Properties of Acids and Bases

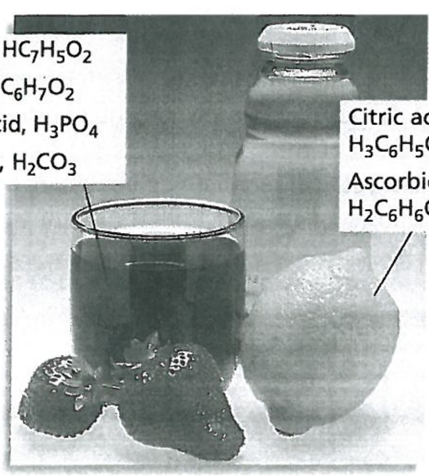
SECTION 1

OBJECTIVES

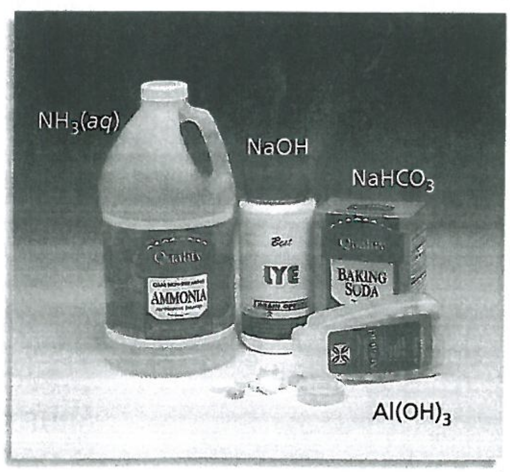
- List five general properties of aqueous acids and bases.
- Name common binary acids and oxyacids, given their chemical formulas.
- List five acids commonly used in industry and the laboratory, and give two properties of each.
- Define *acid* and *base* according to Arrhenius's theory of ionization.
- Explain the differences between strong and weak acids and bases.

How many foods can you think of that are sour? Chances are that almost all the foods you thought of, like those in **Figure 1a,** owe their sour taste to an acid. Sour milk contains *lactic acid.* Vinegar, which can be produced by fermenting juices, contains *acetic acid. Phosphoric acid* gives a tart flavor to many carbonated beverages. Most fruits contain some kind of acid. Lemons, oranges, grapefruits, and other citrus fruits contain *citric acid.* Apples contain *malic acid,* and grape juice contains *tartaric acid.*

Many substances known as bases are commonly found in household products, such as those in **Figure 1b.** Household ammonia is an ammonia-water solution that is useful for all types of general cleaning. Sodium hydroxide, NaOH, known by the common name *lye,* is present in some commercial cleaners. Milk of magnesia is a suspension in water of magnesium hydroxide, $Mg(OH)_2$, which is not very water-soluble. It is used as an antacid to relieve discomfort caused by excess hydrochloric acid in the stomach. Aluminum hydroxide, $Al(OH)_3$, and sodium hydrogen carbonate, $NaHCO_3$, are also bases commonly found in antacids.



(a)



(b)

FIGURE 1 (a) Fruits and fruit juices contain acids such as citric acid and ascorbic acid. Carbonated beverages contain benzoic acid, phosphoric acid, and carbonic acid. (b) Many household cleaners contain bases such as ammonia and sodium hydroxide. Antacids contain bases such as aluminum hydroxide.

FIGURE 2 A strip of pH paper dipped into vinegar turns red, showing that vinegar is an acid.

Acids

Acids were first recognized as a distinct class of compounds because of the common properties of their aqueous solutions. These properties are listed below.

