Acids and Bases
How do acids and bases behave in water?

Why?

Acids and bases play an important role in our lives. Numerous biological processes, industrial applications, and even environmental problems are a function of the acidity or basicity (alkalinity) of aqueous solutions. It is therefore important to understand what makes a substance behave as an acid or a base when dissolved in water. In this activity, we will explore the physical and chemical properties of acids and bases.

### Model 1 – Arrhenius Acids and Bases

<table>
<thead>
<tr>
<th>Common Name for Aqueous Solution</th>
<th>Chemical Formula</th>
<th>Found in...</th>
<th>Tastes...</th>
<th>Turns Litmus Paper...</th>
<th>Conducts Electricity?</th>
<th>Acid or Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid</td>
<td>HC₂H₃O₂(aq)</td>
<td>Vinegar</td>
<td>Sour</td>
<td>Red</td>
<td>Yes</td>
<td>Acid</td>
</tr>
<tr>
<td>Benzoic acid</td>
<td>HC₇H₅O₂(aq)</td>
<td>Food preservative</td>
<td>Sour</td>
<td>Red</td>
<td>Yes</td>
<td>Acid</td>
</tr>
<tr>
<td>Phosphoric acid</td>
<td>H₃PO₄(aq)</td>
<td>Soda pop</td>
<td>Sour</td>
<td>Red</td>
<td>Yes</td>
<td>Acid</td>
</tr>
<tr>
<td>Hydrochloric acid</td>
<td>HCl(aq)</td>
<td>Stomach acid</td>
<td>Sour</td>
<td>Red</td>
<td>Yes</td>
<td>Acid</td>
</tr>
<tr>
<td>Citric acid</td>
<td>H₂C₆H₅O₇(aq)</td>
<td>Citrus fruits</td>
<td>Sour</td>
<td>Red</td>
<td>Yes</td>
<td>Acid</td>
</tr>
<tr>
<td>Ascorbic acid</td>
<td>H₂C₆H₈O₆(aq)</td>
<td>Vitamin C</td>
<td>Sour</td>
<td>Red</td>
<td>Yes</td>
<td>Acid</td>
</tr>
<tr>
<td>Magnesium hydroxide</td>
<td>Mg(OH)₂(aq)</td>
<td>Milk of magnesia</td>
<td>Bitter</td>
<td>Blue</td>
<td>Yes</td>
<td>Base</td>
</tr>
<tr>
<td>Aluminum hydroxide</td>
<td>Al(OH)₃(aq)</td>
<td>Antacids</td>
<td>Bitter</td>
<td>Blue</td>
<td>Yes</td>
<td>Base</td>
</tr>
<tr>
<td>Barium hydroxide</td>
<td>Ba(OH)₂(aq)</td>
<td>Lubricants</td>
<td>POISON</td>
<td>Blue</td>
<td>Yes</td>
<td>Base</td>
</tr>
<tr>
<td>Sodium hydroxide</td>
<td>NaOH(aq)</td>
<td>Drain cleaner</td>
<td>POISON</td>
<td>Blue</td>
<td>Yes</td>
<td>Base</td>
</tr>
</tbody>
</table>

1. Refer to Model 1.
   a. What is the common chemical name for Vitamin C?
      *Ascorbic acid.*
   
   b. Is Vitamin C classified as an acid or a base?
      *Acid.*

2. Examine the properties of the Arrhenius acids in Model 1. List three properties that all Arrhenius acids have in common.
   *Arrhenius acids have a sour taste, turn litmus paper red, and conduct electricity.*

3. Examine the chemical formulas for the Arrhenius acids in Model 1. What feature do all the Arrhenius acid chemical formulas have in common?
   *They all have a hydrogen written separately at the beginning of the formula.*

4. Examine the properties of the Arrhenius bases in Model 1. List two properties that all Arrhenius bases have in common.
   *Arrhenius bases have a bitter taste, turn litmus paper blue, and conduct electricity.*
5. Examine the chemical formulas for the Arrhenius bases in Model 1. What anion do all the Arrhenius base chemical formulas have in common?

_They all contain a hydroxide (OH⁻) ion._

6. A student dissolved a small amount of baking soda in water and tested it with litmus paper. The litmus paper turned blue. Is baking soda likely an acid or a base?

