

The Separation of Substances

In this chapter, we shall use the characteristic properties we have studied to work out a variety of methods for separating mixtures of different substances. These mixtures may be gases, liquids, or solids. By learning how to separate many kinds of mixtures, we also hope to come closer to understanding how simple substances are put together to form the many complex materials that are all around us. We shall start with a careful investigation of what happens when we distill a mixture of liquids.

5.1 EXPERIMENT FRACTIONAL DISTILLATION

In this experiment, you will determine some of the properties of a mixture of liquids. Then you will distill the mixture and examine the properties of the fractions to see if you succeeded in separating the liquids that made up the original mixture.

Part A

- Can you tell just by looking at it that the liquid is a mixture?
- Does the liquid have an odor?

Dip a small piece of paper in the liquid, and try lighting the

liquid on the paper with a match. Be sure to have a bucket with some water on your table in case the paper burns.

- Does the liquid burn?

- What is its density?

- Does sugar dissolve in the liquid?

Part B

Use the apparatus shown in Figure 5.1 to distill 5 cm³ of the mixture. Use a single collecting tube, and heat the liquid just enough to keep it boiling. Record the temperature of the *vapor* from the boiling liquid every half-minute while it distills. Continue to boil the liquid almost to dryness.

Make a graph of the boiling temperature as a function of the time.

- What do you conclude from your graph about the number of fractions you should collect to separate the different substances in the mixture?

- At what temperatures should you shift from one collecting tube to another?

Indicate on your graph the temperatures at which you decided to change collecting tubes.

Part C

Now fractionally distill about 25 cm³ of the liquid. Label the test tubes containing the fractions, so that you can keep track of them throughout the rest of the experiment. Test each of the fractions for odor and flammability.

Part D

- Does sugar dissolve in fraction 1?

- What is the density of fraction 1?

Distill the fraction into a single test tube, recording the boiling temperature every half-minute until the fraction has nearly boiled away. Draw a boiling-point graph for fraction 1.

Part E

Repeat Part D for each of the other fractions.

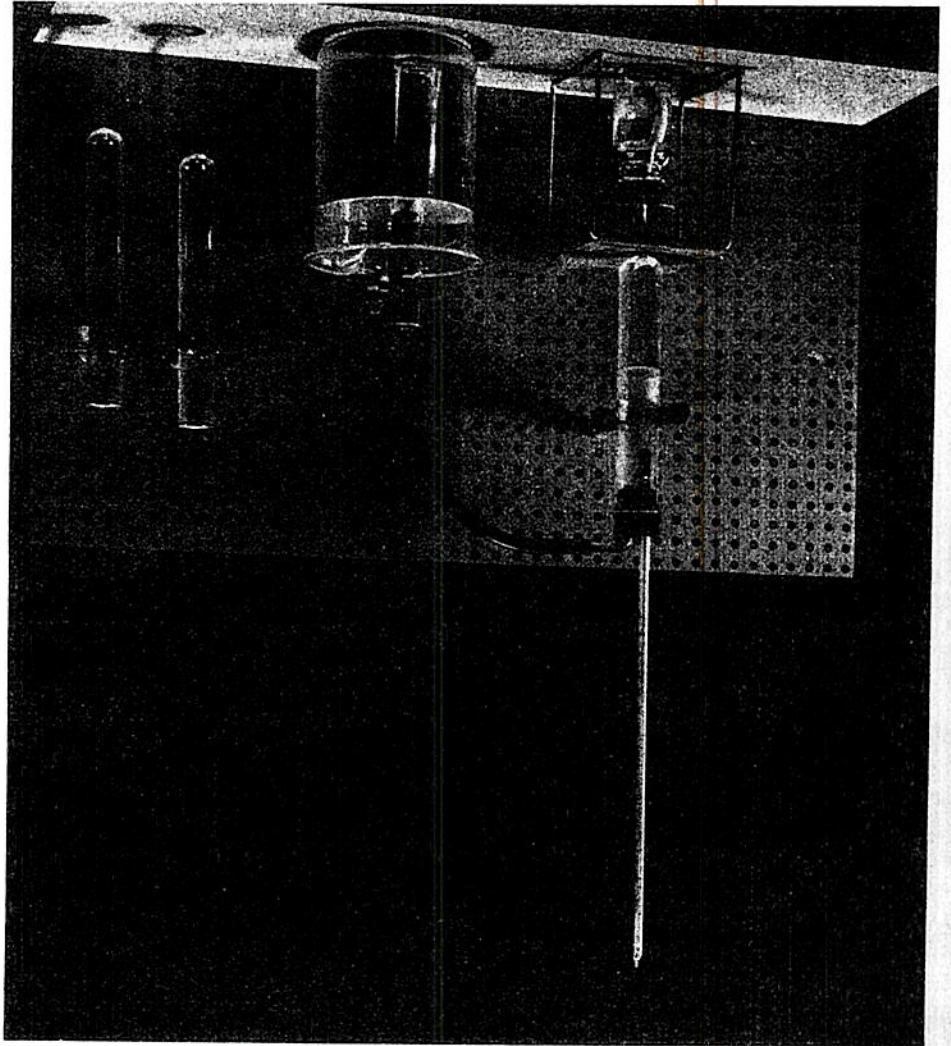


Figure 5.1

Apparatus for the fractional distillation of a liquid. The thermometer bulb is close to the top of the test tube so that it measures the temperature of the vapor that condenses in the outlet tube. If there is more than one liquid in the boiling mixture, most of the high-boiling-point liquids will condense and flow back down the test-tube walls before they reach the upper part of the test tube. The thermometer in this apparatus is not used to measure the boiling temperature of the liquid, but serves to show when collecting tubes should be changed to receive different fractions.

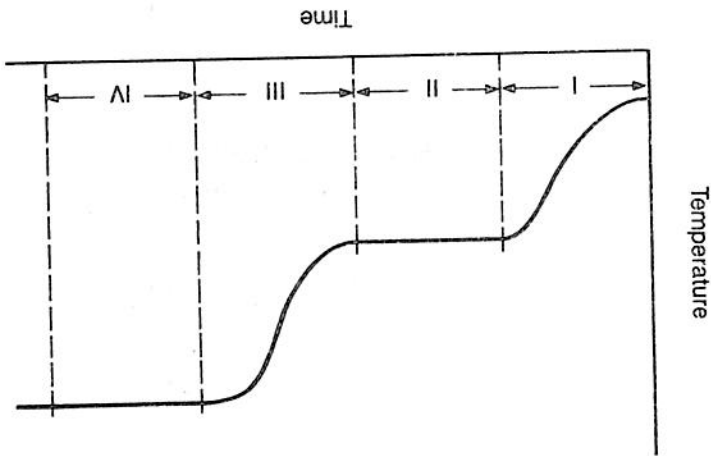
Summarize your findings, and compare the smell, flammability, density, ability to dissolve sugar, and boiling point of each of the fractions and of the original mixture.

- What do you conclude about the composition of the fractions?
- Can you identify the substances in the mixture? (See Table 3.2, page 65.)
- What other tests might you make to help identify these substances?
- What do you think would happen if you were to redistill each of the fractions separately into three fractions of equal volume?

† In what characteristic property must two liquids differ before we can consider separating a mixture of them by fractional distillation?

2 The temperature-time graph shown in Figure A was made during the fractional distillation of a mixture of two liquids, E and F, and fractions were collected during the time intervals I, II, III, and IV. Liquid E has a higher boiling point than liquid F. What liquid or liquids were collected during each of the time intervals?

Figure A
For problem 2



3 Carlos boiled a liquid and recorded the temperature at 1-minute intervals until the liquid had nearly boiled away. How do you explain the shape of the curve he got? (See Figure B.)

