Name:____________________________________
Date:_____________________________________

7 Density

7.1 Introduction

As we explore the objects in our Solar System, we quickly find out that these objects come in all kinds of shapes and sizes. The Sun is the largest object in the Solar System and is so big that more than 1.3 million Earths could fit inside. But the mass of the Sun is only 333,000 times that of the Earth. If the Sun were made of the same stuff as the Earth, it should have a mass that is 1.3 million times the mass of the Earth—obviously, the Sun and the Earth are not composed of the same stuff! What we have just done is a direct comparison of the *densities* of the Sun and Earth. Density is extremely useful for examining what an object is made of, especially in astronomy, where nearly all of the objects of interest are very far away.

In today's lab we will learn about density, both how to measure it, and how to use it to gain insight into the composition of objects. The average or "mean" density is defined as the *mass* of the object divided by its *volume*. We will use grams (g) for mass and cubic centimeters (cm^3) for volume. The *mass* of an object is a measure of how many protons and neutrons (the "building blocks" of atoms) the object contains. Denser elements, such as gold, possess many more protons and neutrons within a cubic centimeter than do less dense materials such as water.

7.2 Mass versus Weight

Before we go any further, we need to talk about *mass* versus *weight*. The *weight* of an object is a measure of the *force* exerted upon that object by the gravitational attraction of a large, nearby body. An object here on the Earth's surface with a *mass* of 454 grams (grams and kilograms are a measure of the mass of an object) has a weight of one pound. If we do not remove or add any protons or neutrons to this object, its mass and density will not change if we move the object around. However, if we move this object to some other location in the Solar System, where the gravitational attraction is different then what it is at the Earth's surface, than the *weight* of this object will be different. For example, if you weigh 150 lbs on Earth, you will only weigh 25 lbs on the Moon, but would weigh 355 lbs on Jupiter. Thus, weight is not a useful measurement when talking about the bulk properties of an object—we need to use a quantity that does not depend on *where* an object is located. One such property is *mass*. So, even though you often see conversions between pounds (unit of weight) and kilograms (unit of mass), those conversions are only valid on the Earth's surface (the astronauts floating around inside the International Space Station obviously still have mass, even though they are "weightless").

7.3 Volume

Now that we have discussed mass, we need to talk about the other quantity in our equation for density, and that is volume. Volume is pretty easy to calculate for objects with regular shapes. For example, you probably know how to calculate the volume of a cube: V = $s \times s \times s = s^3$, where s is the length of a side of the cube. Let us generalize this to any rectangular solid. In Figure 7.1 we show a drawing for a box that has sides labeled with "length," "width," and "height." What is its volume? Its volume is V = length × width × height. If we told you that the length = 10 cm, the height = 5 cm, and the depth = 5 cm, what is the box's volume? V = 10 cm × 5 cm × 5 cm = 250 cubic cm = 250 cm^3. Do you now see why volume is measured in cm^3? This where that comes from—everyday objects are "three dimensional" in that they *have* volume (cm^3, m^3, km^3, inches^3, miles^3).

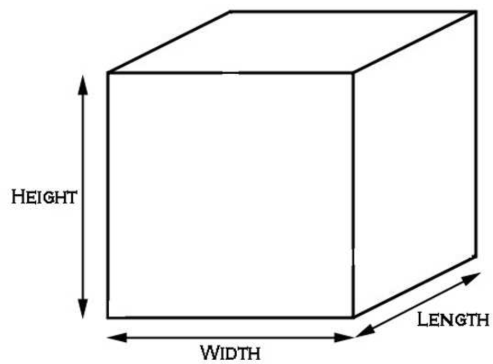

Figure 7.1: A rectangular solid has sides of length, width, and height.

Now that we understand how volume is calculated, how do we do it for objects that have more complicated shapes, like a coke bottle, a car engine, or a human being? You may have heard the story of Archimedes. Archimedes was asked by the King of Syracuse (in ancient Greece) to find out if the dentist making a gold crown for one of his teeth had embezzled some of the gold the king had given him to make this crown (by adding lead, or another cheaper metal, to the crown while keeping some of the gold for himself). Archimedes pondered the problem for a while and hit on the solution while taking a bath. Archimedes became so excited he ran out into the street naked shouting "Eureka!" What Archimedes realized was that you can use water to figure out a solid object's volume. For example, you could fill a teacup to the brim with water and drop an object in the teacup. The amount of water that overflows and collects in the saucer has the same volume as that object. All you need to know to figure out the object's volume is the conversion from the amount of liquid water to its volume in cm^3.

