Freezing water expands, causing crevices in pavement to widen. Traffic turns the crevices into pot-holes.

CHAPTER 2
Some Useful Measurements of the Environment

You will know something about making measurements of the environment if you can:

1. Determine the density of a given sample of material.
2. Describe how the density of a material is affected by changes in temperature and/or pressure.
3. Explain how water differs from most materials when it changes state.
4. Use instruments to measure temperature, pressure, humidity, and wind speed and direction.

The full range of properties of the environment that can be observed and measured is enormous. That is why science is usually subdivided into specialties, with different investigators concentrating on different areas of study. That is also the reason for separating your science education into different subjects. This year you are studying earth science. In later years, you may take courses in biology, chemistry, physics, and so on. But since this is your year for earth science, you will be narrowing your scientific attention to matters of chief importance in that science. In this chapter we will take a look at some of the properties of the environment with which you will be particularly concerned.

DENSITY

You have already learned that some measurements are combinations of two or more of the basic quantities. One combined measurement that is important in earth science is *density*. Density is a measure of the *concentration* of matter (mass) in a given space.

You know from your experience that some things are heavier than others, and that the difference is more than just a difference in size or volume. If you had samples of many different materials, all the same volume, you could arrange them (classify them) by weight from heaviest to lightest. Since all the samples have the same volume, the heavier ones obviously have more mass packed into the same volume than the lighter ones have. This is what we mean by density. It is a characteristic of a material that does not depend on the size of the sample we have.

Now let's be a bit more precise about the meaning of the term density. Density is defined as the *mass per unit volume* of a sample of matter. That is, it is the mass of a single unit of volume. If we measure mass in grams and volume in cubic centimeters, density is the number of grams in 1 cubic centimeter.

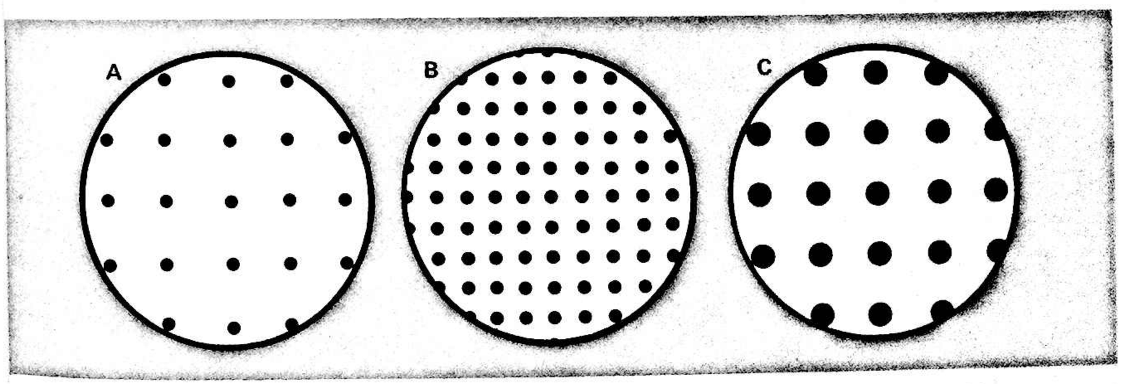
Finding Density. It is easy to see that we don't have to obtain an exact cubic centimeter of a substance, and weigh that cubic centimeter, to find its density. If we know the volume of a sample, and we find its mass by weighing it, we can calculate the density by dividing the mass by the volume:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

In mathematical symbols:

$$D = \frac{M}{V}$$

Figure 2-1. The meaning of density. The density of a material is its mass per unit of volume. Density depends partly on the mass of the particles in a substance and partly on how closely they are packed. In *B* the density is greater than in *A* because there are more particles (with the same mass) in the same volume. In *C* the density is greater than in *A* because the particles in *C* have more mass.



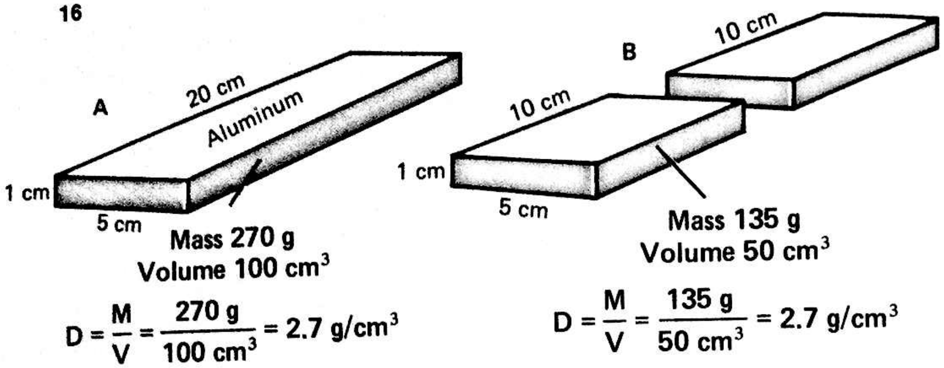


Figure 2-2. Density of pure samples. From these two illustrations you can see that the density of aluminum is the same regardless of the size, shape, or mass of the sample. This is true of any pure substance.

To understand the usefulness of the idea of density, look at Figure 2-2. In A, we see a bar of aluminum that has a mass of 270 grams and a volume of 100 cubic centimeters (100 cm^3). Applying the density formula, we find that the density of the bar is 2.7 grams per cubic centimeter ($D = 2.7\ g/cm^3$).