5.2 PETROLEUM

It is not always easy to separate a mixture of liquids into pure substances by fractional distillation. If the boiling points of the substances in a mixture are nearly the same, they will all boil off together. In a liquid mixture containing many substances, some are sure to have boiling points close together. When we distill such a mixture, each fraction we get is made up of a number of different substances whose boiling points are close together. The first part to condense in one fraction may contain some of the substances that condensed in the last part of the previous fraction. However, the fractions that are more widely separated in boiling range are less likely to contain the same substances. Petroleum is an example of such a mixture; the compositions of typical fractions distilled from petroleum are shown in Table 5.1.

Petroleum is believed to be produced naturally from animal and vegetable matter at the bottoms of shallow seas and swamps. When tiny plants and animals die in the sea, they settle slowly to the bottom, where they become trapped in mud and sand. This sediment of mud, sand, and dead organisms slowly becomes thicker and thicker. In a million years, it may become hundreds of meters deep. Such layers of sediment are very heavy, and the lower layers are compressed so much that they turn into rock layers. During this time, some of the body tissue of the entrapped organisms is changed into a viscous, sticky liquid that is a mixture of many thousands of different substances. This liquid is called "petroleum" or "crude oil." It is slowly squeezed out of the sediment in which it forms and eventually spreads through porous rock layers like water in a sponge.

Figure B
For problem 3

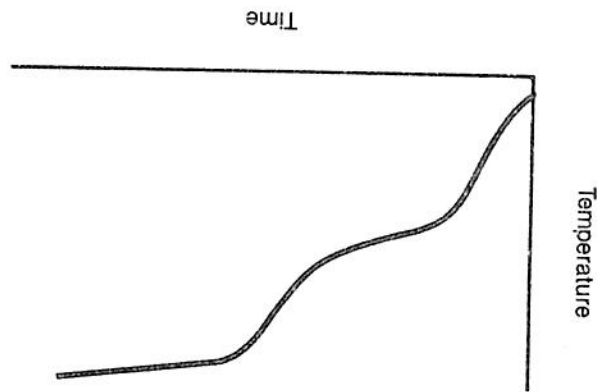


Table 5.1 A Few of the Substances Found in Petroleum

| Substance | Density at 0°C (g/cm ³) | Freezing point (°C) | Boiling point (°C) | Common products of petroleum | fuel gas | gasoline | kerosene |
|-------------|---|---------------------------|--------------------------|------------------------------|----------|----------|----------|
| Methane | 7.16×10^{-4} | -182.5 | -161 | X | | | |
| Ethane | 1.35×10^{-3} | -183 | -88 | X | | | |
| Propane | 2.02×10^{-3} | -190 | -43 | X | | | |
| Butane | 2.68×10^{-3} | -138 | -0.5 | X | | | |
| Pentane | 0.626 | -129 | 36 | | | | |
| Hexane | 0.660 | -94 | 69 | X | | | |
| Heptane | 0.684 | -90 | 98 | X | | | |
| Octane | 0.703 | -57 | 125 | X | | | |
| Nonane | 0.722 | -51 | 151 | X | X | | |
| Decane | 0.730 | -30 | 174 | X | X | | |
| Undecane | 0.741 | -26 | 196 | X | | | |
| Dodecane | 0.750 | -10 | 216 | X | | | |
| Tridecane | 0.755 | -5.5 | 236 | X | | | |
| Tetradecane | 0.765 | 5.5 | 254 | X | | | |
| Pentadecane | 0.776 | 10 | 271 | X | | | |
| Hexadecane | 0.773 | 18 | 287 | X | | | |

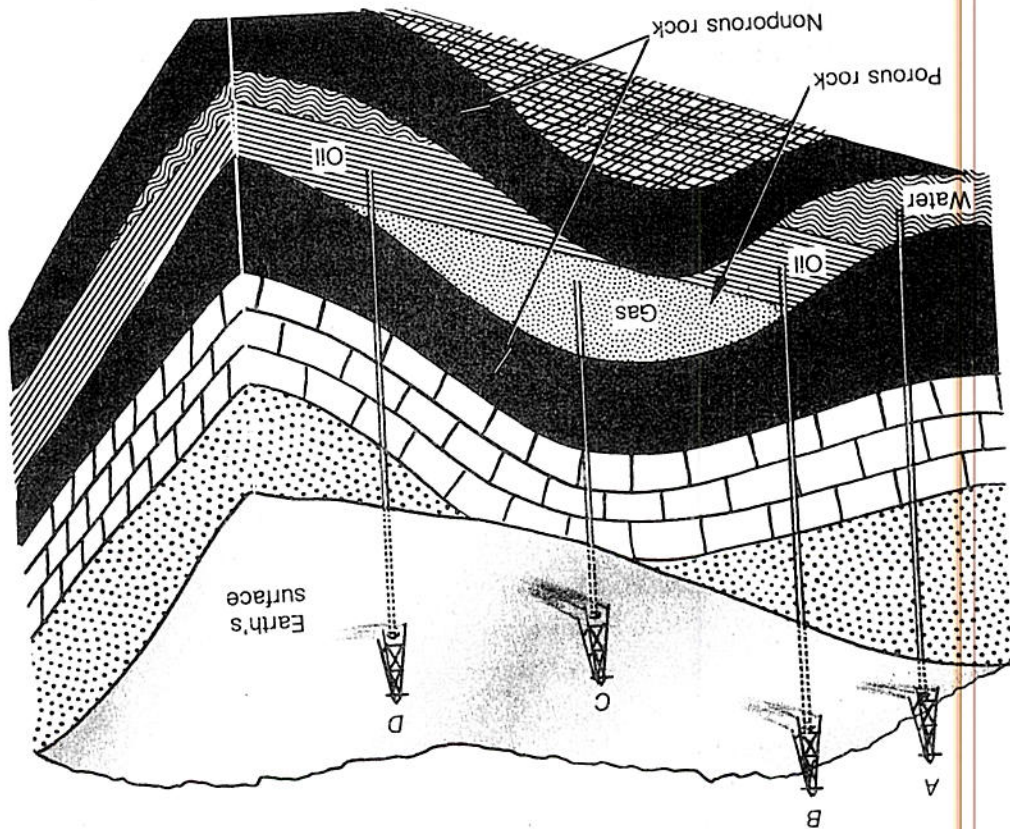
There are many more substances in the above products and also in the higher-boiling-point fractions not listed in the table—fractions such as fuel oils, lubricating oils, waxes, asphalt, and coke (mostly carbon).

In the course of more millions of years, the ever-changing crust of the earth—buckling in some places, rising in others, and sinking in still others—slowly moves and compresses the rock layers that were on the ocean bottom. Sometimes the porous oil-bearing rock is covered by a layer of hard, nonporous rock that has been bent into a dome or arch, as shown in Figure 5.2. Then the oil will be trapped, and cannot by itself squeeze to the surface. If it were not trapped, much of it would wash away and be lost. Most of the petroleum in the earth's crust is stored by nature under formations of nonporous rock, which trap the liquids below them. As Figure 5.2 shows, natural gas (the low-boiling-point substances in petroleum) and salt water from the sea are often trapped along with the oil. The nonporous "cap rock" may be hundreds of meters thick. It is expensive and difficult to drill through all this rock to get to the petroleum below, and it is not easy to predict where oil is trapped. Deep and expensive wells often fail to reach oil or gas. Some wells produce nothing but salt water, whereas others remain dry.

Petroleum was first discovered where it seeped to the surface in shallow pools. Once exposed to the air, some of the lower-boiling-point substances slowly evaporated, leaving behind tarry, almost solid asphalt. These tars, as well as the liquid petroleum, were used for many of the same purposes in the ancient world as were the tars and watery substances obtained from the distillation of wood.

One of the ancient methods used to distill crude oil consisted of heating the oil in a copper urn with a wool "sponge" at the narrow mouth of the vessel. The vapors condensed in the sponge, which was squeezed out into containers from time to time. A variation of this method made use of a heavy wick of wool that led from the mouth of the urn into a collecting vessel. Such a wick was a crude form of condenser.