1. *Aqueous solutions of acids have a sour taste.* Taste, however, should NEVER be used as a test to evaluate any chemical substance. Many acids, especially in concentrated solutions, are corrosive; that is, they destroy body tissue and clothing. Many are also poisons.
2. *Acids change the color of acid-base indicators.* When pH paper is used as an indicator, the paper turns certain colors in acidic solution. This reaction is demonstrated in **Figure 2.**
3. *Some acids react with active metals and release hydrogen gas, H_2.* Recall that metals can be ordered in terms of an activity series. Metals above hydrogen in the series undergo single-displacement reactions with certain acids. Hydrogen gas is formed as a product, as shown by the reaction of barium with sulfuric acid.

$$Ba(s) + H_2SO_4(aq) \longrightarrow BaSO_4(s) + H_2(g)$$

4. *Acids react with bases to produce salts and water.* When chemically equivalent amounts of acids and bases react, the three properties just described disappear because the acid is "neutralized." The reaction products are water and an ionic compound called a *salt.*
5. *Acids conduct electric current.* Some acids completely separate into ions in water and are strong electrolytes. Other acids are weak electrolytes.

Acid Nomenclature

A **binary acid** *is an acid that contains only two different elements: hydrogen and one of the more electronegative elements.* Many common inorganic acids are binary acids. The hydrogen halides—HF, HCl, HBr, and HI—are all binary acids.

The procedure used to name binary acids is illustrated by the examples given in **Table 1.** In pure form, each compound listed in the table is a gas. Aqueous solutions of these compounds are known by the acid names. From the table you can see that naming binary compounds can be summarized as follows.

TABLE 1 *Names of Binary Acids*

Formula	Acid name	Molecule name
HF	hydrofluoric acid	hydrogen fluoride
HCl	hydrochloric acid	hydrogen chloride
HBr	hydrobromic acid	hydrogen bromide
HI	hydriodic acid	hydrogen iodide
H_2S	hydrosulfuric acid	hydrogen sulfide

plastics, dyes, and pharmaceuticals. Initially, nitric acid solutions are colorless; however, upon standing, they gradually become yellow because of slight decomposition to brown nitrogen dioxide gas.

Phosphoric Acid

Phosphorus, along with nitrogen and potassium, is an essential element for plants and animals. The bulk of phosphoric acid produced each year is used directly for manufacturing fertilizers and animal feed. Dilute phosphoric acid has a pleasant but sour taste and is not toxic. It is used as a flavoring agent in beverages and as a cleaning agent for dairy equipment. Phosphoric acid is also important in the manufacture of detergents and ceramics.

Hydrochloric Acid

The stomach produces HCl to aid in digestion. Industrially, hydrochloric acid is important for "pickling" iron and steel. Pickling is the immersion of metals in acid solutions to remove surface impurities. This acid is also used in industry as a general cleaning agent, in food processing, in the activation of oil wells, in the recovery of magnesium from sea water, and in the production of other chemicals.

Concentrated solutions of hydrochloric acid, commonly referred to as *muriatic acid,* can be found in hardware stores. It is used to maintain the correct acidity in swimming pools and to clean masonry.

Acetic Acid

Pure acetic acid is a clear, colorless, and pungent-smelling liquid known as *glacial acetic acid.* This name is derived from the fact that pure acetic acid has a freezing point of 17°C. It can form crystals in a cold room. The fermentation of certain plants produces vinegars containing acetic acid. White vinegar contains 4% to 8% acetic acid.

Acetic acid is important industrially in synthesizing chemicals used in the manufacture of plastics. It is a raw material in the production of food supplements—for example, lysine, an essential amino acid. Acetic acid is also used as a fungicide.

SCILINKS.
www.scilinks.org
Topic: Bases
Code: HC60137

Bases

How do bases differ from acids? You can answer this question by comparing the following properties of bases with those of acids.

1. *Aqueous solutions of bases taste bitter.* You may have noticed this fact if you have ever gotten soap, a basic substance, in your mouth. As with acids, taste should NEVER be used to test a substance to see if it is a base. Many bases are caustic; they attack the skin and tissues, causing severe burns.
2. *Bases change the color of acid-base indicators.* As **Figure 5** shows, an indicator will be a different color in a basic solution than it would be in an acidic solution.

