Properties and Models of Acids and Bases

Reflect

Some flowering plants show variations in their flower color depending on soil conditions. Consider hydrangeas, shown in the photos below. When grown in acidic soil, hydrangeas tend to produce blue flowers (left). When grown in basic soil, hydrangeas produce pink flowers (right). What is the difference between acidic and basic soil, and why does this influence flower color in hydrangeas?

Chemists classify some chemical compounds as acids or bases. The terms *acidic* and *basic* are used when describing solutions or substances. These terms imply the presence of compounds known as acids or bases. Acids and bases are two classifications of chemical compounds. A compound is classified as an acid or a base based on its chemical properties.

The first scientist to recognize and describe acids and bases was the Swedish chemist Svante Arrhenius. In the late 1800s, Arrhenius defined acids and bases as follows:

- Arrhenius acid: a substance that dissociates to form hydrogen ions (H+) in water

$$HCl \xrightarrow{H_2O} H^+_{(aq)} + Cl^-_{(aq)}$$

- Arrhenius base: a substance that dissociates to form hydroxide ions (OH−) in water

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

An example of an Arrhenius acid is hydrochloric acid (HCl). When placed in water (H_2O), HCl dissociates—or breaks apart—to form hydrogen ions (H^+) and chloride ions (Cl^-), and an example of an Arrhenius base is sodium hydroxide (NaOH). When placed in water, NaOH dissociates to form sodium ions (Na^+) and hydroxide ions (OH^-).

According to Arrhenius's definition, only substances that release hydrogen ions may be classified as acids. Likewise, only substances that release hydroxide ions may be classified as bases. However, later scientists found many substances that do not fit these definitions, yet still have properties that are either acid-like or base-like. For example, ammonia, which has the formula of NH_3, acts as a base, but it does not break apart to form hydroxide ions in solution.

Properties and Models of Acids and Bases

In 1923, two scientists each independently proposed new definitions to describe acids and bases. A Danish chemist, Johannes Brønsted, and an English chemist, Thomas Lowry, introduced the following definitions:

- Brønsted-Lowry acid: a substance that donates hydrogen ions

$$HA + H_2O \rightarrow A^- + H_3O^+$$

- Brønsted-Lowry base: a substance that accepts hydrogen ions

$$B + H_2O \rightarrow OH^- + BH^+$$

For example, hydrochloric acid acts as an acid according to the Brønsted-Lowry definition because it donates hydrogen ions to water. Water in this case acts as a Brønsted-Lowry base: It accepts hydrogen ions to form hydronium ions (H_3O^+):

$$\underset{\text{(acid)}}{HCl} \quad + \quad \underset{\text{(base)}}{H_2O} \quad \rightarrow \quad Cl^- \quad + \quad H_3O^+$$

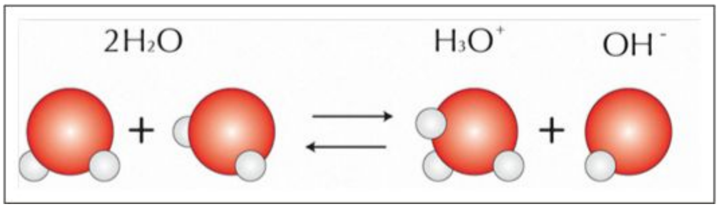
Ammonia (NH_3) acts as a Brønsted-Lowry base because it accepts hydrogen ions from water to form ammonium ions (NH_4^+). Because water donates hydrogen ions in this case, water acts as a Brønsted-Lowry acid:

$$\underset{\text{(base)}}{NH_3} \quad + \quad \underset{\text{(acid)}}{H_2O} \quad \rightarrow \quad NH_4^+ \quad + \quad OH^-$$

From the Brønsted-Lowry definitions, you can infer that acids and bases behave in pairs such that there is always an acceptor and a donor of hydrogen ions. This is an important point because it highlights the differences between the Arrhenius and Brønsted-Lowry definitions. Water behaves as a Brønsted-Lowry base in the example involving hydrochloric acid, above, and as a Brønsted-Lowry acid in the example involving ammonia.