Figure 5.2
 A cross section of the earth's crust, showing how oil and natural gas are trapped in a porous rock layer by nonporous rock layers above and below. Note that well A produces only water, and well C produces only gas.



The widespread use of kerosene lamps a little over 100 years ago—and the more recent use of gasoline engines—created a new demand for petroleum. This led to improved methods of locating oil and drilling wells. Better equipment was also developed for fractionally distilling petroleum on a large scale.

A simplified diagram of this equipment, called a fractionating column, is shown in Figure 5.3. Heated crude oil enters the column near the bottom. The column contains a series of horizontal trays. As vapors from the heated liquid pass up through the column, the high-boiling-point substances condense in the lower, hotter trays. As the vapors move upward, they bubble through the liquid in the trays. In each tray, the condensing vapors increase the concentration of the substances whose boiling points are higher than the temperature of the tray. The rising vapors therefore become richer in the low-boiling substances. Some of the liquid that condenses in each tray overflows into the tray below, where it becomes heated again and redistills. Each tray thus boils a particular mixture at a particular temperature. The temperature of the trays and the boiling points of the substances in them decrease as one goes higher up the column.

The different fractions leave the column at different heights (Figure 5.3). Fractions with which you are familiar are gasoline, kerosene, diesel fuel, heating and lubricating oils, paraffin, and asphalt.

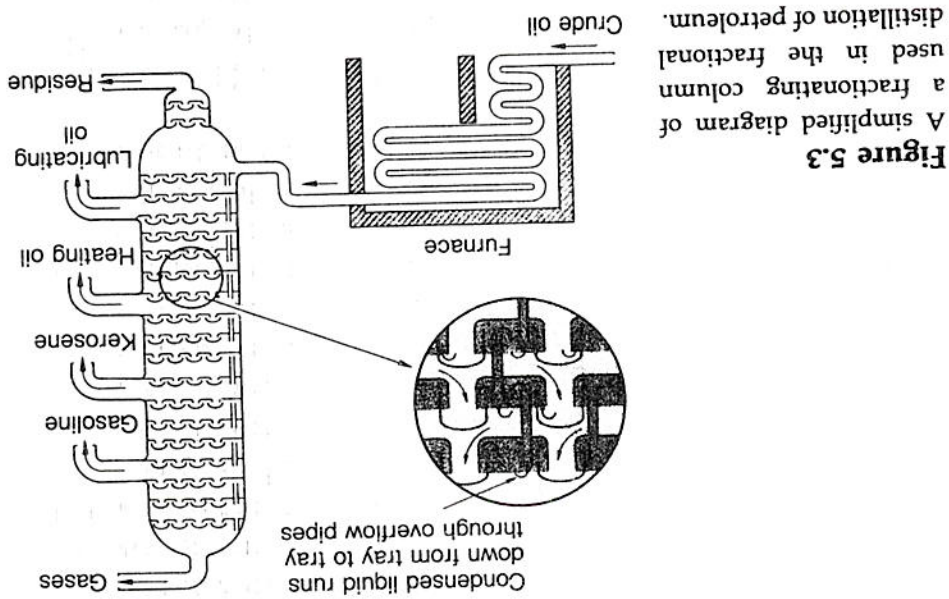


Figure 5.3 A simplified diagram of a fractionating column used in the fractional distillation of petroleum.

4 A sample of crude oil is boiled for several minutes. What change takes place in its density? (See Table 5.1.)

5.3 INDUSTRIAL DISTILLATION OF WOOD

You saw in Experiment 1 on the distillation of wood that liquids could be produced by heating wood strongly in the absence of air. To recover the maximum amount of commercially valuable substances, a different process is used. Such a process was developed about 80 years ago for utilizing the waste wood in pine-tree stumps. The process, with some improvements, is still in use today. Its success makes digging up pine-tree stumps and processing the wood profitable.

The stumps are ground up and shredded at the plant, and the shredded wood is loaded into a large cylindrical vessel called an extractor (Figure 5.4). There the wood is heated and mixed with a

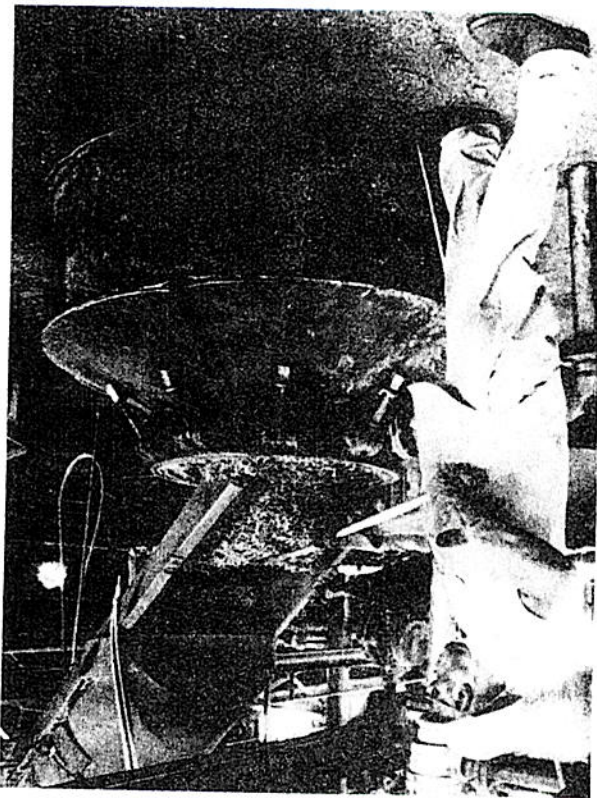


Figure 5.4

The top of an extractor being loaded with shredded pine stump. Most of the vessel is below the floor on which the worker stands. (Courtesy Newport Division, Reichold Chemicals, Inc.)

petroleum solvent—usually one whose properties lie between those of gasoline and kerosene. The solvent dissolves the desired substances contained in the wood. After some intermediate stages, the resulting solution passes through a fractionating column (Figure 5.5). The principal products of the process are turpentine, dipentene, and pine oil, together with the petroleum solvent, which is used over again in the extractors. Some of the products are used directly, some are only the starting point of the manufacture of many other substances used in the chemical industry. Pine oil has a household use in disinfectants and cleaners. Among many other applications, it is often used in ore flotation (see section 5.4). Turpentine has long been used as a paint thinner. It is also used in the manufacture of adhesives, coatings, pesticides, and other materials.

