The Arrhenius Definition

Over the years, chemists have proposed several definitions of acids and bases. The first successful definition came in 1884 from Arrhenius. Arrhenius proposed that an acid was any substance that dissociated in water to produce hydrogen ions (H^+).

Hydrochloric acid is an example of an Arrhenius acid. As the equation below shows, when dissolved in water, it dissociates to form hydrogen ions.

$$HCl(s) \rightarrow H^+(aq) + Cl^-(aq)$$

Similarly, Arrhenius proposed that a base was a substance that dissociates in water to produce hydroxide ions (OH^-).

Sodium hydroxide is an example of an Arrhenius base. As the equation below shows, when dissolved in water, it dissociates to form hydroxide ions.

$$NaOH(s) \rightarrow Na^+(aq) + OH^-(aq)$$

Some common Arrhenius acids and bases are listed below.

Acid	**Formula**	**Base**	**Formula**
hydrochloric acid	HCl	sodium hydroxide	$NaOH$
nitric acid	HNO_3	potassium hydroxide	KOH
acetic acid	$HC_2H_3O_2$	magnesium hydroxide	$Mg(OH)_2$
sulfuric acid	H_2SO_4	calcium hydroxide	$Ca(OH)_2$
carbonic acid	H_2CO_3	barium hydroxide	$Ba(OH)_2$
phosphoric acid	H_3PO_4		

Problems with Arrhenius Model

The Arrhenius model has its shortcomings. First, it restricts acids and bases to water solutions. However, similar reactions occur in the gas phase, and in solvents other than water.

Second, the Arrhenius definition of a base does not include certain compounds that have the characteristic properties of bases. For example, ammonia (NH_3) does not contain a hydroxide group, yet it produces hydroxide ions in solution and is a well known base.

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

There are many substances which are acidic or basic but do not have a hydrogen ion or a hydroxide ion. For example:

- baking soda (sodium bicarbonate, $NaHCO_3$) in water turns litmus blue, but has no apparent hydroxide ion
- metal ions, such as iron (III) and aluminum, turn litmus red, but have no hydrogen ions.

The Arrhenius definition does not account for the acidic and basic nature of these examples. It is not a complete loss, however, since it was important in establishing the concept of dissociation. The Arrhenius Theory was also an essential starting point for the further development of our understanding of acids and bases.

The Brønsted-Lowry Definition

To overcome the limitations of the Arrhenius definition, chemists needed a more general definition of acids and bases. In 1923, Brønsted and Lowry independently proposed the same definition. According to the Brønsted-Lowry definition,

- an acid is any substance that can donate hydrogen ions (H^+).
- a base is any substance that can accept hydrogen ions.

The Brønsted-Lowry definition improves on the Arrhenius definition in two important ways. First, it defines acids and bases independently of how they behave in water. Second, it focuses solely on hydrogen ions. By excluding hydroxide ions from the definition, the Brønsted-Lowry definition opens the door to include many substances that would be excluded by the Arrhenius definition.

It is important to note that a hydrogen atom consists of a single proton surrounded by a single electron. When the electron is removed to form a hydrogen ion, all that is left is the single proton. Thus, a hydrogen ion is simply a proton.

For this reason, the Brønsted-Lowry definition of acids and bases is often presented in terms of protons. A Brønsted-Lowry acid is a proton donor, and a Brønsted-Lowry base is a proton acceptor.

The Hydronium Ion

Thus far, we have discussed hydrogen ions as if they dissolved in water like any other ion. However, because a hydrogen ion is simply a proton, it is strongly attracted to the electrons of surrounding water molecules. Because of this, hydrogen ions will actually react with water molecules as shown below.

$$H^+(aq) + H_2O(l) \rightarrow H_3O^+(aq)$$

The H_3O^+ ion is called a hydronium ion.

From the Brønsted-Lowry perspective, an acid such as hydrochloric acid does not simply dissociate in water to form hydrogen ions and chloride ions. Rather, a molecule of hydrochloric acid transfers a hydrogen ion (a proton) to a water molecule to form hydronium ions and chloride ions.

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

By applying the Brønsted-Lowry definition to this reaction, you can identify not only an acid but a base as well. The hydrochloric acid donates a hydrogen ion, so it is the Brønsted-Lowry acid. The water molecule accepts the hydrogen ion, so it is a Brønsted-Lowry base.

Brønsted-Lowry also explains why water solutions of ammonia are basic. When an ammonia molecule comes in contact with a water molecule, it accepts a hydrogen ion from the water molecule.

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

In this reaction, ammonia is the Brønsted-Lowry base and water is the Brønsted-Lowry acid.