_A base._

**Read This!**

In 1903 Svante Arrhenius won the Nobel Prize in Chemistry for defining acids and bases in terms of the ions produced. An Arrhenius acid is any substance that produces hydrogen ions [or hydronium ions (H₃O⁺) a hydrogen ion attached to a water molecule] when dissolved in water. An Arrhenius base is any substance that produces hydroxide ions when dissolved in water. While the Arrhenius definitions of acids and bases is useful, it is limited. Johannes Brønsted and Thomas Lowry developed more general definitions for acids and bases using H⁺ ion (proton) transfer as the focus.

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**Model 2 – Brønsted–Lowry Acids and Bases**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reaction</th>
<th>Reaction</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HCl(g)</td>
<td>H₂O(l)</td>
<td>H₃O⁺(aq) + Cl⁻(aq)</td>
</tr>
<tr>
<td></td>
<td>(acid)</td>
<td>(base)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>NH₃(aq)</td>
<td>HF(aq)</td>
<td>NH₄⁺(aq) + F⁻(aq)</td>
</tr>
<tr>
<td></td>
<td>(base)</td>
<td>(acid)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>NH₄⁺(aq)</td>
<td>H₂O(l)</td>
<td>NH₃(aq) + H₃O⁺(aq)</td>
</tr>
<tr>
<td></td>
<td>(acid)</td>
<td>(base)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>F⁻(aq)</td>
<td>H₂PO₄⁻(aq)</td>
<td>HPO₄²⁻(aq) + HF(aq)</td>
</tr>
<tr>
<td></td>
<td>(base)</td>
<td>(acid)</td>
<td></td>
</tr>
</tbody>
</table>

7. Identify the Brønsted-Lowry acids in Model 2.
   
   _a._ Atoms of which element are present in all of the Brønsted-Lowry acids in Model 2?
   
   _Hydrogen._
   
   _b._ How can you tell from Reaction 1 that HCl loses an H⁺ ion rather than a hydrogen atom when the reaction occurs? **Hint:** Look at the products.

   _The chlorine ion that is left over has a negative charge. The H₃O⁺ ion is produced when a positively charged H⁺ ion combines with a neutral water molecule._

8. For each acid–base reaction in Model 2, describe the role of the Brønsted-Lowry acid in the H⁺ ion (proton) transfer that occurs.

   _The acid gives up a hydrogen ion and passes it to the base._

9. For each acid–base reaction in Model 2, describe the role of the Brønsted-Lowry base in the proton (H⁺ ion) transfer that occurs.

   _The base takes the hydrogen ion from the acid._
10. As you saw in Model 1, all Arrhenius bases in Model 1 have an OH⁻ ion in their chemical formulas. Write a balanced chemical reaction for the reaction of HCl(aq) with OH⁻(aq) to illustrate that the hydroxide ion is also a Brønsted-Lowry base.

\[ HCl(aq) + OH^-(aq) \rightleftharpoons Cl^-(aq) + H_2O(aq) \]

11. If you reverse Reaction 1 in Model 2, the following reaction is obtained.

\[ H_3O^+(aq) + Cl^-(aq) \rightleftharpoons HCl(aq) + H_2O(l) \]

a. For the reaction above, which reactant is acting like a Brensted-Lowry acid? How can you tell?

\[ H_3O^+ \text{ is a Brønsted-Lowry acid because it gives up a hydrogen ion to become } H_2O. \]

b. For the reaction above, which reactant is acting like a Brønsted-Lowry base? How can you tell?

\[ Cl^- \text{ is a Brønsted-Lowry base because it takes the hydrogen ion to become HCl.} \]

12. Write the reverse reactions for Reactions 2 and 3 in Model 2. Label the Brønsted-Lowry acid and base reactants for each reaction.

**Reaction 2**

\[ \text{(acid)} \quad NH_4^+(aq) + Br^-(aq) \rightleftharpoons NH_3(aq) + HBr(aq) \quad \text{(base)} \]

**Reaction 3**

\[ \text{(base)} \quad NH_3(aq) + H_3O^+(aq) \rightleftharpoons NH_4^+(aq) + H_2O(l) \quad \text{(acid)} \]

**Model 3 – Conjugate Acid–Base Pairs**

\[ \text{HCO}_3^- (aq) + H_2O(l) \rightleftharpoons \text{CO}_3^{2-} (aq) + H_3O^+(aq) \]