Depending on the situation, water can act as a donor of hydrogen ions in some situations and as an acceptor in other situations. This property of water allows it to behave as both an acid and a base. Water is said to be amphoteric because it can be classified as both an acid and a base. In fact, water demonstrates both acidic and basic properties when it reacts with itself, as shown below:

$$\underset{\text{(acid)}}{H_2O} \quad + \quad \underset{\text{(base)}}{H_2O} \quad \rightarrow \quad H_3O^+ \quad + \quad OH^-$$



Two molecules of water (H_2O) react to form ions of hydronium (H_3O^+) and hydroxide (OH^-). Similarly, a hydronium ion and a hydroxide ion react to form two water molecules. These reversible reactions happen continually in water.

Look Out!

Hydrogen ions do not exist freely in aqueous solutions. Rather, they associate with water molecules to form hydronium ions, which have the chemical formula H_3O^+. However, chemists often refer to hydrogen ions, particularly when talking about pH. When chemists talk about hydrogen ions, they are really talking about hydronium ions.

An acid's power can be expressed several different ways. The most common is through pH. It can also be measured through the concentration of hydrogen ions or the percent dissociation of the acid. Bases are measured along similar lines, only they are measured through pOH or the concentration of hydroxide ions. pH is a mathematical conversion of the actual concentration of hydrogen ions in solution. Typically, the concentration of hydrogen ions is much lower (4.5×10^{-5} mol/L is an average concentration, for example) than a normal solution. Because of this, pH is preferred because it makes numbers easier to grasp. To calculate the pH, you take the negative log of the concentration. The mathematical equation looks like this:

$$pH=-\log[H^+]$$

Logarithms are a method of taking very large or very small numbers and turning them into more easy to handle chunks. This is done by relating the number back to 10. A solution with a pH of 1.0 has a hydrogen ion concentration of 0.01 mol/L. This is because: $10^{-1.0}$ = 0.01 mol/L. A log function on the calculator just makes it easier. The greater the acidity of a solution, the greater is the concentration of hydrogen ions. The actual concentration of hydrogen ions in any solution—even one that is very acidic—tends to be low. Concentrations are often measured in ranges of 10^{-1} to 10^{-14} moles per liter. As we discussed earlier, logarithms relate numbers back to 10, so a little shortcut can be taken to estimate how much hydrogen is in solution. Look at the table below:

pH	**1**	**2**	**3**	**4**	**5**	**6**	**7**
10^{-x}	**10^{-1}**	**10^{-2}**	**10^{-3}**	**10^{-4}**	**10^{-5}**	**10^{-6}**	**10^{-7}**
Actual Concentration	0.1 mol/L *or* 1×10^{-1} mol/L	0.01 mol/L *or* 1×10^{-2} mol/L	0.001 mol/L *or* 1×10^{-3} mol/L	0.0001 mol/L *or* 1×10^{-4} mol/L	0.00001 mol/L *or* 1×10^{-5} mol/L	0.000001 mol/L *or* 1×10^{-6} mol/L	0.0000001 mol/L *or* 1×10^{-7} mol/L