In the metric system a gram was defined to be equal to one cubic cm of water, and one cubic cm of water is identical to 1 ml (where "ml" stands for milliliter, i.e., one thousandth of a liter). Today we will measure the water displacement for a variety of objects, and use this conversion directly: 1 ml = 1 cm^3.

Today you will first determine the densities of ten different natural substances, and then we will show you how astronomers use density to give us insight into the nature of various objects in our Solar System.

Exercise #1: Measuring Masses, Volumes and Densities

First, we measure the masses of objects using a triple beam balance. At your table, your TA has given you a plastic box with a number of compartments containing ten different substances, a triple beam balance, two graduated cylinders, a container of water, and an empty plastic cup. Our first task is to measure the masses of all ten of the objects using the triple beam balance. Note: these balances are very sensitive, and quite expensive, so treat them with care. The first thing you should do is make sure all of the weights[1] are moved to their leftmost positions so that their pointers are all on *zero*. When this is done, and there is no mass on the steel "pan," the lines on the right hand part of the scale should line-up with each other **exactly**. The scale must be balanced before you begin. If the two lines do not line-up, slowly twist (in/out) the silver knob located below the pan—note that the balance will oscillate up and down whenever you touch it, so either wait for it to stop moving, or "help it along" by *gently* using your finger to slow the oscillation.

To measure the mass of one of the objects, put it on the pan and slide the weights over to the right. Note that for this lab, none of our objects require movement of the largest weight, just the two smaller weights. You should attempt to read the mass of the object to two significant figures—it is possible, but quite unlikely, that an object will have a mass of exactly 10.0 or 20.0 g. If the sliding weight on the "10 g" beam falls between units, estimate exactly where it is so that you get more precise numbers like 22.15 g (all of your masses should be measured to two places beyond the decimal!).

Task #1: Fill in column #2 ("Mass") of Table 7.1 by measuring the masses of your ten objects. **(10 points)**

Now we are going to measure the volumes of these ten objects using the method of Archimedes. The basic idea is shown in Figure 7.2. You need to fill the graduated cylinder with water to some level (such as 10 ml), and then put in the object and measure the new level. There are two ways to go about this. One is to carefully pour water into the cylinder to the same level each time, drop in your object, and recording the result. This method is shown in Figure 7.2. Alternatively, you could put in any amount of water, record this value, then drop in your object, and measure the new level. In each case, the amount of water displaced is the volume of that object: (water + object) ml − (water, no object) ml. We

[1] This is the historical name for these sliding masses, as the first scales like these were used to measure weight.

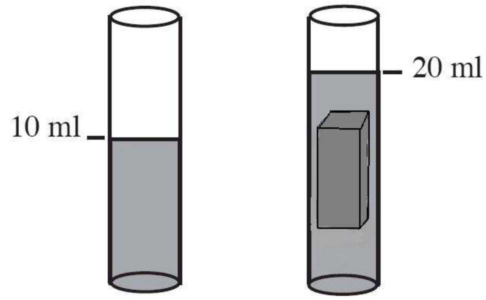

Figure 7.2: The rectangular object displaces 10 ml of water. Therefore, it has a volume of 10 ml = 10 cm^3.

have two separate columns in Table 7.1 to record both values (which ever way you decide to do this). *Note: you should use the smallest cylinder into which the object will fit, and always estimate the exact water level as it will almost always fall between two tick marks on the cylinder!* Slowly pour the water into the cylinders to avoid bubbles (and ask your TA about how to read the miniscus if you do not know what that means).

Task #2: Fill in columns 3, 4 and 5 (again, remember for column #5, that volume = column 4 minus column 3, and 1 ml = 1 cm^3). **(10 points)**

Task #3: Fill in the Density column in Table 7.1. **(5 points)**

Question # 1: Think about the process you used to determine the volume. How accurate do you think it is? Why? How could we improve this technique? **(5 points)**

We chose to supply you with several rectangular solids so that we could check on how well you measured the volume using the Archimedes method. Now we want you to actually

Table 7.1: The Masses, Volumes, and Densities of the Different Objects.

Object **Column #1**	**Mass (g)** **#2**	Water level no object (ml) **#3**	Water level + object (ml) **#4**	**Volume** cm^3 **#5**	**Density** g/cm^3 **#6**
Obsidian					
Gabbro					
Pumice[2]					
Silicon					
Magnesium					
Copper					
Iron (Steel)					
Zinc					
Mystery					
Aluminum					

[2]It is tricky to measure the volume of Pumice, but find a way to *submerge* the entire stone.

measure the volume of the five metal "cubes" (do not assume they are perfect cubes!) using a ruler. You will measure the lengths of their sides in mm, but remember to convert to cm (1 cm = 10 mm). Remember if the length is not a whole mm, estimate to the correct fraction of a mm (such as "12.3 mm").

