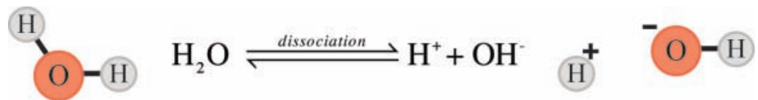
13.1 The Chemical Nature of Acids and Bases

The dissociation of water

Acids and bases are important to chemistry because almost every reaction that occurs in an aqueous solution is affected. This includes your body, the ocean, and much of the biosphere of Earth. The reason is partly because water partially *dissociates*. On average, 1 out of every 550 million water molecules is dissociated into a hydrogen (H^+) ion and a hydroxide (OH^-) ion. *The hydrogen ion is chemically powerful, and quite unique.*



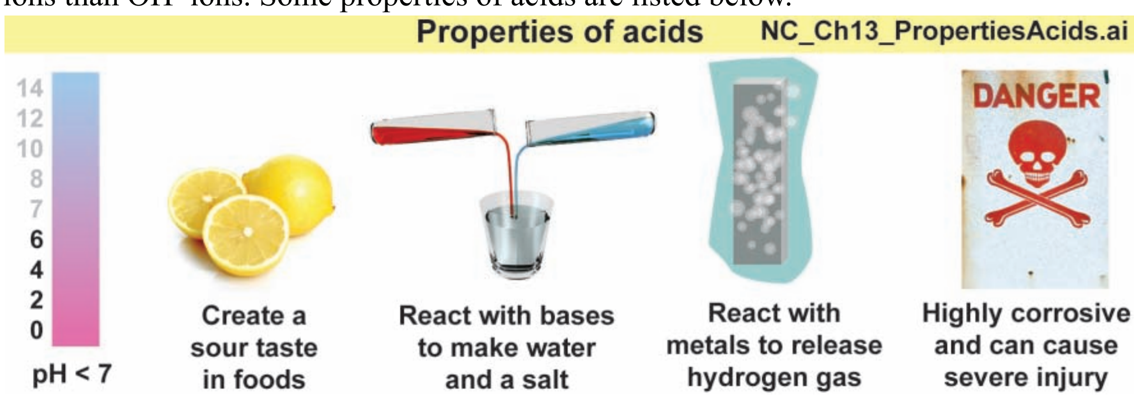
Neutral means $[H^+] = [OH^-]$

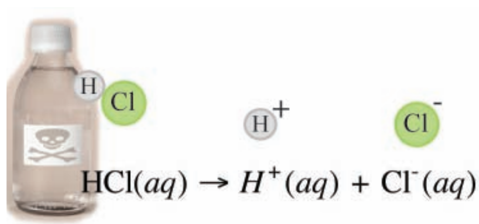
In **neutral** water, the concentration of H^+ ions and OH^- ions is *equal*. This is evident from the balanced equation. In the context of acidity, the word "neutral" means $[H^+] = [OH^-]$.

The dissociation reaction is written with a double arrow to show that the reaction goes both ways. Some H^+ and OH^- ions are always re-combining to make water molecules. In equilibrium, there is a balance between molecules dissociating into H^+ and OH^-, and ions recombining to make whole molecules again.

Properties of acids

An **acid** is a compound that dissolves in water to make a solution that contains *more* H^+ ions than OH^- ions. Some properties of acids are listed below.





When hydrochloric acid (HCl) dissolves in water it ionizes completely into hydrogen (H^+) and chlorine (Cl^-) ions. The fact that H^+ ions are created is what makes HCl an acid. Some other common acids are acetic acid (in vinegar) and citric acid (in citrus fruits).

Chemistry terms

neutral - in the context of acids and bases, neutral means the pH = 7.0 which also means the concentrations of H^+ and OH^- ions are equal.

acid - a chemical that dissolves in water to create more H^+ ions than there are in neutral water.

Bases

A base is the chemical opposite of an acids

A **base** is a compound that dissolves in water to make a solution with *more* OH^- ions than H^+ ions. In many ways a base is the chemical opposite of an acid. Acids make more H^+ ions and bases make more OH^- ions. Some of the properties of bases are listed below.

Properties of bases

Acid or base but not both

Because H^+ and OH^- can combine to make neutral water, a solution that is not neutral must be either acidic or basic. A solution cannot be both acidic and basic at the same time. The pH scale reflects this either-or behavior. Acids have pH < 7, neutral solutions have pH = 7 and bases have pH > 7.

