9.1 Making Predictions About Solubility

Section Preview/ Specific Expectations

In this section, you will

- **describe** and **identify** combinations of aqueous solutions that result in the formation of precipitates
- **communicate**, using appropriate scientific vocabulary, ideas related to solubility and aqueous solutions
- **communicate** your understanding of the following terms: *precipitate, general solubility guidelines*

In Chapter 8, you examined factors that affect the solubility of a compound. As well, you learned that the terms "soluble" and "insoluble" are relative, because no substance is completely insoluble in water. "Soluble" generally means that more than about 1 g of solute will dissolve in 100 mL of water at room temperature. "Insoluble" means that the solubility is less than 0.1 g per 100 mL. While many ionic compounds are soluble in water, many others are not. Cooks, chemists, farmers, pharmacists, and gardeners need to know which compounds are soluble and which are insoluble. (See Figure 9.1.)

Figure 9.1 Plant food may come in the form of a liquid or a powder. Gardeners dissolve the plant food in water, and then either spray or water the plant with the resulting solution.

Factors That Affect the Solubility of Ionic Substances

Nearly all alkali metal compounds are soluble in water. Sulfide and phosphate compounds are usually insoluble. How, then, do you account for the fact that sodium sulfide and potassium phosphate are soluble, while iron sulfide and calcium phosphate are insoluble? Why do some ions form soluble compounds, while other ions form insoluble compounds?

The Effect of Ion Charge on Solubility

Compounds of ions with small charges tend to be soluble. Compounds of ions with large charges tend to be insoluble. Why? Increasing the charge increases the force that holds the ions together. For example, phosphates (compounds of PO_4^{3-}) tend to be insoluble. On the other hand, the salts of alkali metals are soluble. Alkali metal cations have a single positive charge, so the force that holds the ions together is less.

CHEM FACT

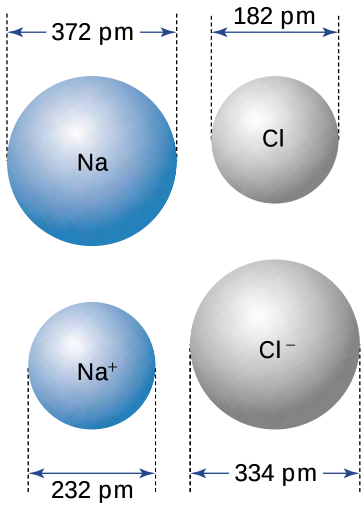
Because the terms "soluble" and "insoluble" are relative, some textbooks give different definitions and units of concentration to describe them. Here are a few examples:

Soluble	Partly or slightly soluble	Insoluble
more than 1 g in 100 mL *or* greater than 0.1 mol/L	between 1 g and 0.1 g in 100 mL *or* between 0.1 mol/L and 0.01 mol/L	less than 0.1 g in 100 mL *or* less than 0.01 mol/L

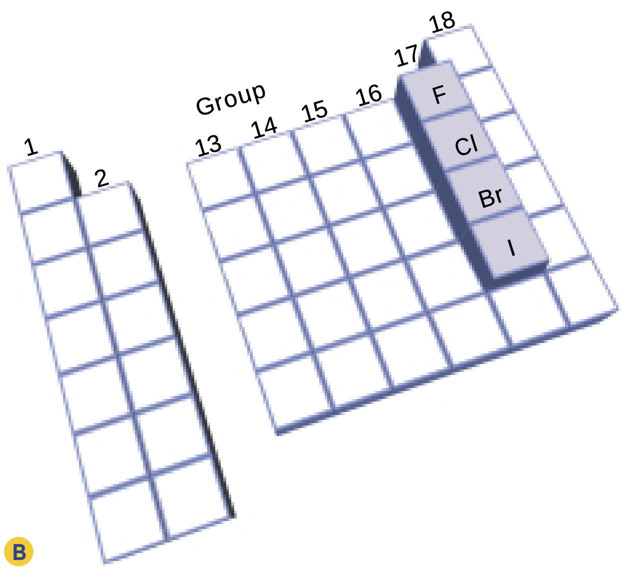
The Effect of Ion Size on Solubility

When an atom gives up or gains an electron, the size of the ion that results is different from the size of the original atom. In Figure 9.2A, for example, you can see that the sodium ion is smaller than the sodium atom. In general, the ions of metals tend to be smaller than their corresponding neutral atoms. For the ions of non-metals, the reverse is true. The ions of non-metals tend to be larger than their corresponding neutral atoms.