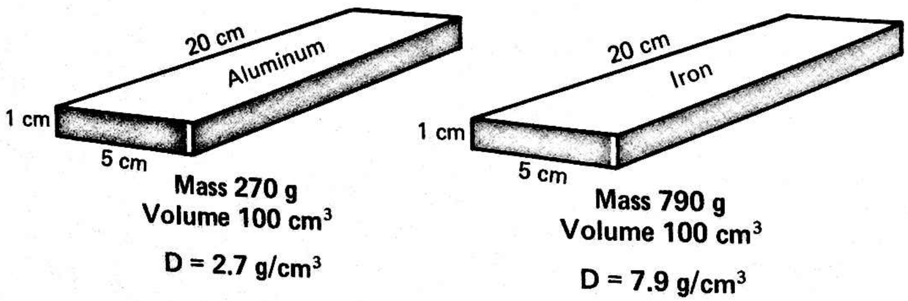
In B, the bar has been cut into two pieces. Each piece now has only half the mass of the original piece—135 g. But the volume of each is also only half as large—50 cm^3. When we calculate the density of each piece, it comes out to the same value—2.7 g/cm^3.

This is, of course, not much of a surprise. We expect a pure material, such as aluminum, to be the same throughout. The ratio of its mass to its volume should naturally be the same no matter how large or small a piece we have. If we cut a piece precisely 1 cm^3 in volume, it would have a mass of 2.7 g.

In short, the density of a piece of aluminum is always the same—2.7 g/cm^3—regardless of its size, shape, or mass. On the other hand, the density of some other material would be different. In Figure 2-3, we see a bar of iron of exactly the same dimensions as the bar of aluminum in Figure 2-2. Its volume is therefore the same—100 cm^3—but its mass is considerably greater—790 g. The density of iron is 7.9 g/cm^3, almost three times as great as that of aluminum.

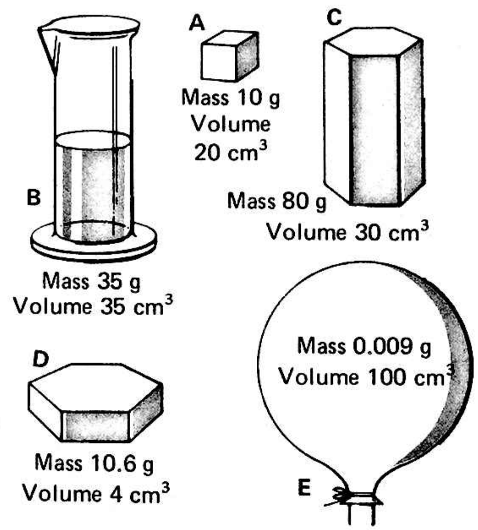
Each pure substance has its own particular density. Density is therefore a characteristic that helps to identify a material. A piece of metal with a density of 2.7 g/cm^3 is probably aluminum; a metal with a density of 7.9 g/cm^3 is probably iron.

Figure 2-3. Densities of two different substances.



Can you apply the principle of density to the samples of matter in Figure 2-4? Arrange the materials in order of increasing density. Can you find two or more specimens that are probably the same material?

Figure 2-4. Arranging samples by density. Samples *C* and *D* are probably aluminum.

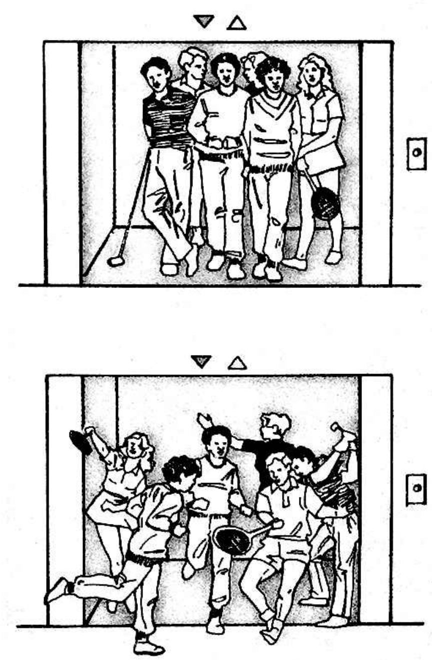


We have said that each substance has a definite density that is characteristic of the material. This is strictly true only when the temperature and pressure remain the same. This is an especially important requirement in the case of gases, as we shall see in a moment. It is also important to remember that only pure substances have a definite density. Materials such as rocks, which can be mixtures of several minerals in various proportions, will not have a very precise density. However, rock types will have a certain average density that can help to identify them.

Changing the Density of a Substance. You have probably heard it said that cold air is heavier than warm air, and that is why cold air sinks and warm air rises. That statement can be made scientifically correct by changing the word "heavier" to "denser." Why is cold air usually denser than warm air? The following example may help you to understand the reason.

If a group of people try to crowd into an elevator, more of them can get in if they all stand still with their arms at their sides. But if they start a heated competition, moving their bodies and jumping up and down, not as many can get into the elevator. There

Figure 2-5. Density and temperature. More people will fit into the elevator if they are behaving calmly and "coolly" than if they are acting "heatedly." As temperature increases, density generally decreases.



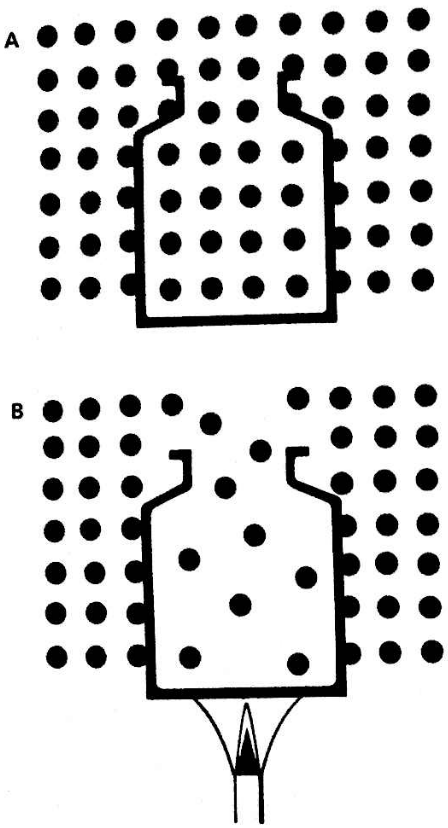


Figure 2-6. Temperature and density of a gas. In an open, unheated bottle *(A)* the density of the gas is the same as that of the surroundings. When the bottle is heated *(B)*, the molecules of the gas inside begin to move more rapidly, and some of them move out of the bottle. Thus the gas inside the bottle becomes less dense.