NaOH is a common base

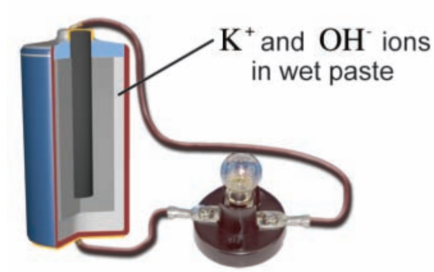
A common base in both the lab and the hardware store is sodium hydroxide (NaOH). This compound is also known by two common names: *lye* and *caustic soda*. When dissolved in water, sodium hydroxide dissociates into sodium ions (Na+) and hydroxide ions (OH-). A 1.0 molar solution of NaOH has a pH of 14, and is a *strong base*. Concentrated NaOH is a dangerous and powerfully reactive substance which can burn skin and especially eyes.

NaOH is also known as **lye** or **caustic soda**

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

Alkaline substances make basic solutions

An *alkaline* substance is a salt of a group I or group II metal that dissolves in water to make a base. A good example is potassium hydroxide (KOH). This ionic compound is used in alkaline batteries. When dissolved in a paste inside a battery, potassium hydroxide dissociates to make potassium ions (K^+) and hydroxide ions (OH^-).



Chemistry terms

base - a chemical that dissolves in water to create less H^+ ions than there are in neutral water, (or equivalently, more OH^- ions).

The importance of the H^+ ion

The H^+ ion is unique because it has no electrons

The H^+ ion is powerful because *it has no electrons*! No other element participates in chemistry as a bare nucleus, a single proton, stripped of its electrons. We learned that chemistry is due to interactions between electrons in atoms. While true, it is ultimately the electrical *energy* linking electrons and protons that drives chemical behavior. Electrons have negative charge. The H^+ ion is a tiny, concentrated *positive* charge with no negative electrons to shield its electrical force. The whole subject of acids and bases has to do with the extraordinary chemical power of the H^+ ion, the "naked proton".

The Arrhenius definition of acid and base

The properties of acids, such as reacting with metals, were known a thousand years before anyone knew *why*. "Acids" were solutions that tasted sour, and dissolved metals. Likewise, bases were identified as solutions that had a bitter taste, were slippery, and neutralized acids. Around 1880, Svante Arrhenius, a Swedish chemist realized that the properties of acids were due to an excess of H^+ ions in aqueous solutions. He also noticed that the properties of bases were associated with an excess of OH^- ions. Arrhenius proposed the first definition of acids and bases.

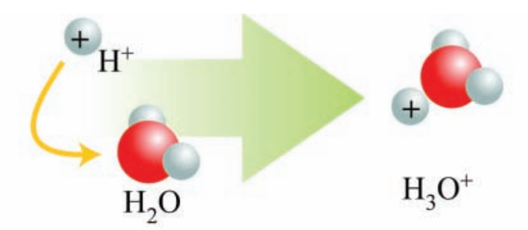
Arrhenius theory

Acids are chemicals that produce H^+ ions in aqueous solutions

Bases are chemicals that produce OH^- ions in aqueous solutions

H^+ and the hydronium ion (H_3O^+)

The H^+ ion is so chemically attractive that it instantly pairs up with a water molecule to make H_3O^+. This is called the **hydronium ion**. Hydronium is sometimes called a *hydrated proton*, since H^+ is a proton and it becomes "hydrated" by bonding to water molecules. When we talk about the H^+ ion in water, we are really talking about H_3O^+ since H^+ really does not exist by itself for very long.



Solitary H^+ ions immediately bond to polar water molecules to form H_3O^+

H^+ is shorthand for H_3O^+

In this chapter (and keeping with history) we will refer the hydronium ion as just H^+ and not H_3O^+. This is really just because H^+ is easier to write and more convenient. However, keep in mind that the hydrated form (H_3O^+) is closer to reality.

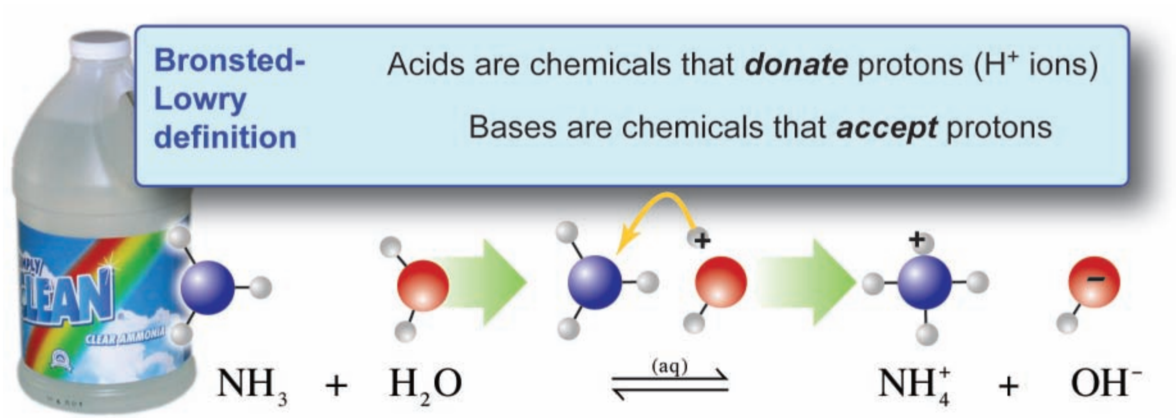
Chemistry terms

hydronium ion - the H_3O^+ ion forms when H^+ bonds to a complete water molecule. Hydronium ions are what give acids their unique properties. Any reference to "H^+" in aqueous solution usually means H_3O^+.