13. All acid–base reactions have two conjugate acid–base pairs. One conjugate acid–base pair in the reaction in Model 3 is H$_3$O$^+$/H$_2$O. List the other acid–base pair in the reaction.

\[ \text{HCO}_3^-/\text{CO}_3^{2-} \]

14. Why is HCO$_3^-$ considered the “acid” part of the pair in the reaction in Model 3?

\[ \text{It gives away its hydrogen ion to form } \text{CO}_3^{2-}. \]

15. Why is CO$_3^{2-}$ considered the “base” part of the pair in the reaction in Model 3?

\[ \text{It takes the hydrogen ion back in the reverse reaction to regenerate } \text{HCO}_3^- \]

16. The “Read This!” box before Model 2 calls the transfer of a H$^+$ ion a "proton transfer." Explain why “H$^+$ ion” and “proton” are synonymous.

\[ \text{The most common hydrogen isotope has one proton, one electron, and no neutrons. When this atom is made into an ion (H$^+$) by removing an electron, the only thing left is a proton.} \]

Acids and Bases
17. Examine the charges on the species in the Model 3 reaction. Why does the charge on the carbon-containing ion change from $-1$ to $-2$?

The hydrogen lost by $\text{HCO}_3^-$ is actually a hydrogen ion (+1), so a negative charge is left over when the hydrogen ion leaves. Removing a +1 ion from a $-1$ ion produces a $-2$ ion.

18. Using the list of substances below, select pairs that are conjugate acids and bases. Enter the pairs in the tables below. The first acid–base pair has been entered for you. Note that you may use a substance more than once or not at all.

<table>
<thead>
<tr>
<th>Acid</th>
<th>Conjugate Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_3\text{PO}_4$</td>
<td>$\text{H}_2\text{PO}_4^-$</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>$\text{OH}^-$</td>
</tr>
<tr>
<td>$\text{HC}_2\text{H}_3\text{O}_2$</td>
<td>$\text{C}_2\text{H}_3\text{O}_2^-$</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}^+$</td>
<td>$\text{H}_2\text{O}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acid</th>
<th>Conjugate Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C}_2\text{H}_3\text{O}_2$</td>
<td>$\text{H}_2\text{CO}_3$</td>
</tr>
<tr>
<td>$\text{CO}_3^{2-}$</td>
<td>$\text{NH}_3$</td>
</tr>
<tr>
<td>$\text{OH}^-$</td>
<td>$\text{H}_2\text{PO}_4^-$</td>
</tr>
</tbody>
</table>

19. Write the formula for the conjugate base of each of the following acids. Hint: Be sure to consider charges.

   a. $\text{HSO}_3^-$
   b. $\text{HF}$
   c. $\text{HS}^-$

20. Write the formula for the conjugate acid of each of the following bases. Hint: Be sure to consider charges.

   a. $\text{SO}_3^{2-}$
   b. $\text{F}^-$
   c. $\text{HS}^-$

21. For the following reactions, label the acid and base in the reactants, and the conjugate acid and conjugate base in the products.

   $\text{HCO}_3^-(\text{aq}) + \text{NH}_3(\text{aq}) \rightleftharpoons \text{NH}_4^+(\text{aq}) + \text{CO}_3^{2-}(\text{aq})$

   (acid) (base) (conj. acid) (conj. base)

   $\text{HCO}_3^-(\text{aq}) + \text{HCl}(\text{aq}) \rightleftharpoons \text{Cl}^-(\text{aq}) + \text{H}_2\text{CO}_3(\text{aq})$

   (base) (acid) (conj. base) (conj. acid)

22. Is the role of a conjugate acid in the reverse direction the same as the role of an acid in the forward direction? Explain.

   Yes—in both the forward and reverse directions of a reaction, the acid (or conjugate acid) donates a hydrogen ion.
Extension Questions

23. Some of the substances used in this activity can behave as both an acid and a base. These substances are said to be *amphiprotic* or *amphoteric*. Provide two examples of amphoteric substances found in this activity.

*Answers will vary. Examples of amphoteric substances are* $H_2O$, $HS^-$, $HCO_3^-$, $NH_3$, $H_2PO_4^-$, $HPO_4^{2-}$.

24. Water is an amphoteric substance. In any sample of water some of the molecules perform acid–base reactions with each other. This is called the *autoionization* of water. Write a chemical reaction showing the acid–base reaction of two water molecules.

$$H_2O + H_2O \rightarrow H_3O^+ + OH^-$$