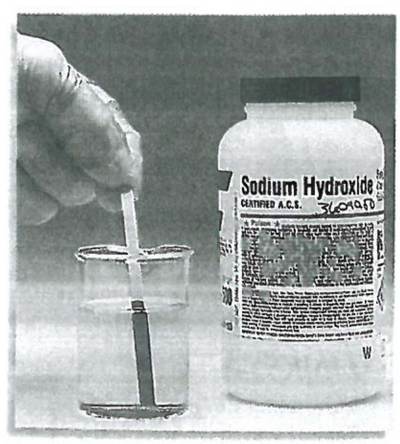


FIGURE 5 pH paper turns blue in the presence of this solution of sodium hydroxide.

QuickLAB

Wear safety goggles, gloves and an apron.

Household Acids and Bases

Question

Which of the household substances are acids, and which are bases?

Procedure

Record all your results in a data table.

1. To make an acid-base indicator, extract juice from red cabbage. First, cut up some red cabbage and place it in a large beaker. Add enough water so that the beaker is half full. Then, bring the mixture to a boil. Let it cool, and then pour off and save the cabbage juice. This solution is an acid-base indicator.
2. Assemble foods, beverages, and cleaning products to be tested.
3. If the substance being tested is a liquid, pour about 5 mL into a small beaker. If it is a solid, place a small amount into a beaker, and moisten it with about 5 mL of water.
4. Add a drop or two of the red cabbage juice to the solution being tested, and note the color. The solution will turn red if it is acidic and green if it is basic.

Discussion

1. Are the cleaning products acids, bases, or neither?
2. What are acid/base characteristics of foods and beverages?
3. Did you find consumer warning labels on basic or acidic products?

Materials

- **dishwashing liquid, dishwasher detergent, laundry detergent, laundry stain remover, fabric softener, and bleach**
- **mayonnaise, baking powder, baking soda, white vinegar, cider vinegar, lemon juice, soft drinks, mineral water, and milk**
- **fresh red cabbage**
- **hot plate**
- **beaker, 500 mL or larger**
- **beakers, 50 mL**
- **spatula**
- **tap water**
- **tongs**

Red cabbage, which contains an anthocyanin pigment, can be made into an acid-base indicator.

SCILINKS.
www.scilinks.org
Topic: Household Acids and Bases
Code: HC60762

3. *Dilute aqueous solutions of bases feel slippery.* You encounter this property of aqueous bases whenever you wash with soap.
4. *Bases react with acids to produce salts and water.* The properties of a base disappear with the addition of an equivalent amount of an acid. It could also be said that "neutralization" of the base occurs when these two substances react to produce a salt and water.
5. *Bases conduct electric current.* Like acids, bases form ions in aqueous solutions and are thus electrolytes.

Arrhenius Acids and Bases

Svante Arrhenius, a Swedish chemist who lived from 1859 to 1927, understood that aqueous solutions of acids and bases conducted electric current. Arrhenius therefore theorized that acids and bases must produce ions in solution. *An* **Arrhenius acid** *is a chemical compound that increases the concentration of hydrogen ions, H^+, in aqueous solution.* In other words, an acid will ionize in solution, increasing the number of hydrogen ions present. *An* **Arrhenius base** *is a substance that increases the concentration of hydroxide ions, OH^-, in aqueous solution.* Some bases are ionic hydroxides. These bases dissociate in solution to release hydroxide ions into the solution. Other bases are substances that react with water to remove a hydrogen ion, leaving hydroxide ions in the solution.

Aqueous Solutions of Acids

The acids described by Arrhenius are molecular compounds with ionizable hydrogen atoms. Their water solutions are known as *aqueous acids.* All aqueous acids are electrolytes.