Bronsted-Lowry acids and bases

How is NH_3 a base?

Ammonia (NH_3) is a weak base, even though the ammonia molecule does not contain the OH^- ion. When ammonia dissolves in water, the ammonia molecule strips a proton from a water molecule, leaving an OH- ion. This makes NH_3 a base because it dissolves to create OH^- ions, but does it by taking protons (H^+) from water molecules. Ammonia is a *weak* base because only a fraction of the ammonia molecules form NH_4^+ and OH^-.



The Bronsted-Lowry theory

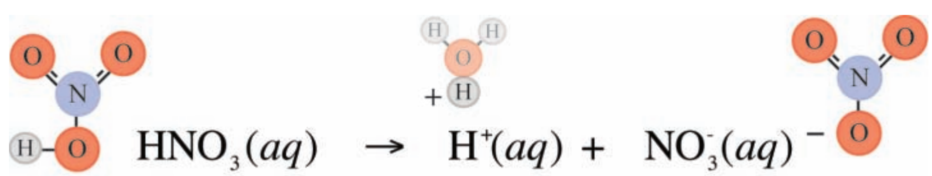
Ammonia acts as a *proton acceptor* when dissolved in water. This give us another, more powerful way to define a base. *A base is a compound that accepts protons*. Ammonia is a base because it accepts a proton from a water molecule, leaving an OH- ion. This idea is known as the **Bronsted-Lowry definition** of acids and bases.

A better way to define acids and bases

According to the Bronsted-Lowry definition, an acid is a compound that donates a proton. A base is a compound that accepts a proton. In many ways the Bronsted-Lowry perspective is a better way to think about acids and bases because it explicitly recognizes the relationship between acids (proton donors) and bases (proton acceptors).

All acids are Bronsted-Lowry acids

All acids and bases can be thought of in the Bronsted-Lowry sense. Nitric acid (HNO_3) dissociates in water to make H^+ ions and NO_3^- ions. The nitric acid molecule donates the proton (H^+), which is why it is an acid.



Chemistry terms

Bronsted-Lowry definition - a different way to look at what defines acids and bases. Acids are compounds that donate protons (H^+). Bases are compounds that accept protons.

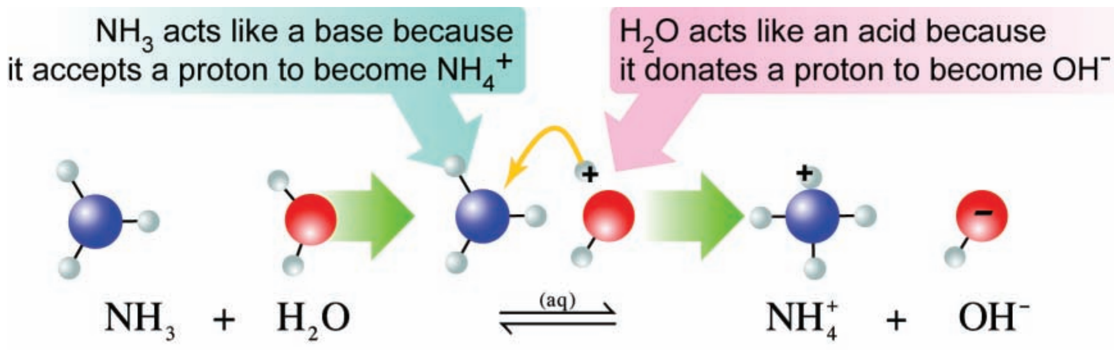
Acids and bases are always paired

Acids and bases act in pairs

The Bronsted-Lowry definition brings up an important idea: for a molecule or ion to act like an acid by donating a proton, another molecule or ion must act like a base by accepting the proton! The opposite is also true. You cannot have something acting like an acid without something else acting like a base and vice versa.