Task #4: Fill in Table 7.2. Copy the mass measurements from Table 7.1 for the five metal "cubes". Calculate the volumes of these "cubes" using a ruler. **(5 points)**

Table 7.2: The Masses, Volumes, and Densities of the Metal Cubes.

Object	**Mass (g)**	$l \times \ w \times \ h \quad =$	**Volume** cm^3	**Density** g/cm^3
Copper				
Iron (Steel)				
Zinc				
Mystery				
Aluminum				

Question #2: Compare the two sets of densities you found for each of the five metal cubes. How close are they? Assuming the second method was better, which substance had the biggest error? Why do you think that happened? **(5 points)**

Question #3: One of the objects in our table was labeled as a "mystery" metal. This particular substance is composed of two metals, called an "alloy." You have already measured the density of the two metals that compose this alloy. We now want you to figure out which of these two metals are in this alloy. Note that this particular alloy is a 50-50 mixture! So its mean density is (Metal A + Metal B)/2.0. What are these two metals? Did its color help you decide? **(3 points)**

You have just used density to attempt to figure out the composition of an unknown object. Obviously, we had to tell you additional information to allow you to derive this answer. Scientists are not so lucky, they have to figure out the compositions of objects without such hints (though they have additional techniques besides density to determine what something is made of–you will learn about some of these this semester).

Exercise #2: Using Density to Understand the Composition of Planets.

We now want to show you how density is used in astronomy to figure out the compositions of the planets, and other astronomical bodies. As part of Exercise #1, you measured the density of three rocks: Obsidian, Gabbro, and Pumice. All three of these rocks are the result of volcanic eruptions. Even though they are volcanic in origin ("igneous rocks"), both Obsidian and Gabbro have densities similar to most of the rocks on the Earth's surface. So, what elements are found in Obsidian and Gabbro? Their chemistries are quite similar. Obsidian is 75% Silicon dioxide (SiO_2), with a little bit (25%) of Magnesium (Mg) and Iron (Fe) oxides (MgO, and Fe_3O_4). Gabbro has the same elements, but less Silicon dioxide ($\sim$ 50%), and more Magnesium and Iron.

Question #4: You measured the densities of (pure) silicon, iron and magnesium in Exercise #1. Compare the density of Gabbro and Obsidian to that of pure silicon. Can you tell that there must be some iron and/or magnesium in these minerals? How? Which of these two elements *must* dominate? Were your density measurements good enough to demonstrate that Gabbro has less silicon than Obsidian? **(4 points)**

Now let's compare the densities of these rocks to two familiar objects: the Earth and the Moon. We have listed the mean densities of the Earth and Moon in Table 7.3, along with the density of the Earth's crust. As you can see, the mean density of the Earth's crust is similar to the value you determined for Gabbro and/or Obsidian–it better be, as these rocks *are from the Earth's crust*!

Table 7.3: Densities of the Earth and Moon

Object	Density g/cm^3
Earth	5.5
Moon	3.3
Earth's Crust	3.0

Question #5: Compare the mean densities of the Earth's crust and the Moon. The leading theory for the formation of the Moon is that a small planet crashed into the Earth 4.3 billion years ago, and blasted off part of the Earth's crust. This material went into orbit around the Earth, and condensed to form the Moon. Do the densities of the Earth's crust and the Moon support this idea? How? **(4 points)**

Question #6: If you were asked "What are the main elements that make-up the Moon?", what would your answer be? Why? **(2 points)**

It is clear from Table 7.3, that the mean density of the whole Earth is much higher than the density of its crust. There must be denser material below the crust, deep inside the Earth.

Question #7: Given that the mean density of the Earth's crust is 3.0 g/cm^3, and the mean density of the whole Earth is 5.5 g/cm^3, what (common) element do you suppose is partially responsible for the higher mean density of the whole Earth? If we guess, and say that the Earth is a 50-50 mixture of this element, and the crust material, what density do you calculate? Does the resulting density compare with that for the whole Earth? **(4 points)**

Now let's return to the rocks in our set of objects. We included Pumice into this set to show you that nature can sometimes surprise you—have you ever seen a rock that floats?

Would it surprise you to find out that Pumice has almost the same composition as Gabbro and Obsidian? It is mostly SiO_2! So how can this rock float?! Let's try to answer this.