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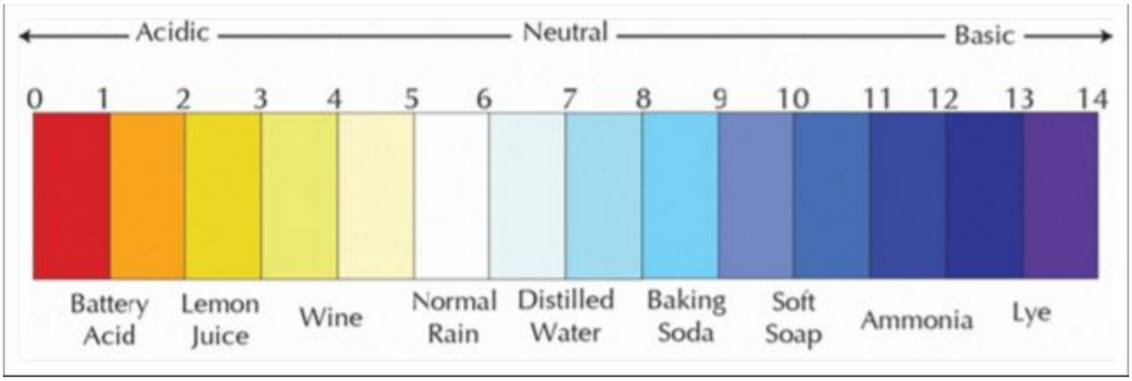
When thinking about pH, just remember that changing the pH by 1 will change the concentration by 10. An acid with a pH of 2 has 10 times as much hydrogen as an acid with a pH of 3. An acid of pH 3 has 100 times as much hydrogen as an acid of pH 5.

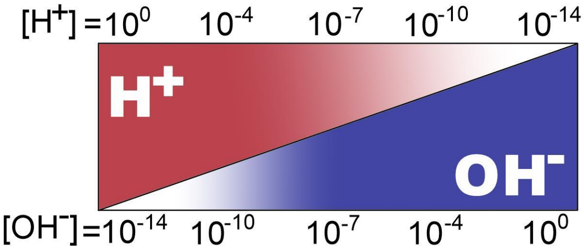


As you go from left to right across this pH scale, the concentration of hydrogen decreases by 10 with each increase of pH by 1. At the same time, the concentration of hydroxide increases by 10 with each increase of pH by 1. At pH 7, the concentrations of hydrogen and hydroxide are exactly equal. The mixture is neutral. At pH greater than 7, there is more hydroxide in the solution than hydrogen, and the solution is called "basic."

So far, we have discussed solutions in terms of their hydrogen ion concentration or pH. In cases of solutions made using water as the solvent, it is also possible to talk about the solutions in terms of their hydroxide ion concentration. This is because water undergoes a reversible reaction in which it dissociates to form a hydrogen ion and a hydroxide ion:

$$H_2O \rightarrow H^+ + OH^-$$

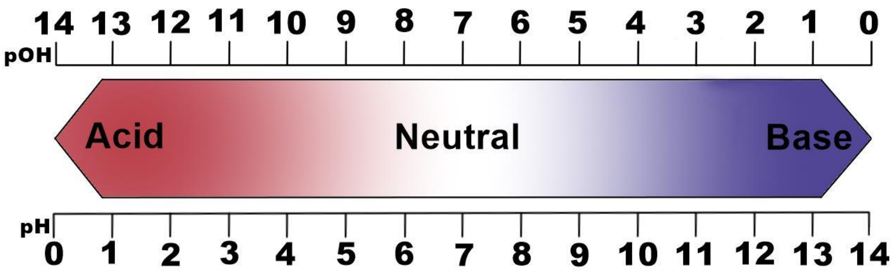
For bases, the power is measured by pOH, which is a conversion from the actual concentration of hydroxide ions in solution. For a solution that is 0.1 mol/L of base, it would have a pOH of 1.0, much like an acid would for pH. Because of the dissociation of water, as the hydroxide ion concentration increases, the hydrogen ion concentration will decrease.



This means that as pOH becomes smaller and smaller, pH will become larger and larger. This relationship is shown by the equation below:

$$pH + pOH = 14$$

For the base above, with a pOH of 1.0, it would have a pH of 13. Correspondingly, an acid with a pH of 3.0 would have a pOH of 11.0



What Do You Think?

Many common items around your house are acidic or basic. Pick out three foods (like bread or coffee) and write them in the table below. Then, using a search engine, try to find out what the pH of the food is. Then using the pH scale above, figure out if the food is acidic or basic.

Food Item	pH	Acid, Basic, or Neutral

Another way to describe the power of an acid is through its strength. The strength of an acid (or base) describes how much of the acid will react with water (or the base) to produce hydrogen in the solution. A strong acid will react 100 percent, producing the maximum amount of hydrogen in the solution. There are seven strong acids. All of the strong bases are Arrhenius bases, and produce hydroxide in solution. Strong bases will react 100 percent and will produce the maximum amount of hydroxide (or accept the maximum amount of hydrogen) in solution. There are eight strong bases.