Small ions bond more closely together than large ions. Thus, the bond between small ions is stronger than the bond between large ions with the same charge. As a result, compounds with small ions tend to be less soluble than compounds with large ions. Consider the ions of elements from Group 17 (VIIA), for example. Recall, from Chapters 2 and 3, that the size of the ions increases as you go down a family in the periodic table. (See Figure 9.2B.) Therefore, you would expect that fluoride compounds are less soluble than chloride, bromide, and iodide compounds. This tends to be the case.



A



B

Ionic size

F^-		133 pm
Cl^-		181 pm
Br^-		196 pm
I^-		220 pm

Figure 9.2A The radius of the cation of a metal, such as sodium, tends to be smaller than the radius of the atom from which it was formed. The radius of the anion of a non-metal, such as phosphorus, tends to be larger than the radius of its atom.

Figure 9.2B In Group 17 (VIIA), fluoride ions are smaller than chloride, bromide, and iodide ions. How does this periodic trend affect the solubility of compounds that are formed from these elements?

Making Predictions About Solubility

Sulfides (compounds of S^{2-}) and oxides (compounds of O^{2-}) are influenced by both ion size and ion charge. These compounds tend to be insoluble because their ions have a double charge *and* are relatively small. Even so, a few sulfides and oxides are soluble, as you will discover in Investigation 1-A.

Many interrelated factors affect the solubility of substances in water. This makes it challenging to predict which ionic substances will dissolve in water. By performing experiments, chemists have developed guidelines to help them make predictions about solubility. In Investigation 9-A, you will perform your own experiments to develop quidelines about the solubility of ionic compounds in water.

mind STRETCH

Sketch an outline of the periodic table. Add labels and arrows to indicate what you think are the trends for ionic size (radius) across a period and down a group. Then suggest reasons for these trends. Specifically, identify the factors that you think are responsible for the differences in the sizes of ions and their "parent" atoms.

Investigation 9-A

SKILL FOCUS

- Predicting
- Performing and recording
- Analyzing and interpreting
- Communicating results

The Solubility of Ionic Compounds

In this investigation, you will work with a set of solutions. You will chemically combine small quantities, two at a time. This will help you determine which combinations react to produce a **precipitate**. A precipitate is an insoluble solid that may result when two aqueous solutions chemically react. *The appearance of a precipitate indicates that an insoluble compound is present.* Then you will compile your data with the data from other groups to develop some guidelines about the solubility of several ionic compounds.

Problem

How can you develop guidelines to help you predict the solubility of ionic compounds in water?

Prediction

Read the entire Procedure. Predict which combination of anions and cations will likely be soluble and which combination will likely be insoluble. Justify your prediction by briefly explaining your reasoning.

Materials

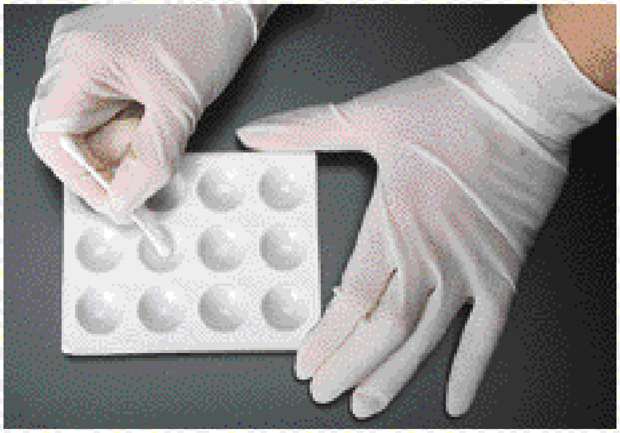
12-well or 24-well plate, or spot plate
toothpicks
cotton swabs
wash bottle with distilled water
piece of black paper
piece of white paper
labelled dropper bottles of aqueous solutions that contain the following cations:
, , , , , , , ,
,
labelled dropper bottles of aqueous solutions that contain the following anions:
, , , , , ,
,

Safety Precautions

- Do not contaminate the dropper bottles. The tip of a dropper should not make contact with either the plate or another solution. Put the cap back on the bottle immediately after use.
- Dispose of solutions as directed by your teacher.
- Make sure that you are working in a well-ventilated area.
- If you accidentally spill any of the solutions on your skin, wash the area immediately with plenty of cool water.

