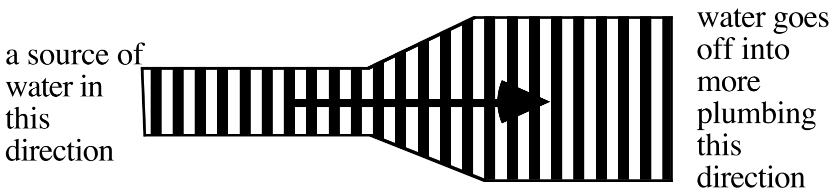
Now share your predictions and observations within your group. Were you surprised? In what way? Do you have any idea why what you saw happened?

To make some sense of this, we need to understand what happens to fluid velocity as the fluid flows through complicated plumbing, and how that relates to forces and pressure.

Guidebook Entry I.8: Accelerating Fluids.

One feature of an established flow (that is, one that has been flowing long enough for flow patterns and fluid velocities to stabilize) is that the flow rate is constant anywhere through a circuit. If 5 liters per second are flowing at one point in a pipe, there must be 5 liters per second flowing further on in the pipe. (This makes the assumption that the fluid is incompressible, which is a very good approximation for water at typical pressures we deal with.)

With this in mind, consider the plumbing shown below:



What can you say about the *velocity (or speed)* of the fluid on the left relative to the right? Why?

Now imagine that you have an object (take a bowling ball to be specific) that is initially moving quickly, and you want to make it slow down. What do you need to do to it to accomplish this?

The forces that make fluids move are described in terms of pressures. With this in mind, what can you say about the pressure on the left side of the picture relative to the right side of the picture. **This picture is often confusing; make sure to discuss this (and your comments above) with your group members and an instructor!**

You should have discovered in the first question of the above exercise the qualitative understanding of what is known as the equation of continuity. That is, the velocity of the fluid must be greater in the narrow portions of tubing. Quantitatively, the fluid velocity times the cross-sectional area of the tube at that point gives the flow rate (in volume per unit time--check the units to see). If the flow is conserved over the pathway (no leaks, and no significant expansion or compression of the fluid) then this can be expressed as the continuity equation:

$$v_1A_1 = v_2A_2 \; .$$

We can then use this with the full Bernoulli equation to describe the pressure changes in a system where fluid is flowing. The full Bernoulli equation takes into account only the effects of height and acceleration of the fluid; **viscous drag (friction) is neglected**. It is represented as an equation as follows:

$$P_1 + \rho g h_1 + (1/2)\,\rho v_1^2 = P_2 + \rho g h_2 + (1/2)\,\rho v_2^2$$

In this equation, the subscript refers to a particular point in the fluid. The left hand side refers to the fluid at point one, the right hand side to the fluid at point two. The symbol P stands for the pressure, the symbol h for the vertical height, the symbol v for the velocity of the fluid at that point, and the symbol ρ stands for the density of the fluid. You should convince yourself (and your partners) that this equation gives the right behavior; that is, regions with higher fluid velocity have lower pressure, and that regions deeper in the fluid have higher pressure. *This is not a trivial exercise, so please attempt this with seriousness!*

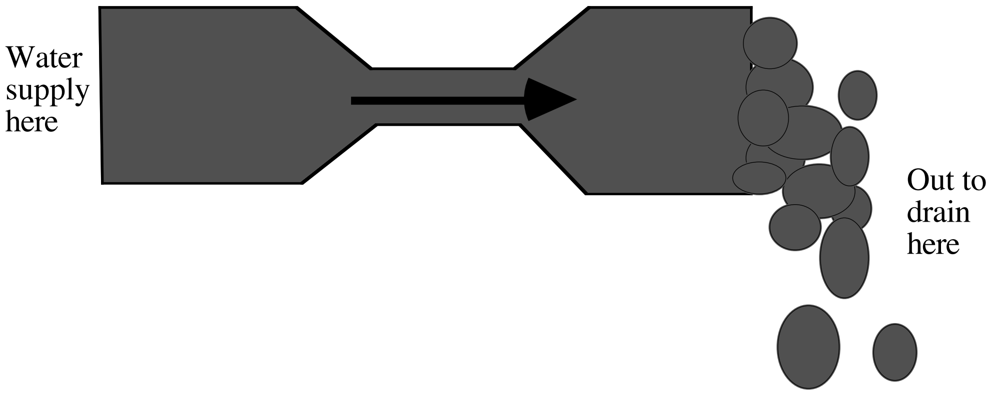
Guidebook Entry I.9: Using Bernoulli to Explain Examples.

Now that you understand the Bernoulli principle, use it to predict what will happen in several examples**:**

Take two sheets of paper. Hold one in each hand, parallel to one another, hanging down and separated by about an inch. What do you predict will happen if you blow between the sheets? Why? See if you and your group agree.

Do the experiment with two sheets of paper. What happens?

A device known as an aspirator makes use of the Bernoulli principle to create a vacuum. Its basic features are just a fluid flow with a constriction that then opens out to atmospheric pressure. This is shown in the following figure:



What must the pressure of the fluid be on the right side, where it is exiting the tube, and is in contact with the air and the fluid velocity is small?

Is the fluid velocity large or small in the narrow part of the tube? Why?

Is the pressure greater than or less than atmospheric pressure in the narrow part of the tube? Explain why in your own words. Then exchange your paper with your partners, and each of you add your own additions or corrections to what each other has said. Then discuss this and see if you can come to agreement on what is happening.

An aspirator uses a tube with a narrowing like this to produce a vacuum. A small hole in the narrow region is connected to a tube, so that one can effectively use this vacuum. When you are ready, your instructor will demonstrate how this works with a simple aspirator using our own tubing, and then show a commercial aspirator with one of our vacuum gauges.

Now that you have had some practice using Bernoulli qualitatively, let's come back to our first examples. Try your hand at explaining why the ball stays in the air stream coming out of the straight tube:

and why the ball is sucked into the funnel, even though it seems the air should push it out.

Guidebook Entry I.10: A Final Puzzle

The aspirator is a good example of one of the counter-intuitive features of Bernoulli. The exit region of the aspirator is at a pressure of one atmosphere, whereas the region in the middle of the aspirator is at a pressure well below one atmosphere. Explain in your own words how you can possibly have fluid flowing from a region of lower pressure to one of higher pressure, in such obvious contrast to our capillary case.

Now try to draw analogies with the mechanical cases. To be specific, a mechanical example where friction is completely negligible is a rock in outer space, or a cart on an air track or air table. A mechanical example where friction dominates is a block of wood sliding on the ground. For each case answer the question of where and how you have to push to get the object started, to keep it going, and to stop it.

The rock in outer space or air track cart:

The block of wood on the ground.

Now answer the same questions about net forces (or net pressure differences) in the fluid case for:

The capillary or very viscous fluids.

Low viscosity fluids (like water) in large diameter tubes.

Consider now the question of energy. We know from General Physics I that a force exerted in the direction of motion gives [kinetic] energy to the object--the opposite direction takes it away. Where does the energy go in the low viscosity case?

Where does the energy go in the high viscosity case.

Make sure to discuss all these answers at least briefly with an instructor.

Might want to elaborate. This unit goes fast. Drawing connections with energy, and with mechanical systems. Inertia dominated is like ballistic car on wheels, viscosity dominated is like cart sliding on its back. Perhaps draw analogy to ball or cart rolling on a hilly landscape--energy and pressure, etc.