Because acid molecules are sufficiently polar, water molecules attract one or more of their hydrogen ions. Negatively charged anions are left behind. As explained in Chapter 13, the hydrogen ion in aqueous solution is best represented as H_3O^+, the hydronium ion. The ionization of an HNO_3 molecule is shown by the following equation. **Figure 6** also shows how the hydronium ion forms when nitric acid reacts with water.

$$HNO_3(l) + H_2O(l) \longrightarrow H_3O^+(aq) + NO_3^-(aq)$$

Similarly, ionization of a hydrogen chloride molecule in hydrochloric acid can be represented in the following way.

$$HCl(g) + H_2O(l) \longrightarrow H_3O^+(aq) + Cl^-(aq)$$

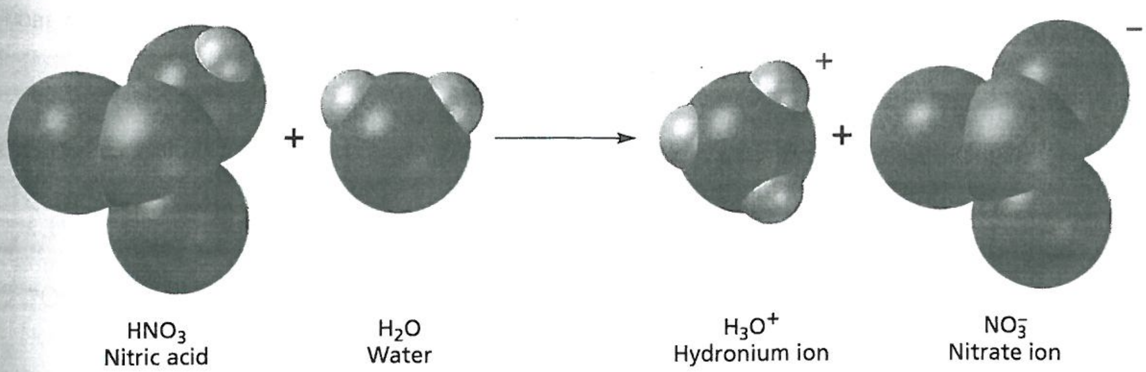


FIGURE 6 Arrhenius's observations form the basis of a definition of acids. Arrhenius acids, such as the nitric acid shown here, produce hydronium ions in aqueous solution.

TABLE 3 Common Aqueous Acids

Strong acids	Weak acids
$HI + H_2O \longrightarrow H_3O^+ + I^-$	$HSO_4^- + H_2O \rightleftharpoons H_3O^+ + SO_4^{2-}$
$HClO_4 + H_2O \longrightarrow H_3O^+ + ClO_4^-$	$H_3PO_4 + H_2O \rightleftharpoons H_3O^+ + H_2PO_4^-$
$HBr + H_2O \longrightarrow H_3O^+ + Br^-$	$HF + H_2O \rightleftharpoons H_3O^+ + F^-$
$HCl + H_2O \longrightarrow H_3O^+ + Cl^-$	$CH_3COOH + H_2O \rightleftharpoons H_3O^+ + CH_3COO^-$
$H_2SO_4 + H_2O \longrightarrow H_3O^+ + HSO_4^-$	$H_2CO_3 + H_2O \rightleftharpoons H_3O^+ + HCO_3^-$
$HClO_3 + H_2O \longrightarrow H_3O^+ + ClO_3^-$	$H_2S + H_2O \rightleftharpoons H_3O^+ + HS^-$
	$HCN + H_2O \rightleftharpoons H_3O^+ + CN^-$
	$HCO_3^- + H_2O \rightleftharpoons H_3O^+ + CO_3^{2-}$

Strength of Acids

A **strong acid** *is one that ionizes completely in aqueous solution.* A strong acid is a strong electrolyte. Perchloric acid, $HClO_4$, hydrochloric acid, HCl, and nitric acid, HNO_3, are examples of strong acids. In water, 100% of the acid molecules are ionized. The strength of an acid depends on the polarity of the bond between hydrogen and the element to which it is bonded and the ease with which that bond can be broken. Acid strength increases with increasing polarity and decreasing bond energy.