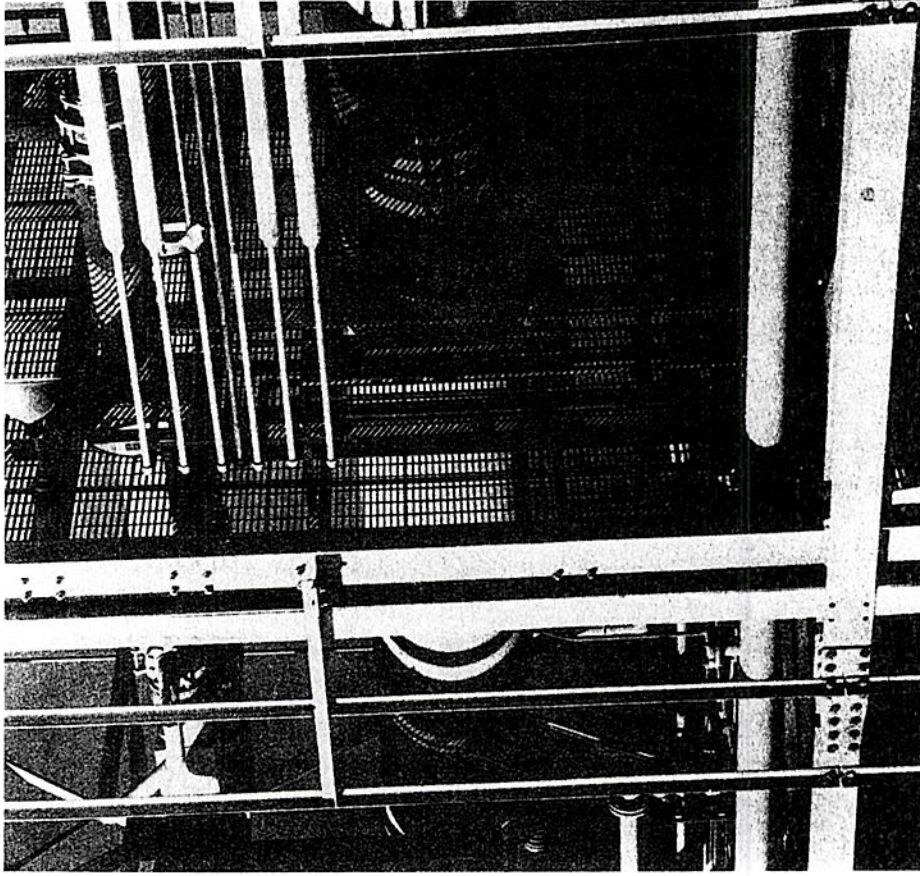


Figure 5.5

A general view of a fractionating column used in the processing of pine stumps. (Courtesy Newport Division, Reichold Chemicals, Inc.)

5.4 THE SEPARATION OF INSOLUBLE SOLIDS

- 5 Suggest a reason why stump wood is shredded before being loaded into the extractors.
- 6 Suggest a reason why the petroleum solvent is heated in the extractors.

5.4 THE SEPARATION OF INSOLUBLE SOLIDS

Solids with a density greater than that of water sink in water, and those with a lesser density float, provided they are insoluble (section 3.9). We can use this fact to separate a mixture of sawdust and sand. After stirring the mixture in water, we can skim off the floating sawdust. Then we can pour off the water and dry the sand. This method is called separation by flotation and is widely used in industry to concentrate ores (Figure 5.6). For example, a common copper ore, copper sulfide, is usually found mixed with

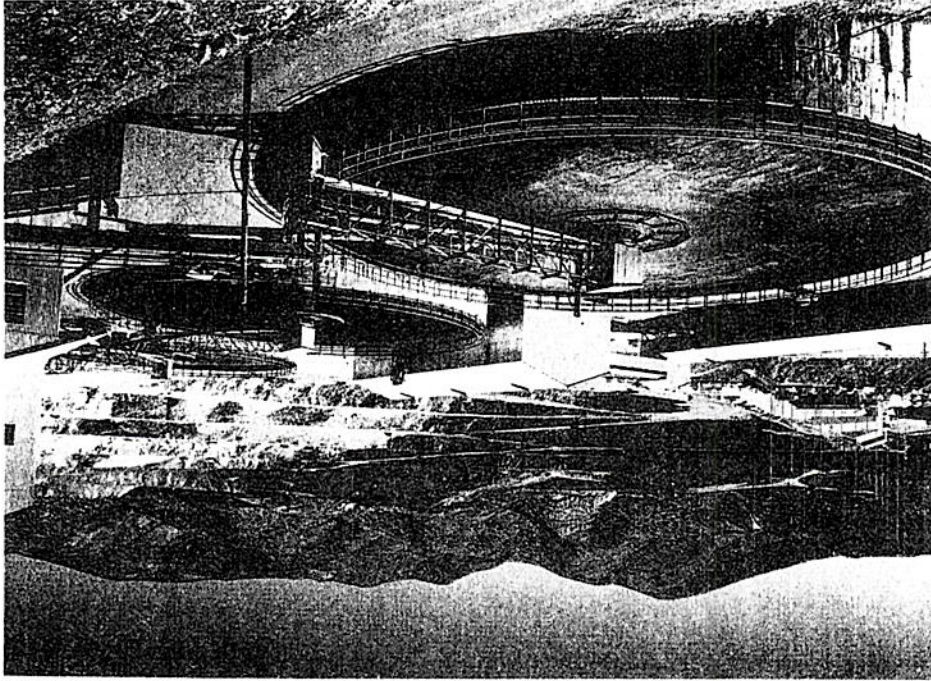


Figure 5.6 Three flotation tanks at a copper plant. (Arizona Photographic Associates, Inc.)

large amounts of worthless rock. The ore is finely ground, and then mixed with water and selected reagents. This mixture is agitated violently with air to produce a heavy foam. The copper sulfide is contained in the floating foam; the ground rock settles. The foam is removed, and the copper sulfide is recovered.

5.5 EXPERIMENT SEPARATION OF A MIXTURE OF SOLIDS

Examine the mixture of solids supplied by your teacher. If one solid is soluble in water and the other is not, you can separate them eas-

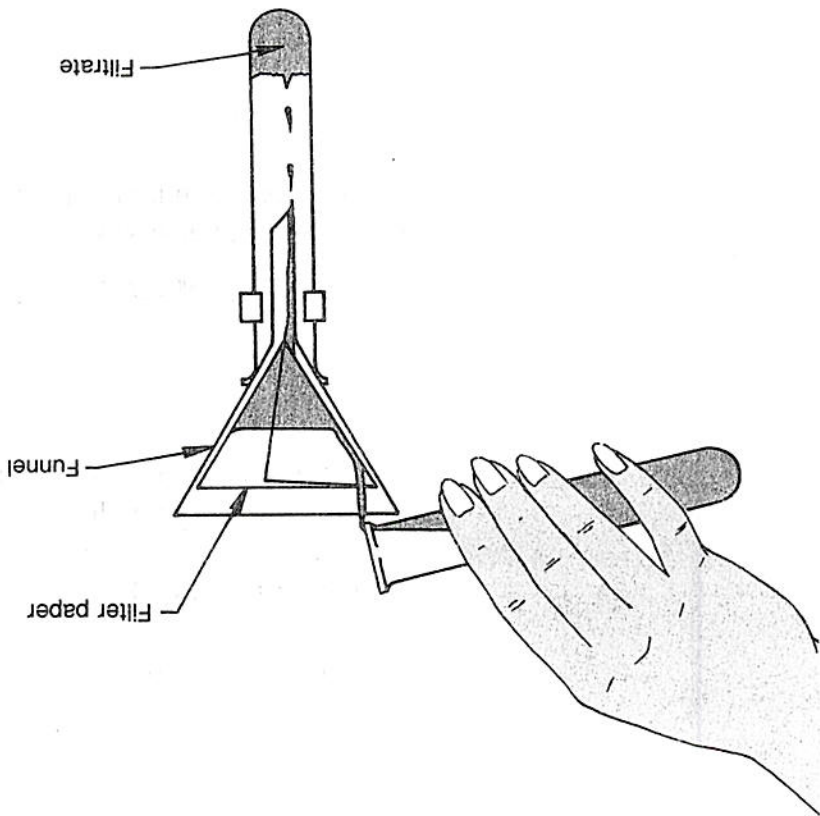


Figure 5.7 Filtering a liquid. The filter paper is folded into a cone, which fits snugly into the funnel.

ily by dissolving one and separating it from the other by filtering. You can do this in the following way: Put about 1.5 g of the mixture into a test tube, and add 5 cm³ of water. Stopper the test tube, and shake it for several minutes.

• Do you think either substance dissolved?

To find out, filter out the undissolved material, as shown in Figure 5.7. Wash the precipitate left on the filter paper by pouring an additional 10 cm³ of water into the funnel. You can now put about 5 cm³ of the clear liquid—the filtrate—into an evaporating dish and boil it to dryness.

• Have the two substances been separated?

7† In what characteristic property must two solids differ if they are to be separated merely by being dissolved at room temperature and filtered?