Question #8: If Pumice has the same basic composition as Gabbro, how might it have such a low density? [Hint: think about a boat. As you have found out, cubes of pure metals do not float. But then how does a boat made of iron (steel) or aluminum actually float? What is found in the boat that fills most of its volume?] **(2 points)**

Question #9: Dry air has a density of 0.0012 g/cm^3, let's make an estimate for how much air must be inside Pumice to give it the density you measured. Note: this is like the alloy problem you worked on above, but the densities of one of the two components in the alloy is essentially zero. **(6 points)**

You measured the volume of the piece of Pumice along with its mass, and then calculated its density. We stated that density = mass/volume. But you could re-arrange this equation to read volume = mass/density. **Assume that the density of the material that comprises the solid parts of Pumice is the same as that for Gabbro.**

a) What would be the volume of a piece of Gabbro that has the same mass as your piece of Pumice?

$$\text{Volume(Gabbro)} = \text{Mass(Pumice)/Density(Gabbro)} = \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} \quad \text{cm}^3$$

b) Now take the value of the volume you just calculated and divide it by the volume of the Pumice stone that you measured:

$$\text{r} = \text{Volume(Gabbro)/Volume(Pumice)} = \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} \, \%$$

This ratio, "r", shows you how much of the volume of Pumice is occupied by **rocky material**. The volume of Pumice occupied by "air" is:

$$1 - \text{r} = \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} \, \%$$

Pumice is formed when lava is explosively ejected from a volcano. Deep in the volcano the liquid rock is under high pressure and mixed with gas. When this material is explosively ejected, it is shot into a low pressure environment (air!) and quickly expands. Gas bubbles get trapped inside the rock, and this leads to its unusually low density.

Name:________________________________
Date:_________________________________

7.4 Take Home Exercise (35 points total)

For the take-home part of this lab, we are going to explore the densities and compositions of other objects in the Solar System.

1. Use your textbook, class notes, or other sources to fill in the following table **(10 points)**:

Object	**Average Density (g/cm^3)**
Sun	
Mercury	
Venus	
Mars	
Ceres (largest asteroid)	2.0
Jupiter	
Saturn	
Titan (Saturn's largest moon)	
Uranus	
Neptune	
Pluto	
Comet Halley (nucleus)	0.1

2. Mercury, Venus, Earth, and Mars are classified as Terrestrial planets ("Terrestrial" means Earth-like). Do they have similar densities? Do you think the have similar compositions? Why/Why not? **(3 points)**

3. Jupiter, Saturn, Uranus and Neptune are classified as Jovian planets ("Jovian" means Jupiter-like). Why do you think that is? Compare the densities of the Jovian planets to that of the Sun. Do you think they are made of similar materials? Why/why not? **(6 points)**

4. Saturn has an unusual density. What would happen if you could put Saturn into a huge pool/body of water?? (Remember water has a density of 1 g/cm^3, and recall the density and *behavior* of Pumice.) **(2 points)**

5. The densities of Ceres, Titan and Pluto are very similar. Most astronomers believe that these three bodies contain large quantities of water ice. If we assume roughly half of the volume of these bodies is due to water (density = 1 g/cm^3) and half from some other material, what is the approximate mean density of this other material? Hint: this is identical to the alloy problem you worked-on in lab:

$$\text{Density(Ceres/Titan/Pluto)} = (1.0\ \text{g/cm}^3 + \text{X g/cm}^3)/2.0$$

Just solve for "X" (if this hard for you, see the section "Solving for X" in Appendix A at the end of this manual). What material have we been dealing with in this lab that has a density with a value *similar* to "X"? What do you conclude about the composition of Ceres, Titan and Pluto? **(8 points)**

6. The nucleus of comet Halley has a very low density. We know that comets are mostly composed of water and other ices, but those other ices still have a higher density than that measured for Halley's comet. So, how can we possibly explain this low density? [Hint: Look back at Question #9. Why is Pumice so light, even though it is a silicate rock?] What does this imply for the nucleus of comet Halley?!!] **(6 points)**

7.5 Possible Quiz Questions

1. What is the difference between mass and weight?
2. How do you calculate density?
3. What are the physical units on density?
4. How do astronomers use density to study planets?
5. Does the shape of an object affect its density?

7.6 Extra Credit (ask your TA for permission before attempting, 5 points)

Look up some information about the element Mercury (chemical symbol "Hg"). Note that at room temperature, Mercury is a liquid. You found out above that, depending on density, some objects will float in water (like pumice). What is the density of Mercury? So, if you had a beaker full of Mercury, which of the metals you experimented with in this lab do you think would float in Mercury? In Question # 7, we discussed that the core of the Earth is much more dense than its crust, and concluded that there must be a lot of iron at the center of the Earth. Given what you have just found out about rather dense materials floating in Mercury, apply this knowledge to discuss why the Earth's core is made of molten (=liquid) iron, while the crust is made of silicates.