An acid that releases few hydrogen ions in aqueous solution is a **weak acid.** The aqueous solution of a weak acid contains hydronium ions, anions, and dissolved acid molecules. Hydrocyanic acid is an example of a weak acid. In aqueous solution, both the ionization of HCN and the reverse reaction occur simultaneously. In a 1 M solution of HCN there will be only two H^+ ions and two CN^- ions out of 100,000 molecules. The other 99,998 molecules remain as HCN.

$$HCN(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CN^-(aq)$$

Common aqueous acids are listed in **Table 3.** Each strong acid ionizes completely in aqueous solution to give up one hydrogen ion per molecule. Notice that the number of hydrogen atoms in the formula does not indicate acid strength. Molecules with multiple hydrogen atoms may not readily give up each hydrogen. The fact that phosphoric acid has three hydrogen atoms per molecule does not mean that it is a strong acid. None of these ionize completely in solution, so phosphoric acid is weak.

Organic acids, which contain the acidic carboxyl group —COOH, are generally weak acids. For example, acetic acid, CH_3COOH, ionizes slightly in water to give hydronium ions and acetate ions, CH_3COO^-.

$$CH_3COOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + CH_3COO^-(aq)$$

A molecule of acetic acid contains four hydrogen atoms. However, only one of the hydrogen atoms is ionizable. The hydrogen atom in the carboxyl group in acetic acid is the one that is "acidic" and forms the hydronium ion. This acidic hydrogen can be seen in the structural diagram in **Figure 7.**

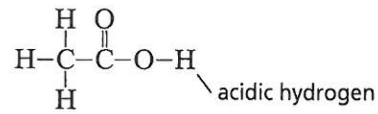


FIGURE 7 Acetic acid contains four hydrogen atoms, but only one of them is "acidic" and forms the hydronium ion in solution.

Aqueous Solutions of Bases

Most bases are ionic compounds containing metal cations and the hydroxide anion, OH^-. Because these bases are ionic, they dissociate when dissolved in water. When a base completely dissociates in water to yield aqueous OH^- ions, the solution is referred to as strongly basic. Sodium hydroxide, NaOH, is a common laboratory base. It is water-soluble and dissociates as shown by the equation below.

$$NaOH(s) \xrightarrow{H_2O} Na^+(aq) + OH^-(aq)$$

You will remember from Chapter 5 that Group 1 elements are the alkali metals. This group gets its name from the fact that the hydroxides of Li, Na, K, Rb, and Cs all form alkaline (basic) solutions.

Not all bases are ionic compounds. A base commonly used in household cleaners is ammonia, NH_3, which is molecular. Ammonia is a base because it produces hydroxide ions when it reacts with water molecules, as shown in the equation below.

$$NH_3(aq) + H_2O(l) \rightleftarrows NH_4^+(aq) + OH^-(aq)$$

extension

Chemistry in Action

Go to **go.hrw.com** for a full-length article on drain cleaners.

Keyword: HC6ACDX

Strength of Bases

As with acids, the strength of a base also depends on the extent to which the base dissociates, or adds hydroxide ions to the solution. For example, potassium hydroxide, KOH, is a strong base because it completely dissociates into its ions in dilute aqueous solutions.

$$KOH(s) \xrightarrow{H_2O} K^+(aq) + OH^-(aq)$$

Strong bases are strong electrolytes, just as strong acids are strong electrolytes. **Table 4** lists some strong bases.