The 7 Strong Acids	
HCl	Hydrochloric Acid
HBr	Hydrobromic Acid
HI	Hydroiodic Acid
HNO_3	Nitric Acid
H_2SO_4	Sulfuric Acid
$HClO_3$	Chloric Acid
$HClO_4$	Perchloric Acid

The 8 Strong Bases	
$LiOH$	Lithium Hydroxide
$NaOH$	Sodium Hydroxide
KOH	Potassium Hydroxide
$RbOH$	Rubidium Hydroxide
$CsOH$	Cesium Hydroxide
$Ca(OH)_2$	Calcium Hydroxide
$Sr(OH)_2$	Strontium Hydroxide
$Ba(OH)_2$	Barium Hydroxide

All other acids and bases are weak. This means that when they are dissolved in water, only part of the hydrogen is released. Or only some of the hydrogen is accepted. Citric acid, phosphoric acid, baking soda, and milk of magnesia are all weak. The amount that reacts is called the percent dissociation. Dissociation refers to the acid or base reacting with the water in solution. The following table shows examples of each type of acid or base.

Chemical	Classification	Reaction in Water	Percent dissociation in a 0.10 mol/L solution
Acetic Acid (vinegar)	Weak Acid	$HC_2H_3O_2 + H_2O \leftrightarrow H_3O^+ + C_2H_3O_2^-$	1.3 percent
Ammonia (glass cleaner)	Weak Base	$NH_3 + H_2O \leftrightarrow OH^- + NH_4^+$	1.3 percent
Hydrochloric Acid	Strong Acid	$HCl + H_2O \rightarrow H_3O^+ + Cl^-$	100.0 percent
Sodium Hydroxide	Strong Base	$NaOH \rightarrow OH^- + Na^+$	100.0 percent

To find the percentage dissociation of an acid or a base, divide the concentration of reacted (or dissociated) acid or base by the total concentration and multiply by 100.

For the reaction:

$$HA + H_2O \leftrightarrow H_3O^+ + A^-$$

You can see from the very low percentage dissociation values that weak acids and bases dissociate very weakly compared to strong acids and strong bases.

Look Out!

Acid strength is not measured in pH. Acid strength is an inherent characteristic of any acid regardless of its concentration. A strong acid can have a high pH if it is diluted and a low pH if it is concentrated. Similarly, a weak acid can have a high pH if it is diluted and a low pH if it is concentrated. Therefore, you cannot use pH as a measure of the strength of an acid.

Now that we have defined acids, bases, and pH, we can return to the question raised at the beginning of this companion. Recall that hydrangeas produce blue flowers when grown in acidic soil, but they produce pink flowers when grown in basic soil. So why does soil acidity influence hydrangea flower color? A colored pigment present in the cells in hydrangea flower petals provides color. The pigment molecule is a weak acid. In the acid form (abbreviated below as HA), the molecule has a blue color. In the basic form (abbreviated as A^-), the molecule has a pink color:

$$HA + H_2O \leftrightarrow H_3O^+ + A^-$$

Because this pigment is a weak acid, it can shift between its blue and pink forms depending on pH. The presence of aluminum ions also tends to stabilize the blue acid form. When planted in soils of low pH, hydrangea plants are better able to take up aluminum ions from the soil. As these ions accumulate in the petals, they shift the pigment to the acid (or blue) form. Soils of high pH inhibit the plants from taking up aluminum, resulting in a shift toward the pink form of the pigment.

Try Now

1. Sort the following compounds into the categories listed in the table below. Some compounds may be listed in more than one category.