8 Much salt is obtained from salt mines, in which great masses of salt occur mixed with insoluble earthy impurities. What steps can be taken to purify the salt?

9 How could drinking water be obtained from seawater?

5.6 THE SEPARATION OF A MIXTURE OF SOLUBLE SOLIDS

In the previous experiment, you were able to separate two solids because one of them was soluble in water and the other was not. Suppose that you have a mixture containing 5 g of sodium chloride and 5 g of potassium nitrate. Both of these substances readily dissolve in water. In fact, as you see from Figure 5.8, at room temperature they have nearly the same solubility. Therefore, if we completely dissolve the 5 g of potassium nitrate in water, at room temperature, all of the sodium chloride will also dissolve. How can these substances be separated? Figure 5.8 shows that the solubility of sodium chloride hardly changes with temperature, whereas the solubility of potassium nitrate rises sharply with temperature. We can make use of the effect of temperature on the solubility of these two substances to separate them.

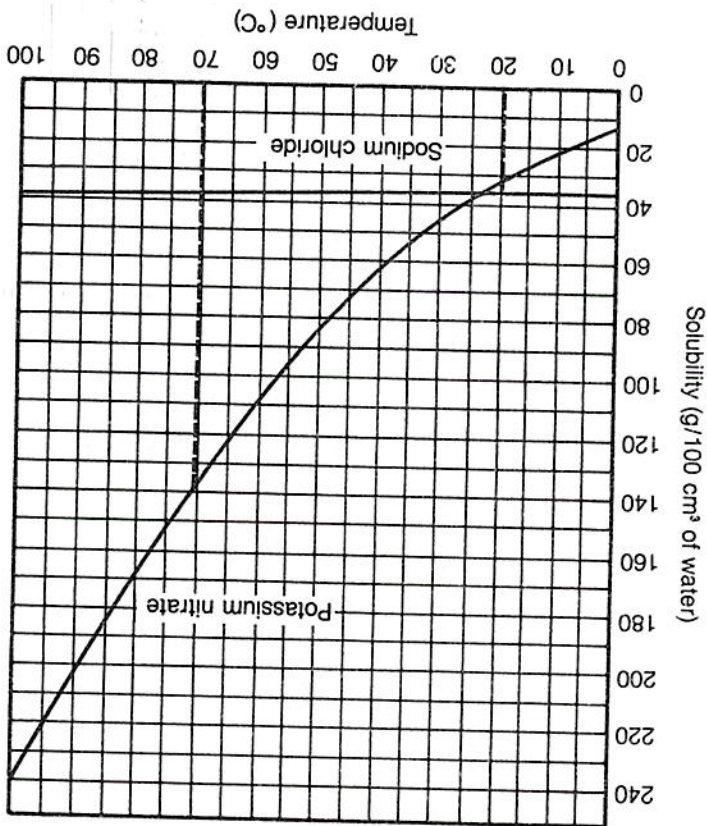


Figure 5.8 Solubility curves of sodium chloride and potassium nitrate.

Note that at 70°C, for example, 138 g of potassium nitrate will dissolve in 100 cm³ of water. Therefore, the amount of water needed to dissolve completely only 5.0 g of potassium nitrate at this temperature is 100 cm³ × 5.0 g/138 g = 3.6 cm³.

How much sodium chloride will dissolve in 3.6 cm³ of water at 70°C? To answer this question, first note from Figure 5.8 that 38 g of sodium chloride will dissolve in 100 cm³ of water at 70°C. Therefore, only 38 g × 3.6 cm³/100 cm³ = 1.4 g of sodium chloride will dissolve in 3.6 cm³ of water.

Thus, if we add a mixture of 5.0 g of potassium nitrate and 5.0 g sodium chloride to 3.6 cm³ of water, all the potassium nitrate and a small amount of sodium chloride will remain as a solid at the bottom of the test tube. Therefore, filtering the hot solution will leave most of the sodium chloride on the filter paper. The solution that passes

5.6 THE SEPARATION OF A MIXTURE OF SOLUBLE SOLIDS

through the filter paper will contain all the potassium nitrate and some sodium chloride. What will happen if we let the filtered solution cool to room temperature? Referring again to Figure 5.8, we see that practically all of the dissolved sodium chloride and some potassium nitrate will remain in the solution. However, most of the potassium nitrate will precipitate out as a solid and can then be separated from the solution by filtration. This process is summarized in Figure 5.9.

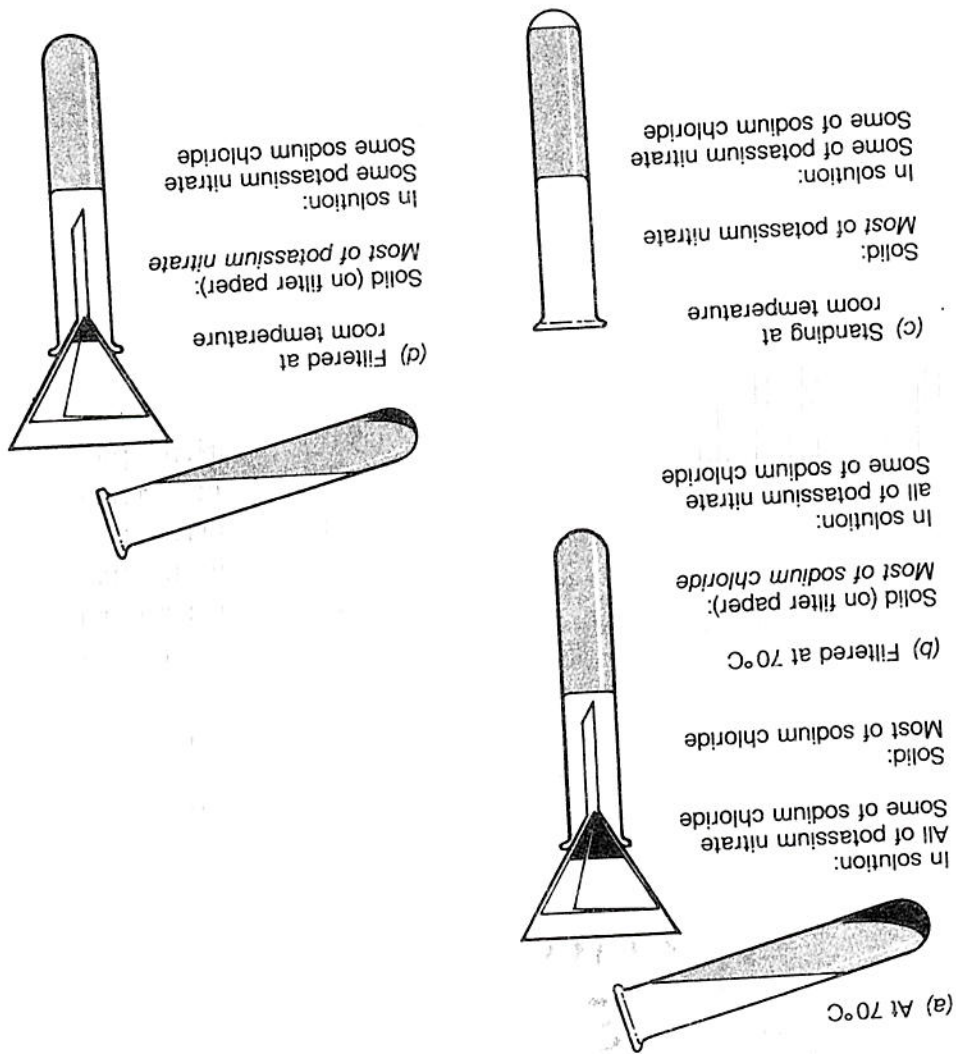


Figure 5.9 A diagram of the series of steps for separating a mixture of equal masses of sodium chloride and potassium nitrate.