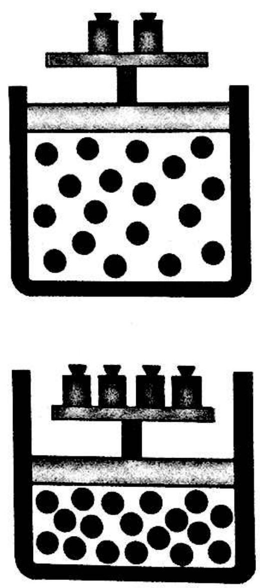
will be less mass (fewer people) in the same volume (the space in the elevator), and the "people density" will be less.

Something similar happens in a heated gas. Heating the gas adds energy to it. Its molecules begin to move more rapidly, they collide with more force, and they therefore tend to spread apart. Thus a heated gas tends to become less dense (see Figure 2-6). Removing energy by cooling the gas tends to make it more dense. These changes in density occur only if the gas is *able* to expand or contract. In a sealed container, heating a gas raises the pressure, rather than lowering the density, since the agitated molecules have no way to get out.

Solids and liquids also expand and contract with changes in temperature, but to a much lesser extent than gases. Therefore their densities are also affected to a much lesser extent.

Pressure is another factor that affects the density of gases. (Solids and liquids are also affected by pressure changes, but to a lesser extent.) Increasing the pressure packs the molecules of a gas closer together (see Figure 2-7). The gas contracts. This

Figure 2-7. Pressure and density of a gas. Increasing the pressure on a gas in a closed container causes an increase in the density of the gas because the molecules of the gas are packed closer together.



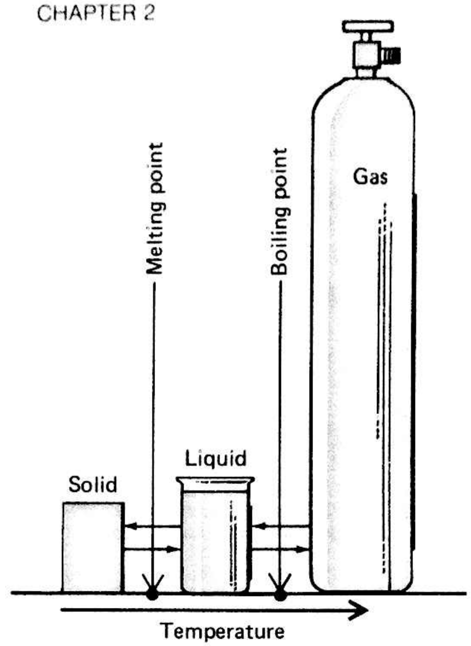


Figure 2-8. Change in volume with change of state. Most common substances increase in volume (and decrease in density) as they change from a solid to a liquid and from a liquid to a gas. Water is an exception.

means that more molecules can fit in a given volume, and so the density is increased. If the pressure is reduced, the gas molecules move farther apart. The gas expands. So there are fewer molecules in a given volume, and the density is decreased.

Density and the States of Matter. As you know, heating or cooling a substance can cause other changes besides a change in volume or density. Heating may cause the material to melt, evaporate, or boil; cooling may cause it to condense or freeze. In other words, it may change its *physical state*, or *phase*.

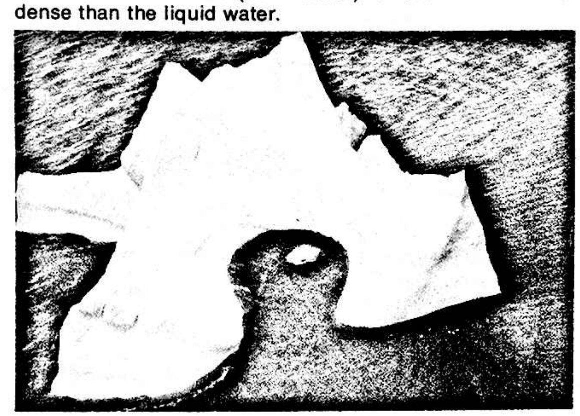
The three states of matter are solid, liquid, and gas. Elements and many chemical compounds change state at definite temperatures, called their melting and boiling points. As a substance changes state, its volume usually changes sharply also, especially between the liquid and gas states. Its density therefore changes in the opposite direction. These ideas are pictured in Figure 2-8.

What Figure 2-8 shows is true of most materials that exist in the three states. But the most common substance on the earth is an exception. That substance is water. Let us examine the behavior of water as its temperature and state change.

Water and Density. Water is the only substance that we find naturally in all three states on the earth. In fact, wherever the temperature is below the freezing point (0°C), we are likely to find all three of the states of water present at the same time.

In Figure 2-9, we see a photograph of water in the solid state (ice) floating in liquid water. This doesn't surprise us, because we are accustomed to the idea of ice floating in water. But if you think about it, you will realize that it is a very unusual phenomenon. An object floats in a liquid only if the object

Figure 2-9. The tip of an iceberg. Icebergs float because the ice (solid water) is less dense than the liquid water.