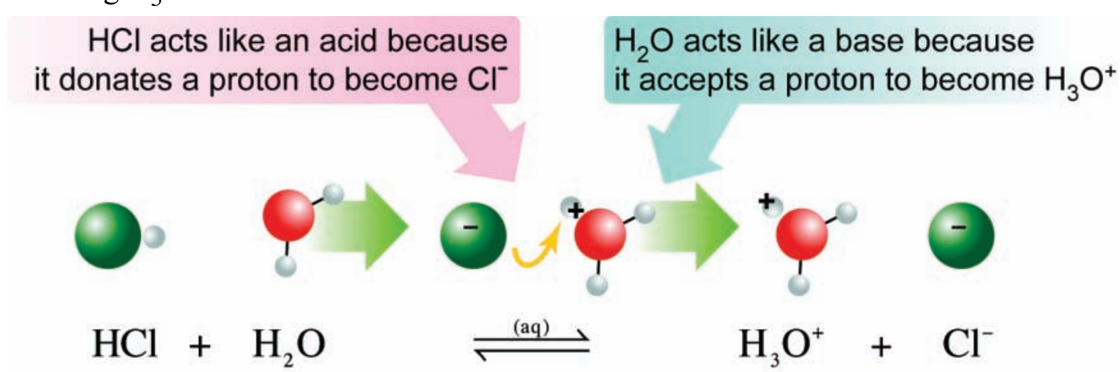
Water can act like an acid

Going back to ammonia again, the NH_3 molecule acts like a base by accepting a proton to become NH_4^+. Water acts like an acid by donating a proton to become OH^-.



Water can also act like a base

Now consider a strong acid. When dissolved in water, hydrochloric acid (HCl) is a proton donor, dissociating to make H^+ ions. Water acts basic by accepting a proton and becoming H_3O^+.



Water is amphoteric

One of the most important properties of water is its ability to act as both an acid and a base. In the presence of an acid, water acts as a base. In the presence of a base, water acts as an acid. A substance that can be either acid or base is **amphoteric**. Water is amphoteric because H_2O can both donate protons ($H_2O \rightarrow H^+ + OH^-$) or accept protons ($H_2O + H^+ \rightarrow H_3O^+$). Other substances are amphoteric too.

Chemistry terms

amphoteric - a substance is amphoteric if it can act as either an acid or a base under different circumstances. Water is amphoteric.

Identifying acids and bases

The chemical formula for an acid starts with an "H"

The chemical formula for an acid is always written with an H first (if the acid contains hydrogen). For example, acetic acid is written $HC_2H_3O_2$ instead of $C_2H_4O_2$. Both formulas give the correct molecule, but the first is quickly recognized as an acid because of the leading "H". If the acid dissolves to make 2 H^+ ions, its chemical formula begins with H_2. Ascorbic acid (vitamin C) is written $H_2C_6H_6O_6$ to indicate that it is both an acid, and that it dissolves to make 2 H^+ ions. Table 13.1 lists some common acids

TABLE 13.1. Common acids

Name	Formula	Strength
Hydrochloric	HCl	strong
Nitric	HNO_3	strong
Sulfuric	H_2SO_4	strong
Phosphoric	H_3PO_4	weak
Ascorbic	$H_2C_6H_6O_6$	weak
Citric	$H_3C_6H_5O_7$	weak
Carbonic	H_2CO_3	weak
Acetic	$HC_2H_3O_2$	weak

The chemical formula of a base

The chemical formula for a strong base is written with the OH last. A good example is sodium hydroxide, written NaOH. The OH at the end of the name reminds chemists that a chemical is a base. Most weak bases such as ammonia (NH_3) do not contain OH so you have to learn other ways to recognize them as bases.

TABLE 13.2. Common bases

Name	Formula	Strength
Sodium hydroxide	$NaOH$	strong
Potassium hydroxide	KOH	strong
Calcium hydroxide	$Ca(OH)_2$	strong
Ammonia	NH_3	weak
Carbonate ion	HCO_3^-	weak
Hypochlorite ion	ClO^-	weak
Caffeine	$C_8H_{10}N_4O_2$	weak
Ephedrine	$C_{10}H_{15}ON$	weak

Strong acids and bases

A **strong** acid or base dissociates completely in water so that each molecule contributes one H^+ ion (acids) or one OH^- ion (bases). Nitric acid is a good example of a strong acid. Every nitric acid molecule dissociates into an H^+ ion and a nitrate (NO_3^-) ion. Sodium hydroxide (NaOH) is a strong base because every mole of NaOH that dissolves creates one mole of OH- ions one mole of Na+ ions.

Weak acids and bases

A **weak** acid or base only dissociates partially or produces relatively few H^+ or OH^- ions in solution. For example a 1M solution of acetic acid creates less than 1% as many H^+ ions as the same concentration of hydrochloric acid.

Chemistry terms

strong acid/base - dissociates completely (or almost completely) usually yielding 1 mole of H^+ or OH^- ions for every mole of acid or base dissolved.

weak acid/base - only partially dissociates in solution, typically only a few percent (or less) of molecules dissociate to yield H^+ or OH^- ions.