- 10 a) How much sodium chloride does not dissolve in the 3.6 cm³ of water at 70°C in Experiment 5.6?
- b) How much sodium chloride remains in solution after cooling to room temperature?
- c) How much solid sodium chloride is recovered at the end of the experiment?
- 11 a) How much potassium nitrate remains in solution at room temperature at the end of the separation?
- b) How much potassium nitrate can be recovered in solid form?
- 12 Suppose you wish to separate more of the two solids remaining in solution at the end of the experiment. How would you proceed to do this?

5.7 EXPERIMENT FRACTIONAL CRYSTALLIZATION

In the preceding section, we considered the separation of a mixture of sodium chloride and potassium nitrate. We predicted the results of a separation procedure based on the solubility curves in Figure 5.8. The purpose of *this* experiment is to test the predictions by using the same quantities of solids and water as determined in the preceding section.

Before you begin the experiment, there are a number of technical questions that you should consider. We chose to have the hot solution at 70°C. This choice of temperature determined the volume of water needed to dissolve all of the potassium nitrate.

• Must you be sure when you filter the liquid that its temperature is indeed 70°C? Why or why not?

After you add 3.6 cm³ of water to the 10-g mixture of solids (5.0 g of potassium nitrate and 5.0 g of sodium chloride), heat the mixture while stirring it, and then filter.

A hot solution cools rapidly. To prevent this, you can pre-heat the funnel, filter paper, and the test tube in which you will collect the filtrate by rinsing them with hot water.

- What do you expect to have on the filter paper?
- What substance do you expect to precipitate from the filtrate?

When solids precipitate slowly out of the solution, the crystals they form have characteristic shapes.

- What is the shape of the crystals that precipitated from the solution when it cooled?

The sodium chloride that you separated in your experiment was never dissolved. To observe its crystals, you can prepare a saturated solution of it and allow it to evaporate overnight.

- What is the shape of the sodium chloride crystals?

- Is there another way, other than by observing the crystal shapes, that you could show that the two solids you separated are different?

- 13 a) If a solution containing 40 g of potassium nitrate in 100 cm³ of water at 100°C is cooled to 25°C, how much potassium nitrate will precipitate out of solution? (See Figure 5.8.)
- b) Suppose that the 40 g of potassium nitrate is dissolved in only 50 cm³ of water at 100°C. How much potassium nitrate will precipitate out if the solution is cooled to 25°C?

- 14 Suppose you dissolve 30 g of sodium chloride in 100 cm³ of water at 100°C and boil away 50 cm³ of the water.
- a) How many grams of sodium chloride will remain in solution?
- b) How many grams will precipitate out of solution?

- 15 Suppose you dissolve 40 g of potassium nitrate in 100 cm³ of water at 100°C.
- a) If half the solution is poured out, how many grams of potassium nitrate will the remaining solution contain?
- b) Now, instead of pouring out part of the solution, you boil away 50 cm³ of water. How many grams of potassium nitrate will remain in solution at 100°C?
- c) If the solution remaining in (b) were cooled to 25°C, how much potassium nitrate would precipitate out of solution?

5.8 EXPERIMENT PAPER CHROMATOGRAPHY

Try filtering some black ink. Is there any evidence that ink is a mixture?

Completely distill about 5 cm³ of ink.

You probably saw evidence, when you filtered the ink, that would lead you to believe that there are several substances of different colors in the ink. The colored fringe that you saw about the black region on the filter paper indicates that substances in the ink move at different speeds across the filter paper. We shall now try to separate these substances from the liquid, using a long strip of filter paper.

Hang a strip of filter paper streaked with ink in a graduate containing water, as shown in Figure 5.10. When the color has risen up the paper to about 2 or 3 cm below the top, remove the paper and hang it up to dry.

- How many different substances can you identify?
- Can you put the substances back together again and make black ink?

Cut out each of the colored sections, and put each one in a separate test tube. Add between $\frac{1}{2}$ and 1 cm³ of water to each tube.

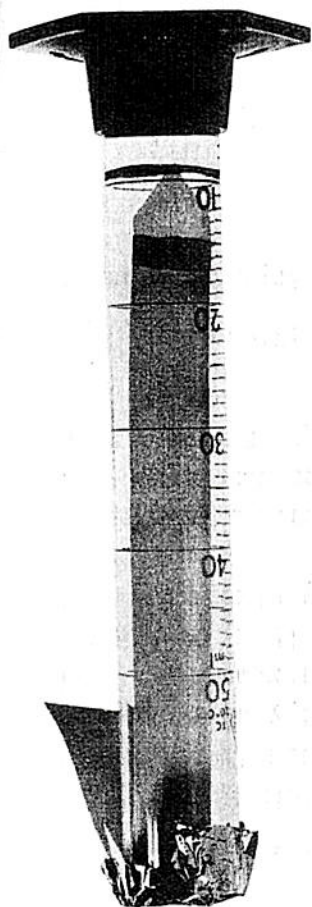
- Do the colored substances dissolve?

Pour the liquids from all three test tubes together into one test tube.

- What color do you get?

One method of making a paper chromatograph of black ink. The point of the filter-paper strip extends into the water so that the ink streak is about 1 cm above the water. The strip is held in place by an aluminum-foil cover bent over the top. The walls of the graduate should be dry, so that the paper will come in contact with water only from the bottom.

Figure 5.10



5.9 MIXTURES OF GASES: NITROGEN AND OXYGEN

In this chapter, we have seen how we can separate mixtures of liquids, mixtures of solids and liquids, and mixtures of solids. We have not yet considered the separation of mixtures of gases. If we have a gas dissolved in a liquid, all we have to do is heat the mixture. (You did this in section 4.12, when you heated a solution of ammonia gas in water.) When a glass of cold water warms up to room temperature, bubbles of air dissolved in the water appear, sticking to the sides of the glass. If we warm the water further, more air bubbles appear, and some rise to the top long before we reach the temperature at which water boils. Separating mixtures of gases alone, however, requires different methods from those we have used in experiments so far.

Mixtures of gases are very common. Table 5.1 (page 94) lists four gases that are mixed together in the petroleum fraction called "fuel gas."

There are a number of ways to separate gases. One of them, which is widely used, is to cool the mixture until it condenses to form a liquid. Then we can make use of the different boiling points of the various liquids and fractionally distill the cold liquid. The gases are thus collected one by one, as the boiling temperature levels off at new plateaus.

If we liquefy air and fractionally distill it in this way, we find that air separates mainly into two fractions: A glowing splint bursts into a bright flame when placed in one of them, but even a splint that is burning goes out when placed in the other. Neither gas turns limewater milky. The gas that causes the glowing splint to burst into flame is called "oxygen"; the one that does not is "nitrogen." These two gases together make up about 99 percent of the gases in air. Nitrogen makes up about 80 percent of the atmosphere, and oxygen about 20 percent. The densities, melting points, and boiling points of nitrogen and oxygen are given in Table 5.2.

Table 5.2

| Gas | Density (g/cm ³) | Melting point (°C) | Boiling point (°C) |
|----------|---------------------------------|-----------------------|-----------------------|
| Nitrogen | 1.2×10^{-3} | -210 | -196 |
| Oxygen | 1.3×10^{-3} | -218 | -183 |

The densities are given for atmospheric pressure and room temperature.

The cheapest way of obtaining oxygen and nitrogen is to condense air into a liquid and then fractionally distill it. Most of the oxygen and nitrogen commercially manufactured is produced by this method.

16 How could you separate ammonia gas from air?

5.10 LOW TEMPERATURES

The melting points and boiling points given in Table 5.2 are far below any temperature you can reach in your laboratory. How is it possible to cool things to such low temperatures?

One method of cooling gases depends on the fact that very highly compressed gases cool when allowed to expand. Figure 5.11 shows how this effect can be used to cool air to temperatures low enough to liquefy it. Air at very high pressure and room temperature flows down the long tube in the center and escapes through a small opening at the bottom. As it escapes, it expands and cools. When the flow is first started, the escaping air does not cool enough to condense into liquid air; but as this escaping cold air flows up past the long tube, it cools the air moving down inside the tube.