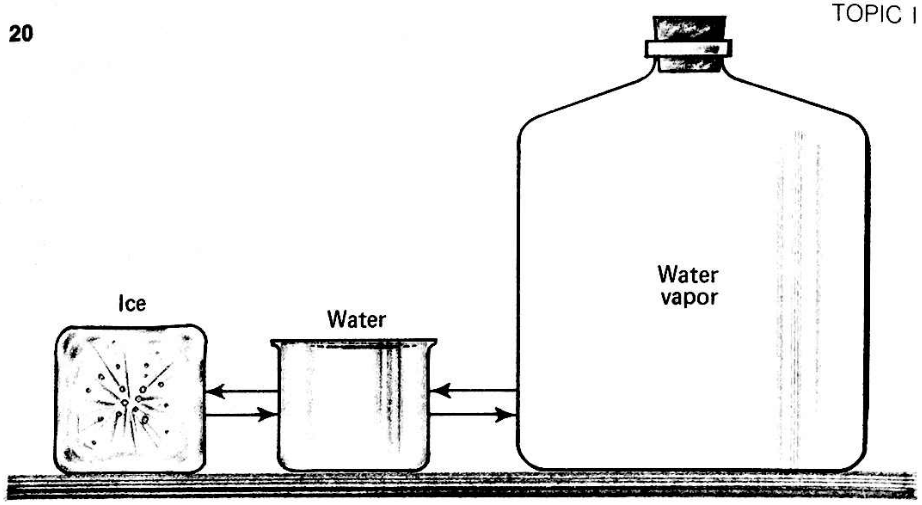


Figure 2-10. Change of state and volume of water. Unlike most other substances, water decreases in volume when it changes from a solid (ice) to a liquid. Like most other substances, it increases in volume when it changes from a liquid to a gas.

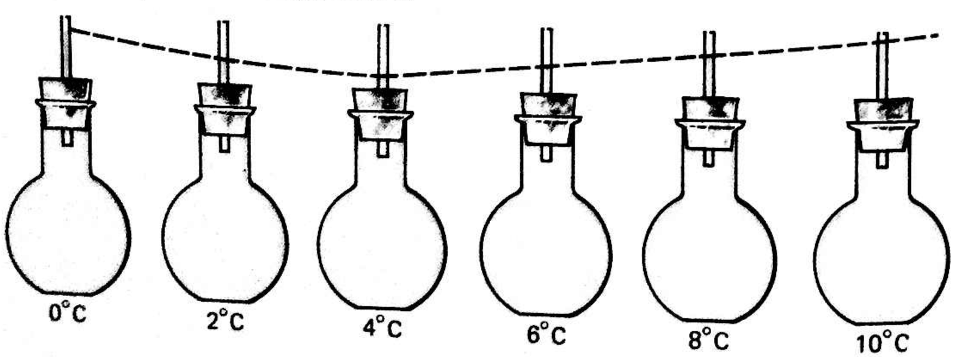
is less dense than the liquid. But as we have already stated, most substances are more dense in the solid state than they are in the liquid state. Therefore, a solid normally sinks in its own liquid. But here is a solid floating in its liquid. This means that ice must be less dense than water. The diagram in Figure 2-10 will help you see this important difference between water and other substances.

Figure 2-10 shows that the behavior of water as it changes from a liquid to a gas is normal. It does what other substances do, which is to become much less dense in the gaseous state.

But in the process of warming up from the melting point (0°C), water behaves strangely. Look at Figure 2-11. It shows a flask of water at various temperatures. The glass tube enables us to detect small changes in the total volume. Normally, a liquid expands as it is heated. But here we see that as the temperature of the water increases from 0°C, its volume *decreases* at first. Its volume does not begin to increase until its temperature passes 4°C.

What all this means is that the maximum density of water occurs in the liquid state, at a temperature of

Figure 2-11. Volume of water and temperature change. The volume of a given quantity of water is smallest at 4°C.