Notice that water acts as a Brønsted-Lowry base in one reaction, but as a Brønsted-Lowry acid in the other. A substance such as water that can act as either an acid or a base depending on the circumstances is described as **amphoteric**.

Conjugate Acid-Base Pairs

In the examples we have given above, we have shown the reactions proceeding in one direction only. However, these reactions can also proceed in the reverse direction. For example, the reaction between ammonia (NH_3) and water is more accurately represented as

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

In the forward reaction, according to the Brønsted-Lowry definition, water is the acid and ammonia is the base. However, if we examine the reverse reaction, you will see that the ammonium ion (NH_4^+) is the acid and the hydroxide ion (OH^-) is the base.

Notice that the base in the forward reaction (NH_3) gains a hydrogen ion to become the acid in the reverse reaction (NH_4^+). Similarly, the acid in the forward reaction (H_2O) loses a hydrogen ion to become the base in the reverse reaction (OH^-).

To emphasize this relationship, chemists use the terms **conjugate acid** and **conjugate base**. When an acid loses a hydrogen ion, it becomes its conjugate base. Likewise, when a base gains a hydrogen ion, it becomes its conjugate acid.

$$\underbrace{NH_3(g)}_{base} + \underbrace{H_2O(l)}_{acid} \Leftrightarrow \underbrace{NH_4^+(aq)}_{conjugate\ acid} + \underbrace{OH^-(aq)}_{conjugate\ base}$$

A pair of compounds that differ by only one hydrogen ion (such as H_2O and OH^-) is called a **conjugate acid-base pair**.

It should be noted that the stronger an acid is, the weaker its conjugate base will be. Also, the weaker an acid, the stronger its conjugate base will be.

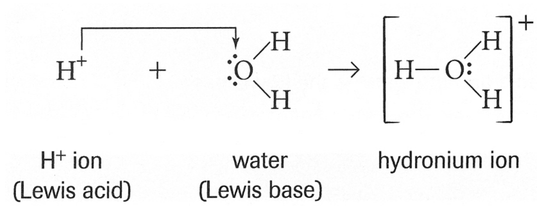
The Lewis Definition

In the early 1920s, Lewis expanded the Brønsted-Lowry model to include a number of substances that would not be considered Brønsted-Lowry acids or bases. According to the Lewis model,

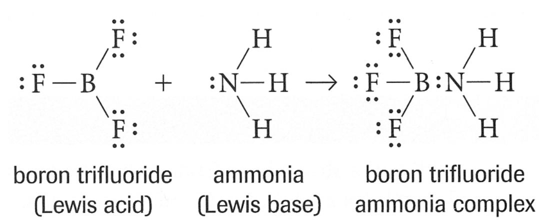
- a Lewis acid is an electron-pair acceptor.
- a Lewis base is an electron-pair donor.

In order to act as a Lewis base, a substance must possess a non-bonded pair of electrons in its valence shell. Conversely, to act as a Lewis acid, a substance must possess a valence shell that can accept a pair of non-bonding valence electrons from a Lewis base.

The following equation illustrates the reaction between a Lewis acid and a Lewis base.



In the above reaction, the hydrogen ion acts as the Lewis acid and the water molecule acts as the Lewis base. In this particular example, the Lewis base is also a Brønsted-Lowry base and the Lewis acid is also a Brønsted-Lowry acid. However, in the following example, this is not the case.



In this reaction, ammonia is both a Lewis base and a Brønsted-Lowry base. Boron trifluoride, however, is a Lewis acid but would not be considered a Brønsted-Lowry acid.

The Lewis model is a more general model of acids and bases that not only encompasses both the Arrhenius and Brønsted-Lowry models, but extends them to include other substances.

Worksheet

1. Classify each of the following as a Brønsted-Lowry acid, a Brønsted-Lowry base, or both.

   a) H_2O
   b) OH^-
   c) NH_3
   d) NH_4^+
   e) NH_2^-
   f) CO_3^{2-}

2. What is the conjugate base of each of the following acids?

   a) $HClO_4$
   b) NH_4^+
   c) H_2O
   d) HCO_3^-

3. What is the conjugate acid of each of the following bases?

   a) CN^-
   b) SO_4^{2-}
   c) H_2O
   d) HCO_3^-

4. Identify the conjugate acid-base pairs in the following reactions.

   a) $NH_4^+ + H_2O \Leftrightarrow NH_3 + H_3O^+$
   b) $HCOOH + CN^- \Leftrightarrow HCOO^- + HCN$
   c) $NH_4^+ + CO_3^{2-} \Leftrightarrow NH_3 + HCO_3^-$
   d) $H_2PO_4^- + OH^- \Leftrightarrow HPO_4^{2-} + H_2O$