TABLE 4 Common Aqueous Bases

Strong bases	Weak bases
$Ca(OH)_2 \longrightarrow Ca^{2+} + 2OH^-$	$NH_3 + H_2O \rightleftarrows NH_4^+ + OH^-$
$Sr(OH)_2 \longrightarrow Sr^{2+} + 2OH^-$	$C_6H_5NH_2 + H_2O \rightleftarrows C_6H_5NH_3^+ + OH^-$
$Ba(OH)_2 \longrightarrow Ba^{2+} + 2OH^-$	
$NaOH \longrightarrow Na^+ + OH^-$	
$KOH \longrightarrow K^+ + OH^-$	
$RbOH \longrightarrow Rb^+ + OH^-$	
$CsOH \longrightarrow Cs^+ + OH^-$	

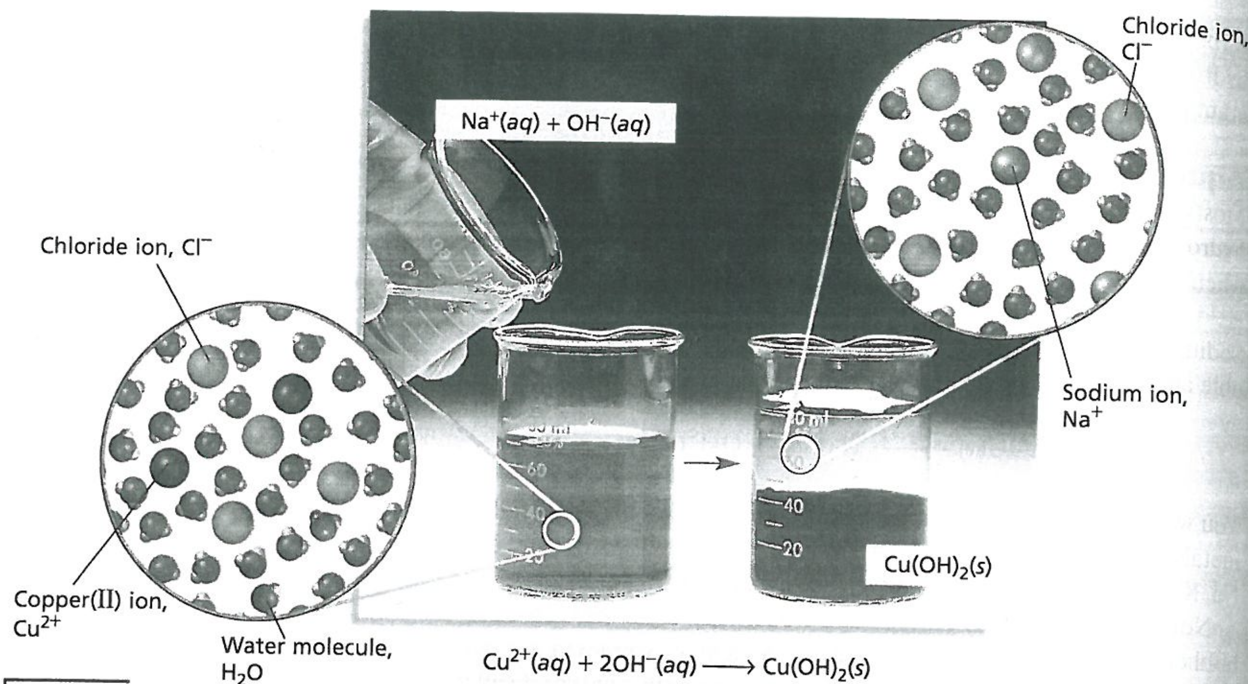


FIGURE 8 The hydroxides of most *d*-block metals are nearly insoluble in water, as is shown by the gelatinous precipitate, copper(II) hydroxide, $Cu(OH)_2$, in the beaker on the right.

Bases that are not very soluble do not produce a large number of hydroxide ions when added to water. Some metal hydroxides, such as $Cu(OH)_2$, are not very soluble in water, as seen in **Figure 8.** They cannot produce strongly alkaline solutions. The alkalinity of aqueous solutions depends on the concentration of OH^- ions in solution. It is unrelated to the number of hydroxide ions in the undissolved compound.