   Compounds: HBr, H_2SO_4, $Mg(OH)_2$, NH_3, H_2O

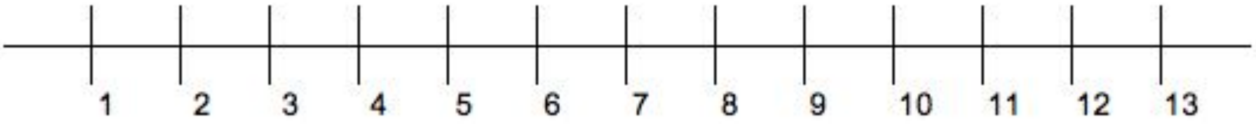
Group	Compound
Arrhenius Acid	
Arrhenius Base	
Brønsted-Lowry Acid	
Brønsted-Lowry Base	

2. Choose two reactants from the bank to write a balanced equation showing an acid-base reaction. Make sure you are dealing with an Arrhenius type reaction or a Brønsted-Lowry type reaction

   Reactant bank: HNO_3, LiOH, H_2O, NH_3, $Mg(OH)_2$, OH^-, H_3O^+

3. The following is a list of solutions located on a bench in a chemistry lab. Place an arrow on the pH scale below to indicate where each solution falls in terms of its pH. Label your arrow with the letter of the solution.

   Solution A: 0.10M HCl
   Solution B: 0.0010M NaOH
   Solution C: 1.0×10^{-5} M HNO_3
   Solution D: 0.10M KOH



4. The following list provides the degree of dissociation for several compounds when these compounds are placed in water at 1M concentrations. Sort the list into groups in the table provided below.

RbOH: 100 percent dissociated
$HC_3H_5O_2$: 0.4 percent dissociated
NH_3: 0.4 percent dissociated
HI: 100 percent dissociated
$HClO_4$: 100 percent dissociated
NH_2CH_3: 2 percent dissociated
NaOH: 100 percent dissociated
$HCHO_2$: 1 percent dissociated

Group	Compound
Strong Acid	
Strong Base	
Weak Acid	
Weak Base	

Connecting With Your Child

Making Homemade Acid-Base Test Paper
You can make acid-base test paper at home!

Materials needed:

- Red cabbage
- Blender
- Sauce pan
- Measuring cups
- Water
  Timer
- Coffee filter or fine mesh strainer
- Blank white paper
- Tray large enough to hold a sheet of paper
- Spoon
- Paper towels
- Newspaper

1. Cut two leaves of red cabbage into small squares, and puree in a blender with one cup of tap water.
2. Transfer the liquefied cabbage leaves to a small saucepan.
3. Repeat the step above several times until the saucepan is half full.
4. Heat the cabbage leaf puree to boiling on the stove.
5. Reduce the temperature to medium and allow the liquid to simmer 20 minutes uncovered.
6. Cool the liquid to room temperature, then pass it through a coffee filter or fine mesh strainer to remove solid plant material.
7. Pour enough of the filtered cabbage juice into the tray so that a sheet of paper is covered with liquid.
8. Carefully add a sheet of paper to the liquid. Press the paper with the spoon so that it becomes covered with liquid.
9. Soak the paper for at least five minutes, then lift it out and place it on paper towels that have been layered over newspaper.
10. Repeat to make several sheets of acid-base test paper.
11. Allow the papers to dry.
12. Test your acid-base test paper to see how its color reacts when exposed to acids and bases. Acids to test include vinegar, lemon juice, and soda. Bases to test include baking soda, ammonia, and window cleaner.
13. You can make a liquid slurry of baking soda and water by adding some of the powder to a small bowl, adding water, and stirring. Dilute vinegar, lemon juice, ammonia, and window cleaner with water to cut down on fumes and odors.
14. Try using a paintbrush dipped in each solution to transfer some of the acid or base to the acid-base test paper.

Here are some questions to discuss with your child after you've tested some items around your house:

1. What color is associated with acidic conditions?
2. What color is associated with basic conditions?
3. How could you use your pH paper to test whether an unknown substance is an acid or a base?
4. Is the compound that you extracted from cabbage leaves itself an acid or a base?
5. How is this similar to the hydrangea pigment discussed earlier?