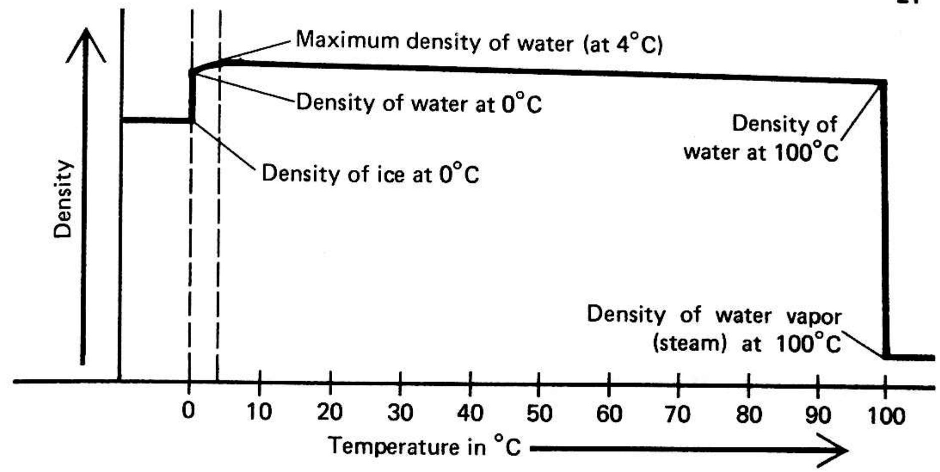


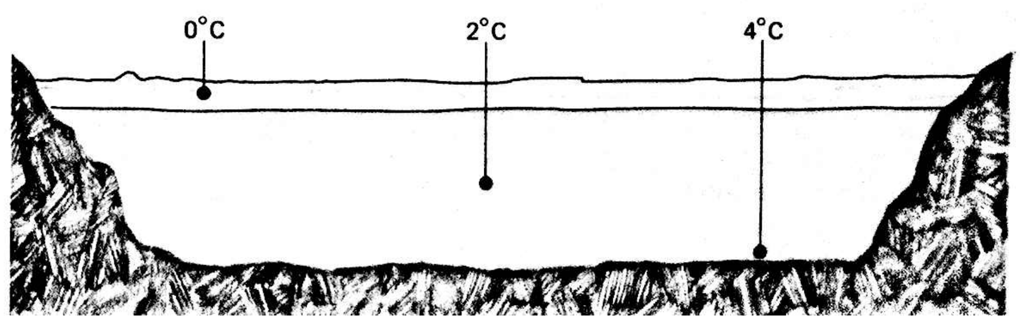
Figure 2-12. Density changes in water with change in state. Although the density of liquid water is greatest at 4°C, the amount of change between 0°C and 100°C is very little.

4°C. At 0°C, the density of water is slightly less than at 4°C, and the density of ice is even less than that. Changes in the density of water as its temperature and state change are shown graphically in Figure 2-12.

Importance of the Strange Behavior of Water. The following facts have some truly vital consequences: (1) Below 4°C water expands slightly and becomes less dense. (2) Ice is less dense than water at any temperature. If you were to measure the temperatures in a frozen pond, you would get readings something like those shown in Figure 2-13. The water at the bottom, which has to be the densest, must be at 4°C. The ice on top must be at 0°C or lower. So the water in between must gradually increase in temperature from 0° to 4° as you go deeper.

Because water near 0°C is less dense than water at 4°C, and because ice, when it forms, floats on water, ponds and lakes freeze from the top down. Since the ice acts as an insulator for the water below it, most lakes do not freeze all the way through in winter. This means that water organisms can survive the winter quite nicely in the protected waters near the bottom. It means, also, that people are able to enjoy some ice skating much earlier in winter than they might otherwise expect.

Figure 2-13. Water temperatures in an ice-covered pond. Although the top of the pond is covered with ice, the water at the bottom of the pond is at a temperature of 4°C. This allows many aquatic organisms to survive over the winter.



SUMMARY

1. Density is defined as the amount of mass in a unit volume and is expressed mathematically as Density = Mass/Volume.
2. The density of a pure substance is a characteristic that helps to identify it.
3. In most cases heating a substance decreases its density, while cooling it increases its density.
4. Increasing the pressure on a substance increases its density, while decreasing the pressure decreases its density.
5. The maximum density of most substances occurs in the solid state.
6. The maximum density of water occurs in the liquid state, at 4°C. The density of ice (water in the solid state) is less than the density of the liquid.

A WEATHER WATCH

Later in this course you will study about weather. As part of your study of that topic you may be asked to analyze and interpret weather data that you yourself have collected. In order to discover patterns or trends in the weather, you must have adequate data, so it is important that you begin your weather watch now, at the beginning of the course.

One of the points made in Chapter 1 was that there are many types of measurements that people cannot make with their unaided senses. These measurements require the use of instruments. Collecting data about the weather will require the use of instruments. Of course, you will be limited to those instruments that your school has available. The measurements that you will want to make include temperature, pressure, humidity, and wind velocity.

Temperature. As you probably know, the instrument used to measure temperature is the *thermometer*. In view of the enormous range of possible temperatures that scientists may want to measure, they need many different types of thermometers. Your window thermometer, for example, would not be much good for measuring the temperatures inside a furnace. However, for your needs in observing the weather, two basic types of thermometer will do.

1. *Liquid thermometers.* The common liquid-in-glass thermometer usually contains mercury or alcohol. The alcohol is often colored to make it easier to see. Heat energy is transferred to or from the thermometer, and the liquid in the tube expands or contracts.

One of the problems of the liquid thermometer is that it breaks easily. It is also obvious that a liquid thermometer cannot be used below the freezing point or above the boiling point of the liquid. So, a thermometer made entirely of solid parts is sometimes more practical.

2. *Bimetallic thermometers.* Bimetallic thermometers are made entirely of solid parts. In this type of thermometer, two strips of metal, usually brass and steel, are bonded together. When the strip is heated, the brass expands faster than the steel. This forces the strip to bend to one side.

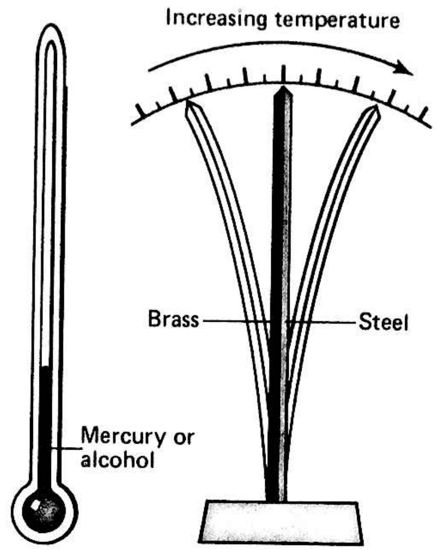


Figure 2-14. A liquid and a bimetallic thermometer.

The bending of the strip moves a pointer or similar device and gives you a temperature reading (see Figure 2-14). One of the most important reasons for using this type of thermometer is that it can be easily attached to a recording instrument.

Pressure. The deeper you go into a body of water, the more pressure you feel. This occurs because there is more water packed above and around you, and its weight is pressing on you. Your eardrums are especially sensitive to pressure.