Now consider ammonia, which is highly soluble but is a weak electrolyte. The concentration of OH^- ions in an ammonia solution is relatively low. Ammonia is therefore a *weak base*. Many organic compounds that contain nitrogen atoms are also weak bases. For example, codeine, $C_{18}H_{21}NO_3$, a pain reliever and common cough suppressant found in prescription cough medicine, is a weak base.

SECTION REVIEW

1. **a.** What are five general properties of aqueous acids?
   b. Name some common substances that have one or more of these properties.
2. Name the following acids: a. HBrO b. $HBrO_3$.
3. **a.** What are five general properties of aqueous bases?
   b. Name some common substances that have one or more of these properties.
4. **a.** Why are strong acids also strong electrolytes?
   b. Is every strong electrolyte also a strong acid?

Critical Thinking

5. **RELATING IDEAS** A classmate states, "All compounds containing H atoms are acids, and all compounds containing OH groups are bases." Do you agree? Give examples.

CROSS-DISCIPLINARY CONNECTION

Acid Water—A Hidden Menace

Many people are unaware of the pH of the tap water in their home until they are confronted with such phenomena as a blue ring materializing around a porcelain sink drain, a water heater suddenly giving out, or tropical fish that keep dying. Each of these events could be due to acidic water. Acidic water can also cause the amount of lead in the water to rise.

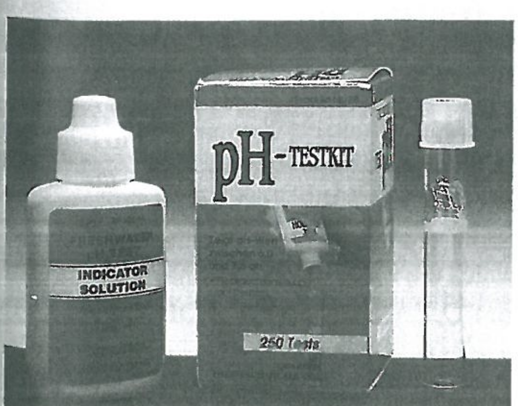
The possibility of lead poisoning from home water supplies is a concern. Many older homes still have lead pipes in their plumbing, while most modern homes use copper piping. Copper pipe joints, however, are often sealed with lead-containing solder. Highly acidic water can leach out both the lead from the solder joints and copper from the pipes themselves, which turns the sink drain blue. In addition, people who are in the habit of filling their tea kettles and coffee pots in the morning without letting the tap run awhile first could be adding copper and lead ions to their tea or coffee.

Lead poisoning is of particular concern in young children. The absorption rate of lead in the intestinal tract of a child is much higher than in that of an adult, and lead poisoning can permanently impair a child's rapidly growing nervous system. The good news is that lead poisoning and other effects of acidic water in the home can be easily prevented by following these tips:

1. Monitor the pH of your water on a regular basis, especially if you have well water. This can easily be done with pH test kits (see photograph) that are sold in hardware or pet stores—many tropical fish are intolerant of water with a pH that is either too high (basic) or too low (acidic). The pH of municipal water supplies is already regulated, but regularly checking your water's pH yourself is a good idea.
2. In the morning, let your water tap run for about half a minute before you fill your kettle or drink the water. If the water is acidic, the first flush of water will have the highest concentration of lead and copper ions.
3. Install an alkali-injection pump, a low-cost, low-maintenance solution that can save your plumbing and lessen the risk of lead poisoning from your own water supply. The pump injects a small amount of an alkali (usually potassium carbonate or sodium carbonate) into your water-pressure tank each time your well's pump starts. This effectively neutralizes the acidity of your water.

Questions

1. What is the source of lead contamination in water in the home?
2. Does the use of copper water pipes ensure that your household water is free from lead?
3. Why does lead poisoning affect children more severely than it affects adults?



◀ *The pH of your home's water supply can be easily monitored using a test kit, such as the one shown here.*

SCILINKS.
www.scilinks.org
Topic: Acid Water
Code: HC60011