Procedure

1. Your teacher will give you a set of nine solutions to test. Each solution includes one of five cations or four anions. Design a table to record the results of all the possible combinations of cations with anions in your set of solutions.
2. Decide how to use the well plate or spot plate to test systematically all the combinations of cations with anions in your set. If your plate does not have enough wells, you will need to clean the plate before you can test all the possible combinations. To clean the plate, first discard solutions into the container provided by your teacher. Then rinse the plate with distilled water, and clean the wells using a cotton swab.
3. To test each combination of anion and cation, add one or two drops into your well plate or spot plate. Then stir the mixture using a toothpick. Rinse the toothpick with running water before each stirring. Make sure that you keep track of the combinations of ions in each well or spot.



Why is it necessary to clean the well or spot plate as described in step 2?

4. Examine each mixture for evidence of a precipitate. Place the plate on a sheet of white or black paper. (Use whichever colour of paper helps you see a precipitate best.) Any cloudy appearance in the mixture is evidence of a precipitate. Many precipitates are white.
   - If you can see that a precipitate has formed, enter "I" in your table. This indicates that the combination of ions produces an insoluble substance.
   - If you cannot see a precipitate, enter "S" to indicate that the ion you are testing is soluble.
5. Repeat steps 2 to 4 for each cation solution.
6. Discard the solutions and precipitates into the container provided by your teacher. Rinse the plate with water, and clean the wells using a cotton swab.
7. If time permits, your teacher may give you a second set of solutions to test.
8. Add your observations to the class data table. Use your completed copy of the class data table to answer the questions below.

Analysis

1. Identify any cations that
   (a) always appear to form soluble compounds
   (b) always appear to form insoluble compounds
2. Identify any anions that
   (a) always appear to form soluble compounds
   (b) always appear to form insoluble compounds
3. Based on your observations, which sulfates are insoluble?
4. Based on your observations, which phosphates are soluble?
5. Explain why each reagent solution you tested must contain both cations and anions.
6. Your teacher prepared the cation solutions using compounds that contain the nitrate ion. For example, the solution marked was prepared by dissolving in water. Why were nitrates used to make these solutions?

Conclusions

7. Which group in the periodic table most likely forms cations with salts that are usually soluble?
8. Which group in the periodic table most likely forms anions with salts that are usually soluble?
9. Your answers to questions 7 and 8 represent a preliminary set of guidelines for predicting the solubility of the compounds you tested. Many reference books refer to guidelines like these as "solubility rules." Why might "solubility guidelines" be a better term to use for describing solubility patterns?

Application

10. Predict another combination of an anion and a cation (not used in this investigation) that you would expect to be soluble. Predict another combination that you would expect to be insoluble. Share your predictions, and your reasons, with the class. Account for any agreement or disagreement.

Soluble or Insoluble: General Solubility Guidelines

As you have seen, nearly all salts that contain the ammonium ion or an alkali metal are soluble. This observed pattern does not tell you how soluble these salts are, however. As well, it does not tell you whether ammonium chloride is more or less soluble than sodium chloride. Chemists rely on published data for this information. (See Figure 9.3.)