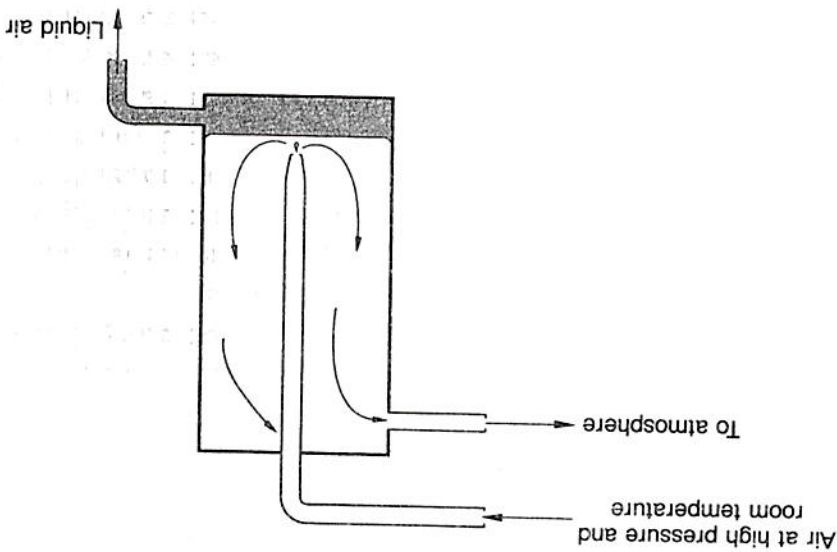


Figure 5.11

A simplified diagram showing the essential steps in liquefying air.

Thus, when the air inside escapes at the bottom, it is already cold and cools off still more on expansion. After the apparatus has run for some time, the expanding air cools enough so that some of it condenses into liquid and collects at the bottom of the apparatus. Of course, the whole apparatus shown in the figure must be well insulated to keep the inside cold. Actual liquid-air machines are more complicated than this simplified diagram shows, but many of them operate on this principle.

It is one thing to produce very low temperatures, but another to measure them. The usual way of calibrating a liquid thermometer is to mark on the stem the liquid levels when the thermometer is placed in melting ice and then in boiling water. These temperatures are labeled 0°C and 100°C . The scale is then marked off into 100 equal divisions between the points, each division representing 1°C . If we specify the liquid used—mercury, for example—we have then defined a temperature scale. Many liquids behave the same way between 0°C and 100°C . For example, two thermometers calibrated in this way, one containing mercury and the other toluene, will both read very nearly the same temperature when they are placed together in water at any temperature between 0°C and 100°C .

If we extend the temperature scale on a calibrated liquid thermometer by marking equal divisions below 0°C , we still find very close agreement between thermometers containing different liquids, such as mercury and toluene. This agreement continues until very low temperatures are reached, where we run into trouble. Substances that are liquids between 0°C and 100°C solidify at some lower temperature. However, gases also expand and contract with temperature changes. Many of them do not condense until they are extremely cold, and we can use them in thermometers to measure very low temperatures. A simple gas thermometer is shown in Figure 5.12. If

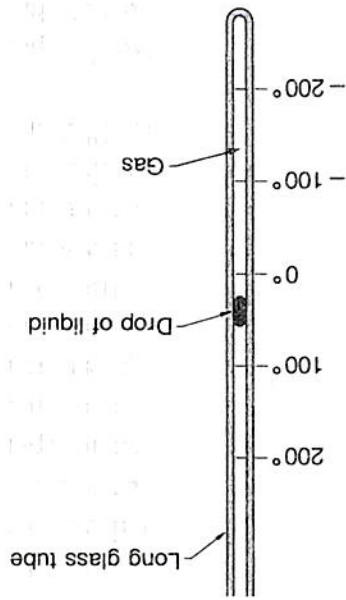


Figure 5.12 A simple gas thermometer calibrated in degrees Celsius.

we calibrate it the same way we calibrate a liquid thermometer, we find that it will give the same temperature readings as will a standard liquid thermometer. This is true of nearly all gas thermometers. Furthermore, at very low temperatures, where thermometers containing various liquids freeze, most gas thermometers containing different gases continue to agree closely. Thus, gas thermometers extend our temperature scale. To measure the freezing point of oxygen, we need a gas that condenses below -218°C . Helium boils at -269°C and is used in gas thermometers.

5.11 MIXTURES AND PURE SUBSTANCES

In this chapter, we have found ways to separate different substances from each other by using characteristic properties. We learned that a difference in density can be used to separate two solids; that solids can also be separated by differences in solubility; and that a difference in the boiling points of different liquids enables us to separate them by fractional distillation.

Suppose we experiment with a piece of solid material to see if we can separate it into two or more substances. First we grind it up and mix it with water, stirring it thoroughly. We observe that some particles of a yellowish solid float on the surface, while particles of a gray solid sink to the bottom. We skim off the floating material, whose density is obviously less than that of water. We dry it, call it fraction 1, and set it aside. Then we filter the water and the more dense solid that is in the bottom of the test tube. This solid, which remains on the filter paper, we dry, label fraction 2, and set aside also. We know that these two solids, fractions 1 and 2, are different substances, because they have different densities.

We now test the filtrate to see if any material has dissolved in the water. Evaporating away the water, we find a small amount of white solid. This substance is different from both fractions 1 and 2 because it is soluble in water, and we call it fraction 3. The whole process of the separation of three fractions from a piece of solid material is diagrammed in Figure 5.13.

We now have separated out three different substances, but perhaps each of these can be further separated. To find out, we use other separation methods. We may, for example, try to melt and even fractionally distill each of the fractions, or we may try dissolv-