Pressure, however, is not simply a force. It is the amount of force exerted on a unit of area. Pressure can be expressed in such units as pounds per square inch or grams per square centimeter. The same total force can result in different intensities of pressure, depending on the area over which the force is spread. A clear demonstration of this fact can be obtained with a sharpened lead pencil. Press the eraser end against your palm with moderate force. Then press the pointed end against your palm with the same force. There is much more pressure when the force is concentrated on the small area of the point—and you can feel the difference!

The atmosphere extends upward to a height of hundreds of kilometers above the surface of the earth. The weight of this air exerts pressure in the same way that water does. The amount of pressure exerted by the atmosphere varies with altitude. It is less at the top of a high mountain than it is at sea level, because the amount of air above you is less on the mountaintop. Atmospheric pressure also depends on weather conditions, so that at any location, the pressure changes constantly with the weather. There will be more about this in Chapters 10 and 11. Right now we are simply concerned with measuring air pressure.

Air pressure is measured with an instrument called a *barometer*. There are two types of barometers—mercurial and aneroid.

1. *Mercurial barometers.* The mercurial barometer is the one most commonly used by scientists. It consists basically of a narrow glass tube that is closed at one end, and a dish of mercury (see Figure 2-15).

The tube is filled with mercury and then put into the dish of mercury with the open end down. Not all the mercury runs out of the tube. Instead, a column of mercury about 76 cm high remains in the tube. The space above the mercury in the tube is a nearly complete vacuum.

The mercury is held in the tube by the force of the atmospheric pressure

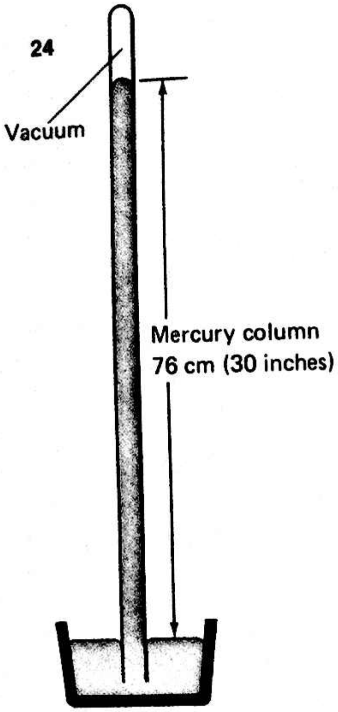


Figure 2-15. A mercurial barometer.

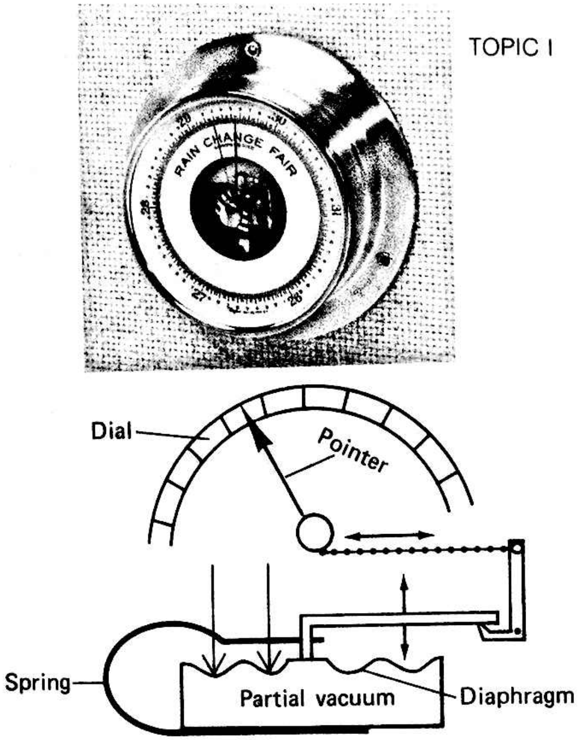


Figure 2-16. An aneroid barometer.

pressing down on the surface of the mercury in the dish. When the air pressure drops, it can support only a smaller weight of mercury, and the level of mercury in the tube drops. (Now you know what is meant by a "falling barometer.") When the air pressure rises, the mercury level in the tube rises again.

2. *Aneroid barometers*. Mercurial barometers are very delicate. They are also difficult to carry from one place to another, and cannot be read very well unless firmly fixed in proper position. These characteristics limit their usage. As an answer to these problems, *aneroid* ("without liquid") *barometers* were developed. Aneroid barometers are not as accurate as mercurial barometers, but they are much more portable and resistant to breakage. Most home barometers are aneroid barometers.

An aneroid barometer consists of an airtight box from which some of the air has been removed (see Figure 2-16). Across the top of this box is a thin, flexible sheet of metal. An increase in air pressure pushes the sheet in. A decrease in pressure permits the sheet to move out. Thus this flexible metal sheet moves in and out in response to pressure changes. This movement is magnified by a mechanical system that also moves a pointer. The pressure is read by the position of the pointer against a marked dial. The scale on the dial is marked in the same units as the scale on a mercurial barometer.

Barometer Readings. Although the units of pressure are force per unit area, barometers are usually read in terms of the height of the mercury column that the air pressure can support. Thus standard atmospheric

pressure at sea level is usually given as 76 cm. This is the height of the mercury column. (It is understood that the centimeter is not a unit of pressure, and that we are just using a convenient shorthand notation.) Since atmospheric pressure varies with altitude, barometric readings taken above or below sea level are corrected for this variation. Atmospheric pressure at sea level seldom falls below 71 cm, except possibly in the eye of a hurricane or tornado. High pressures rarely go above 79 cm.

In weather reports in the United States the barometric pressure is commonly given in *inches* of mercury, instead of in centimeters. Standard barometric pressure at sea level is 29.92 inches. Low readings rarely go below 28 inches, while high readings are rarely above 31 inches.