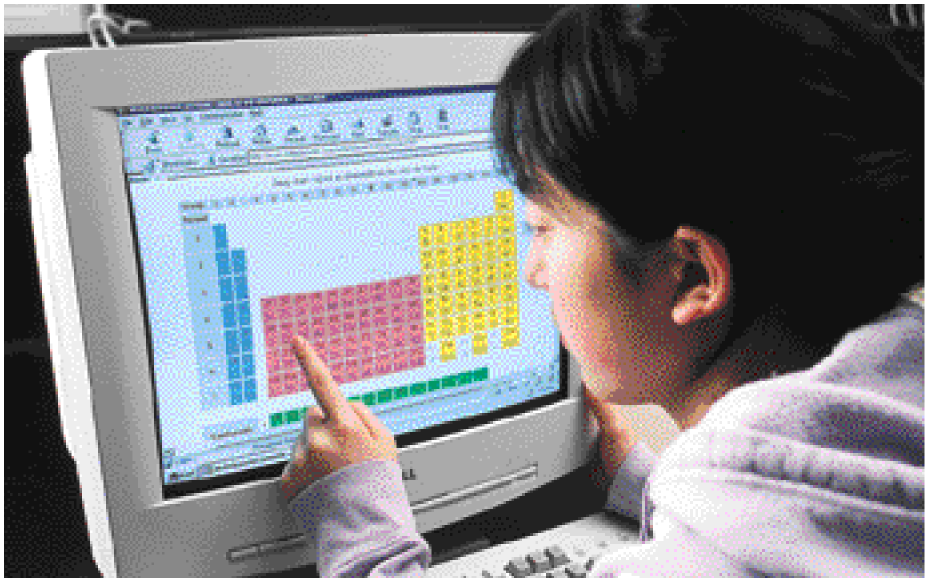


Figure 9.3 **Many web sites on the Internet provide chemical and physical data for tens of thousands of compounds. Print resources, such as *The CRC Handbook of Chemistry and Physics*, provide these data as well.**

Many factors affect solubility. Thus, predicting solubility is neither straightforward nor simple. Nevertheless, the **general solubility guidelines** in Table 9.1 are a useful summary of ionic-compound interactions with water. To use Table 9.1, remember that a higher guideline number always takes precedence over a lower guideline number. For example, barium chloride, , is a white crystalline powder. The barium ion, , is listed in guideline 4 as insoluble. The chloride ion, , is listed in guideline 3 as soluble. The higher guideline number takes precedence. Thus, you would predict that barium chloride is soluble.

You will be referring to the general solubility guidelines often in this chapter and in Chapter 10. They will help you identify salts that are soluble and insoluble in aqueous solutions. Always keep in mind, however, that water is a powerful solvent. Even an "insoluble" salt may dissolve enough to present a serious hazard if it is highly poisonous.

Table 9.1 General Solubility Guidelines

Guideline	Cations	Anions	Result	Exceptions
1	Li^+, Na^+, K^+, Rb^+, Cs^+, NH_4^+	NO_3^-, CH_3COO^-, ClO_3^-	soluble	$Ca(ClO_3)_2$ is insoluble
2	Ag^+, Pb^{2+}, Hg^+	CO_3^{2-}, PO_4^{3-}, O^{2-}, S^{2-}, OH^-	insoluble	BaO and $Ba(OH)_2$ are soluble. Group 2 sulfides tend to decompose.
3		Cl^-, Br^-, I^-	soluble	
4	Ba^{2+}, Ca^{2+}, Sr^{2+}		insoluble	
5	Mg^{2+}, Cu^{2+}, Zn^{2+}, Fe^{2+}, Fe^{3+}, Al^{3+}	SO_4^{2-}	soluble	

Practice Problems

1. Decide whether each of the following salts is soluble or insoluble in distilled water. Give reasons for your answer.
   (a) lead(II) chloride, $PbCl_2$ (a white crystalline powder used in paints)
   (b) zinc oxide, ZnO (a white pigment used in paints, cosmetics, and calamine lotion)
   (c) silver acetate, $AgCH_3COO$ (a whitish powder that is used to help people quit smoking because of the bitter taste it produces)
2. Which of the following compounds are soluble in water? Explain your reasoning for each compound.
   (a) potassium nitrate, KNO_3 (used to manufacture gunpowder)
   (b) lithium carbonate, Li_2CO_3 (used to treat people who suffer from depression)
   (c) lead(II) oxide, PbO_2 (used to make crystal glass)
3. Which of the following compounds are insoluble in water?
   (a) calcium carbonate, $CaCO_3$ (present in marble and limestone)
   (b) magnesium sulfate, $MgSO_4$ (found in the hydrated salt, $MgSO_4{\cdot}7H_2O$, also known as Epsom salts; used for the relief of aching muscles and as a laxative)
   (c) aluminum phosphate, $AlPO_4$ (found in dental cements)