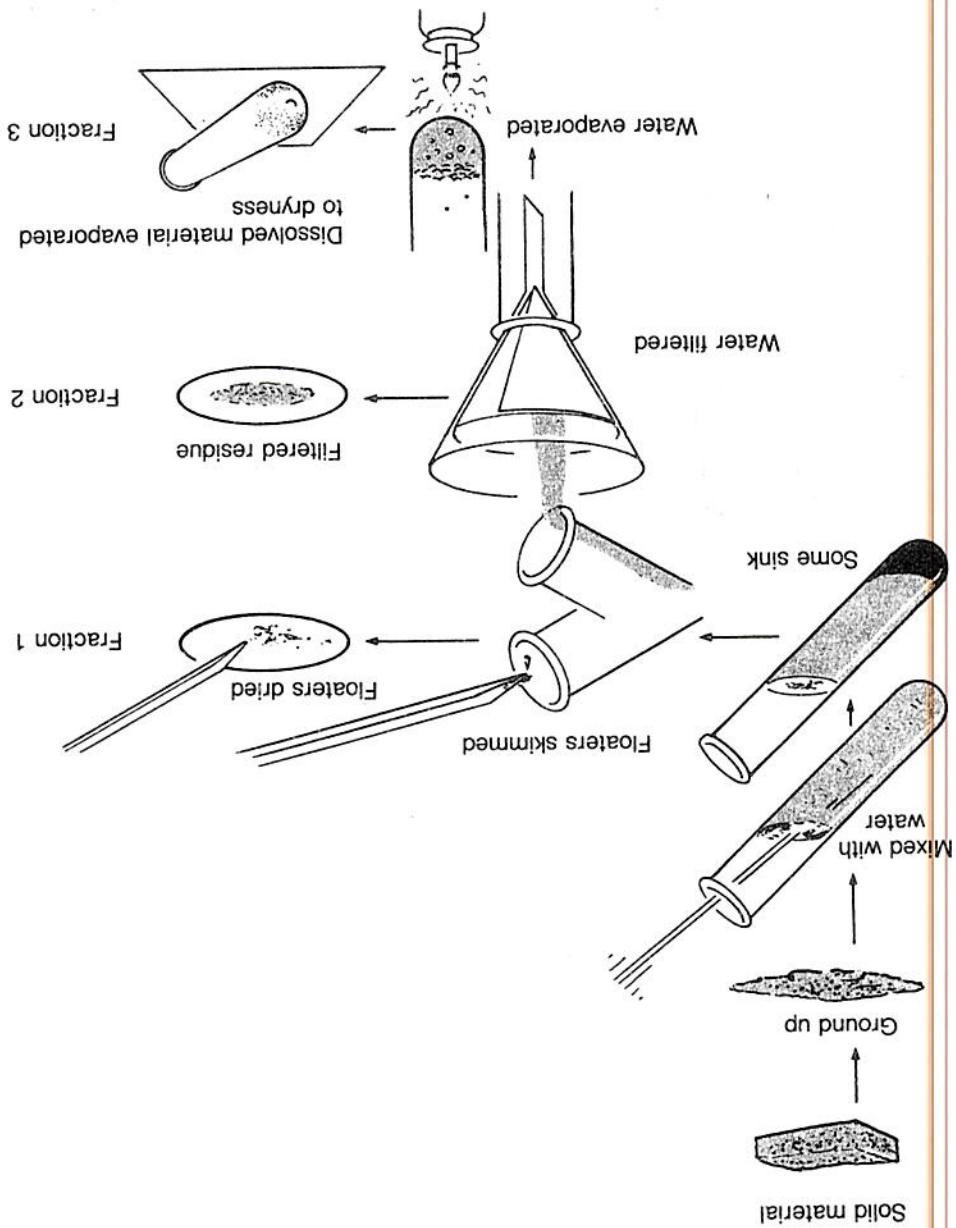


Figure 5.13
A diagram of an example of the series of steps for separating three fractions obtained from a ground-up solid.

ing them in different liquids. Suppose that boiling, melting, and mixing with alcohol and other liquids do not produce anything with characteristic properties different from those of the three fractions we have already found. By using all these various tools of separa-

tion again and again, we find that the characteristic properties of our three fractions remain unaltered. We call such substances whose properties are not changed by repeating any of these procedures "pure" substances.

Suppose we mix together all the pure substances that we obtain in this way and get back a material that has the same characteristic properties as the original sample. We can say that the original sample was a *mixture* of the pure substances. For example, if you mixed all the fractions you separated in your experiment on fractional distillation (Experiment 5.1), you would get back a substance that has the same properties you started with. Similarly, mixing together the various fractions obtained from the distillation of liquid air would yield a gas with exactly the same properties as ordinary air. Therefore, air is a mixture.

Note that many properties of a mixture are intermediate between the properties of the pure substances that form the mixture. For example, the density of air is between the density of nitrogen and that of oxygen. A mixture of alcohol and water will smell like alcohol, but it will only burn if it contains enough alcohol.

However, it is not always possible to get back the original sample by mixing the parts separated by the various processes. For example, mixing the distillation products of petroleum will yield a liquid similar but not identical to the original sample. You know, of course, from your own experience that you cannot mix together the products of the dry distillation of wood and get back anything resembling wood. Wood is not, therefore, a mixture of the substances separated by distillation.

A simple example of a substance that breaks up when heated and that is not a mixture is the orange powder mercuric oxide. If you try to determine its melting point, you will discover that when it is heated, it gives off a gas. You can test this gas and find it to be oxygen. Furthermore, you can detect some droplets of a silvery liquid—mercury—in the test tube. Mixing the oxygen and the mercury together, however, will not give back the mercuric oxide. The two components remain separated as a gas and a silvery liquid.

Mercuric oxide is a pure substance that cannot be separated into simpler substances by most of the methods we used to separate mixtures. When it is separated by heating, it cannot be put back together simply by mixing.

- 17 Suppose you mixed together all the fractions you obtained from the fractional distillation of the liquid in Experiment 5.1. What do you think would be the properties of this liquid?
- 18 The substances you obtained by distilling wood (Experiment 1.1), when mixed together, will not give anything like wood—even ground-up, finely powdered wood. What does this tell you about the substances in wood as compared with the substances you obtained in the distillation?

For Home, Desk, and Lab

- 19 In earlier times, people would search out sandy stream beds in which small particles of gold were mixed with the sand. They separated this gold from the sand by "panning." Find out how this was done. What characteristic property of the substances made panning possible?
- 20 Figure 5.2 shows four oil wells drilled into oil-bearing porous rock. Can you suggest some method, other than drilling deeper, for getting more oil from well *D* after the oil level drops below the end of the well?
- 21 a) In Table 5.1 (page 94), which fractions would be liquid at room temperature (20°C)? Which would be solids? Which would be gases?
- b) You can see from the table that pentane is not an ingredient in any of the common products listed. How can you account for this?
- 22 Using the data in Table 5.1 (page 94), draw and label a possible distillation curve for a mixture of hexane, nonane, and tetradecane.
- 23 When ethanol is to be used for industrial or commercial purposes other than as a beverage, it is customarily "denatured"; that is, a small quantity of another substance is added to it so that it is unfit for use as a beverage. What, in general, do you think some of the properties of the added substance might be?
- 24 How would you separate a mixture of powdered sugar and powdered citric acid?

25 The mineral called "Gay-Lussite" appears to be a pure substance, but it is actually a mixture composed of calcium carbonate (limestone), sodium carbonate (soda ash), and water. Describe how you would go about separating these three substances from the rock. Some properties of calcium carbonate and sodium carbonate are listed in the following table.

| Property | Calcium carbonate | Sodium carbonate |
|---------------------------------|---------------------|--|
| Melting point | Decomposes at 825°C | 851°C |
| Solubility in alcohol | Insoluble | Insoluble |
| Solubility in hydrochloric acid | Soluble | Soluble |
| Solubility in water | Insoluble | 7 g/100 cm ³ at 0°C; 45 g/100 cm ³ at 100°C |

- 26 If you have 100 cm³ of water at 100°C, saturated with both potassium nitrate and sodium chloride, what happens if the temperature is lowered to 10°C? (Refer to Figure 5.8, and assume that the solubility curves of these substances are the same as in the figure, even when they are dissolved together.)
- 27 You can use paper chromatography to separate the components in many common substances. Try this technique with any of the following substances you can find at home: tomato paste, different colors and brands of ink, the coloring in leaves and vegetables (grind the leaves first in alcohol), and flower petals.
- 28 Chlorophyll can be extracted from leaves by grinding them with alcohol to give a dark-green solution. By careful application of paper chromatography, bands of yellow and red color, as well as green bands, can be detected. What other reason do you have to suspect the presence of substances producing these colors in leaves? Why don't you ordinarily see them?
- 29 As liquid air boils away, the remaining liquid becomes richer in one of the two gases—nitrogen or oxygen. Which one is it? How do you know?
- 30 a) How would you calibrate the simple gas thermometer shown in Figure 5.12 to read in degrees Celsius?
b) Which end of the liquid drop would you take as a reference point?
- 31 What would you do to separate (a) alcohol from water, (b) sodium chloride from sodium nitrate, and (c) nitrogen from oxygen?

- 32 A sample of a liquid was boiled for 12 minutes. During that time, the boiling point remained constant, and the volume was reduced to half. Is the liquid a pure substance?
- 33 Suppose you had a mixture of sand and salt in a small box.
- a) How could you separate these substances?
 - b) How would you determine the ratio of the mass of sand to the mass of salt?
 - c) If you were mixing sand and salt together, what mass ratios would it be possible for you to make?

Theme for a Short Essay

You devoted several hours to the "sludge test." Do you think this test is a good way to assess your progress in this course? Why, or why not? Include enough information about the test so that a friend who has never heard about the "sludge test" will be able to understand your reasoning.