Another system for measuring air pressure uses a unit called a *millibar* (mb). This unit is derived from a unit of force called a dyne. Since this unit is no longer in favor with scientists, we won't go into a complete explanation of its meaning. Standard pressure at sea level is 1013.2 mb. Normal pressure varies from about 950 to 1050 mb. A comparison of barometric scales is shown in Figure 2-17.

Humidity. Humidity is the amount of water vapor, or water in the gaseous phase, in the air. Water vapor in the air comes from the evaporation of water from the earth's surface and from water vapor given off by living organisms.

The amount of water vapor that can be present in the air varies with temperature. The higher the temperature, the more water vapor the air can hold. Air containing the maximum amount

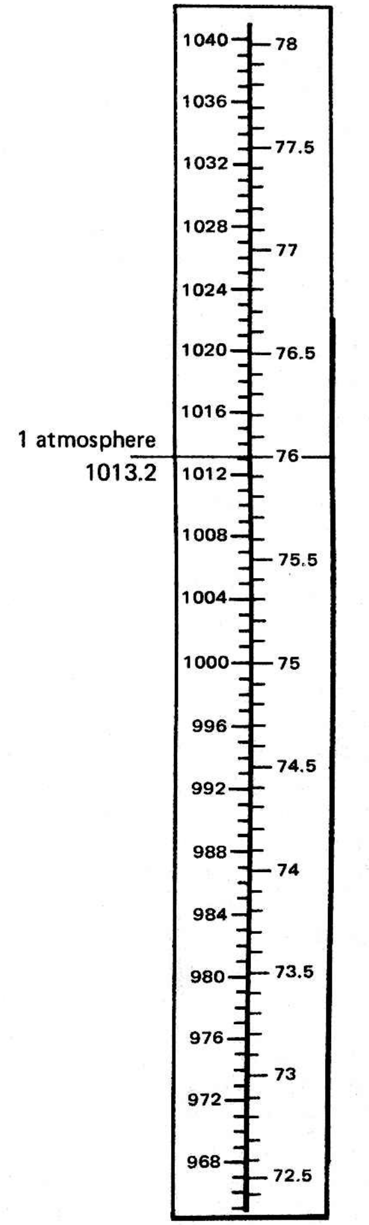


Figure 2-17. Barometric scales.

of water vapor it can hold at that temperature is said to be *saturated.*

The water vapor content of the air is often given in terms of *relative humidity* or *dew point*.

1. *Relative humidity.* Relative humidity is the ratio of the amount of water vapor in the air to the maximum amount that could be present at that temperature. It is expressed as a percent. Air containing one-half the amount of water vapor that it could hold at the temperature has a relative humidity of 50%. Absolutely dry air has a relative humidity of 0%, while saturated air has a relative humidity of 100%.

2. *Dew point.* As we have already mentioned, the amount of water vapor the air can hold decreases with falling temperature. If the amount of water vapor in the air remains the same, the relative humidity of the air increases as the temperature drops.

Think of what happens to a cold can of soda on a hot summer day. When you take it out of the refrigerator, the outside of the can is dry. But after it sits out in the air for a little while, the outside of the can becomes covered with drops of water. What has happened is that the air that is in contact with the can has become colder. This cold air cannot hold as much water vapor as the surrounding hot air, so some of the water vapor condenses on the can.

What this shows is that it is not necessary to add water vapor to increase the relative humidity of air. Decreasing its temperature will have the same effect. As the temperature of air drops, its relative humidity increases. Eventually the relative humidity becomes 100%, which

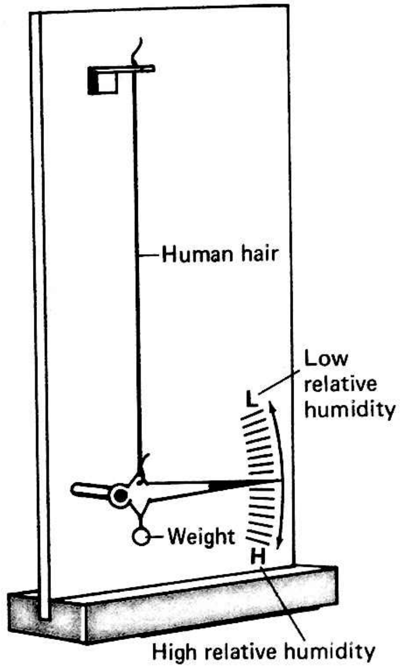


Figure 2-18. A hygrometer.

means that the air is saturated. The temperature at which air becomes saturated is called the *dew point*. It is the temperature at which water vapor begins to condense out of the air, forming drops of dew on surfaces in contact with it.

Measuring Relative Humidity. An instrument used to measure relative humidity of the air is called a *hygrometer* (see Figure 2-18). One type of hygrometer contains a thin bundle of human hair connected to a pointer. Hair is very sensitive to changes in relative humidity, lengthening with increased relative humidity, and shortening with decreased relative humidity. With this type of hygrometer, relative humidity is read directly from the position of the pointer on a scale (or similar arrangement).

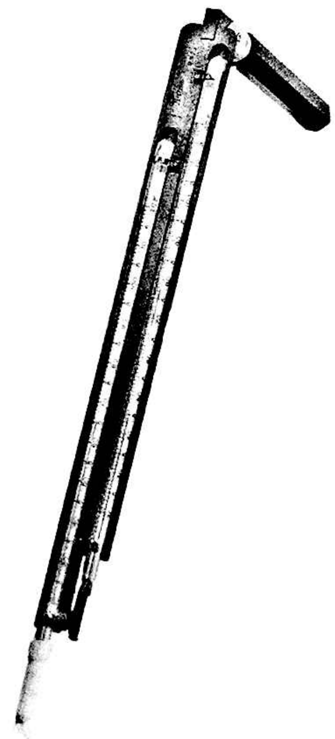


Figure 2-19. A psychrometer.