Section Wrap-up

In Chapter 8, you focussed mainly on physical changes that involve solutions. In the first section of this chapter, you observed that mixing aqueous solutions of ionic compounds may result in either a physical change (dissolving) or a chemical change (a reaction that forms a precipitate). Chemical changes that involve aqueous solutions, especially ionic reactions, are common. They occur in the environment, in your body, and in the bodies of other organisms. In the next section, you will look more closely at reactions that involve aqueous solutions. As well, you will learn how to represent these reactions using a special kind of chemical equation, called an ionic equation.

Web LINK

www.school.mcgrawhill.ca/resources/

Different references present solubility guidelines in different ways. During a 1 h "surf session" on the Internet, a student collected ten different versions. See how many versions you can find. Compare their similarities and differences. Which version(s) do you prefer, and why? To start your search, go to the web site above. Go to **Science Resources**, then to **Chemistry 11** to find out where to go next.

Section Review

1. (a) K/U Name the two factors that affect the solubility of an ionic compound in water.

   (b) Briefly explain how each factor affects solubility.

2. K/U Which would you expect to be less soluble: sodium fluoride, NaF (used in toothpaste), or sodium iodide, NaI (added to table salt to prevent iodine deficiency in the diet)? Explain your answer.

3. K/U Which of the following compounds are soluble in water?

   (a) calcium sulfide, CaS (used in skin products)

   (b) iron(II) sulfate, $FeSO_4$ (used as a dietary supplement)

   (c) magnesium chloride, $MgCl_2$ (used as a disinfectant and a food tenderizer)

4. MC Which of the following compounds are insoluble in water? For each compound, relate its solubility to the use described.

   (a) barium sulfate, $BaSO_4$ (can be used to obtain images of the stomach and intestines because it is opaque to X-rays)

   (b) aluminum hydroxide, $Al(OH)_3$ (found in some antacid tablets)

   (c) zinc carbonate, $ZnCO_3$ (used in suntan lotions)

5. C Calcium nitrate is used in fireworks. Silver nitrate turns dark when exposed to sunlight. When freshly made, both solutions are clear and colourless. Imagine that someone has prepared both solutions but has not labelled them. You do not want to wait for the silver nitrate solution to turn dark in order to identify the solutions. Name a chemical that can be used to precipitate a silver compound with the silver nitrate solution, but will produce no precipitate with the calcium nitrate solution. State the reason for your choice.

6. C Suppose that you discover four dropper bottles containing clear, colourless liquids in your school laboratory. The following four labels lie nearby:

   - barium, Ba^{2+}
   - chloride, Cl^-
   - silver, Ag^+
   - sulfate, SO_4^{2-}.

   Unfortunately the labels have not been attached to the bottles. You decide to number the bottles 1, 2, 3, and 4. Then you mix the solutions in pairs. Three combinations give white precipitates: bottles 1 and 2, 1 and 4, and 2 and 3. Which ion does each bottle contain?

Language LINK

This poem is by an unknown author. It is not great literature. For decades, however, it has helped many students remember the solubility guidelines. Maybe it will do the same for you. If not, you can try writing your own poem!

Potassium, sodium, and
ammonium salts
Whatever they may be,
Can always be relied upon
For solubility.

Every single sulfate
Is soluble it's said,
Except barium and calcium
And strontium and lead.

Most every chloride's soluble,
That's what we've always read,
Save silver, mercurous mercury,
And (slightly) chloride of lead.

When asked about the nitrates,
The answer's always clear;
They each and all are soluble,
That's all we want to hear.

Metallic bases won't dissolve,
That is, all but three;
Potassium, sodium, and
ammonium
Dissolve quite readily.

But then you must remember,
You must surely not forget,
Calcium and barium
Dissolve a little bit.

Carbonates are insoluble,
It's lucky that it's so,
Or all our marble buildings
Would melt away like snow.