Another type of hygrometer is called a *sling psychrometer*. It is a simple instrument consisting basically of two ordinary liquid-in-glass thermometers fastened together. They are attached to a handle by which they can be whirled through the air (see Figure 2-19). One of the thermometers has a cloth sock or cover over its bulb, which is moistened before the instrument is used. This is the *wet-bulb thermometer.* The other thermometer has its bulb exposed to the air. It is called the *dry-bulb thermometer.*

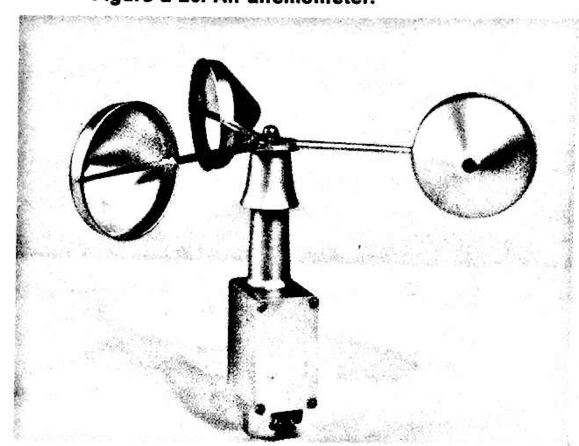
As you whirl, or sling, the psychrometer, evaporation of water from the cloth lowers the temperature of the wet-bulb thermometer. The temperatures of the wet-bulb and dry-bulb thermometers and the difference between them (the "wet-bulb depression") can be used to find both the relative humidity and the dew point of the air. Special tables and charts enable you to do this. (See page 539.)

Wind Velocity. Wind speed and wind direction are usually reported as one reading, which is called *wind velocity.* In terms of weather conditions and patterns it is important to know not only how hard the wind is blowing, but also from which direction it is blowing. It may make a great difference whether the wind is from the north or from the south.

The direction given is always the direction from which the wind is blowing. A north wind is coming from the north, and going toward the south.

An instrument used to measure wind speed is called an *anemometer* (see Figure 2-20). A *wind vane,* or *weather vane,* indicates wind direction.

Figure 2-20. An anemometer.



SUMMARY

1. The most common weather measurement is the measurement of air temperature.
2. Pressure is force per unit of area.
3. Atmospheric pressure is caused by the weight of the air above a given unit of area. The pressure at a given time and place decreases with increasing altitude.
4. Atmospheric pressure is most frequently expressed in terms of the height of the mercury column it will support.
5. Relative humidity is the ratio (expressed as a percent) between the amount of water vapor in the air and the maximum amount that could be present at the given temperature.
6. The dew point temperature is the temperature at which the air becomes saturated.
7. Wind velocity includes speed and direction.

REVIEW QUESTIONS

Group A

1. Define *density*. How is density expressed mathematically?
2. How can a measurement of density help to identify a substance?
3. How does heating or cooling a substance affect its density?
4. How does increasing or decreasing the pressure on a substance affect its density?
5. The maximum density of most materials occurs in which state—solid, liquid, or gas?
6. In which state does the maximum density of water occur? At what temperature does it occur?
7. What are the most common weather measurements?
8. Define the term *pressure*.
9. What causes atmospheric pressure?
10. How does atmospheric pressure vary with altitude?
11. What is *relative humidity*?
12. What is the *dew point*?
13. What two factors must be given in describing wind velocity?

Group B

1. You have just determined the density of a 50-gram sample of granite to be 2.5 g/cm^3.
   a. What would be the density and the volume of a 100-gram sample of granite taken from the same location?
   b. What would be the density and the mass of a 40-cm^3 sample of granite taken from the same location?
   c. What will be the effect on your determination of the density of a particular material if you use a larger sample of the material? If you use a smaller sample?

2. During an early spring morning the air temperature rises from 2°C (just above the freezing point) to 10°C. What effect does this rise in temperature have on the density of the air? Would the effect on the density of the soil be (greater than, the same as, less than) the effect on the density of the air? Why?
3. Water in the solid state (ice) floats in water in the liquid state. Would you expect a piece of solid lead to float in liquid lead? Explain your answer.
4. Suppose you wanted to keep a record of the following weather conditions: temperature, pressure, humidity, wind speed, and wind direction. Suppose also that you had to compile your record without the help of *any* equipment. Compare the accuracy and precision of your records with the records kept by a classmate who used ordinary weather instruments.

REVIEW EXERCISES

1. Choose a convenient location (at school, at home, outdoors). Examine the area carefully. Make a list of statements about the area. Now on another sheet of paper classify each statement as either an observation (0) or an inference (I). Have another student read your list of statements and classify them. Compare your classifications with his to see if they agree. Discuss any statements that you did not agree on.
2. Obtain an almanac or similar reference book from your library. Find ten facts (sports records, etc.) that involve measurements. Classify the measurements as fundamental (F) or derived (D). Try to identify the units involved in each measurement (time, length, etc.).
3. How accurate is your car's odometer (mileage meter)? Measure a certain distance on a road map. Now have someone drive over the same route. Using the map distance as the correct one, what was the percentage error in your odometer reading?
4. Find the density of a piece of modeling clay. (Hint: Think of the mathematical formula for density. How can you find mass? How can you find volume?) Now press or roll the clay into different shapes, and measure the density each time. Are all your density measurements equal? Should they be?
5. What is the density of water at room temperature? Is the density of ice really less than that of water? Can you think of a way to measure the density of ice accurately? (Hint: Ice floats in water, but will it float in liquids that are less dense than water? How can such liquids help you find the density of ice?)