Chapter 8
Acids, Bases, and Acid-Base Reactions

An Introduction to Chemistry

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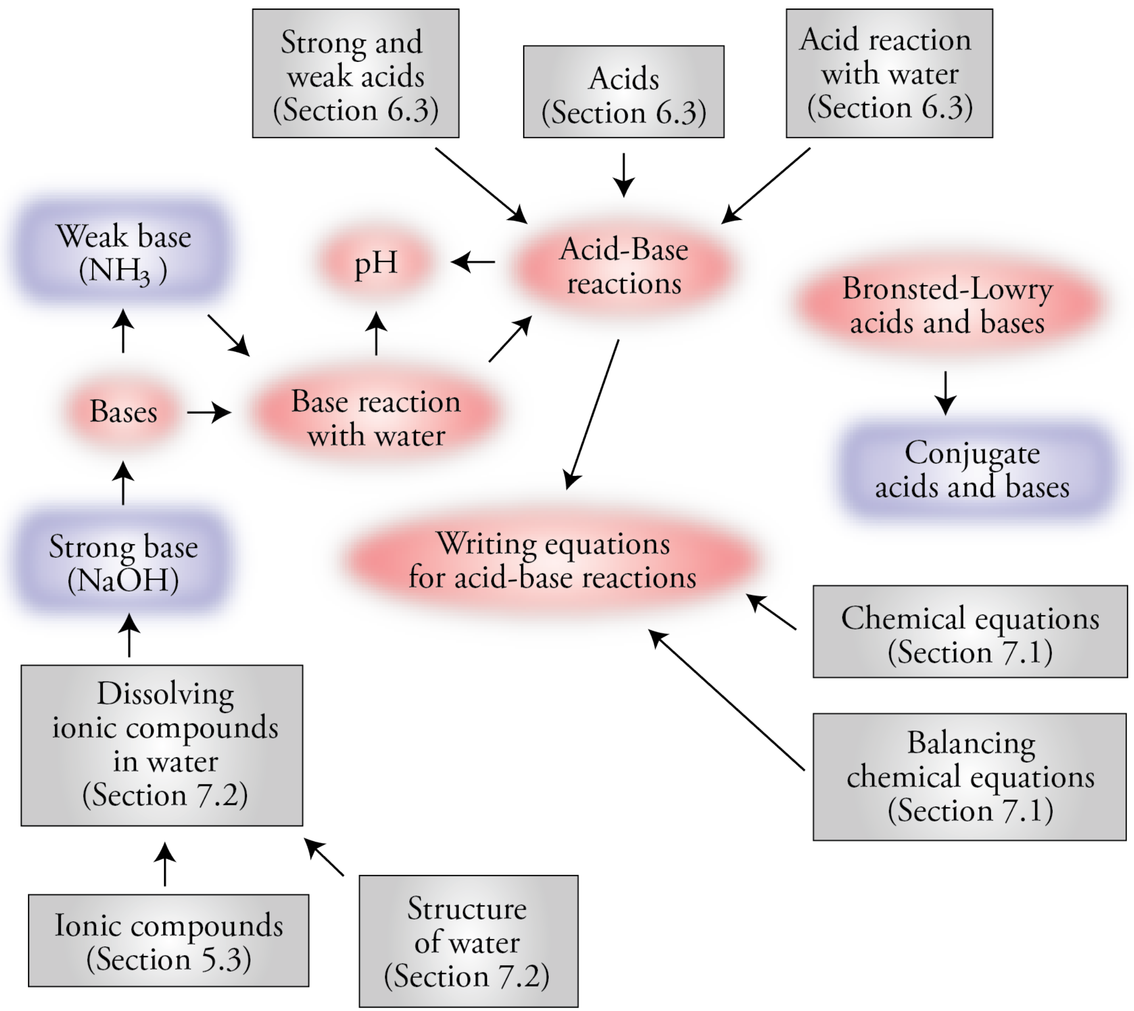
Chapter Map



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Arrhenius Base Definitions

- A ***base*** is a substance that generates OH^- when added to water.
- A ***basic*** solution is a solution with a significant concentration of OH^- ions.

Characteristics of Bases

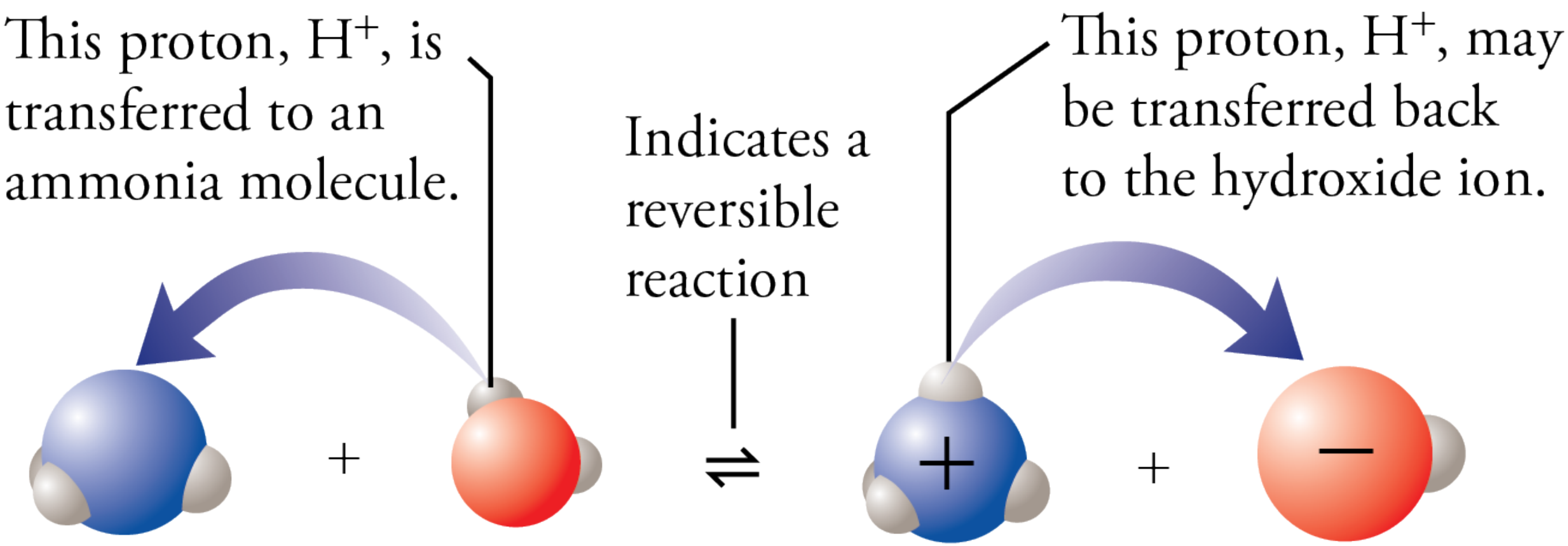
- Bases have a bitter taste.
- Bases feel slippery on your fingers.
- Bases turn litmus from red to blue.
- Bases react with acids.

Strong Bases

- ***Strong Base*** = due to a completion reaction with water, generates close to one (or more) OH^- for each formula unit of base added to water.
  - Metal hydroxides are strong bases.

Ammonia and Water

Ammonia reacts with water in a reversible reaction, which forms ammonium and hydroxide ions.

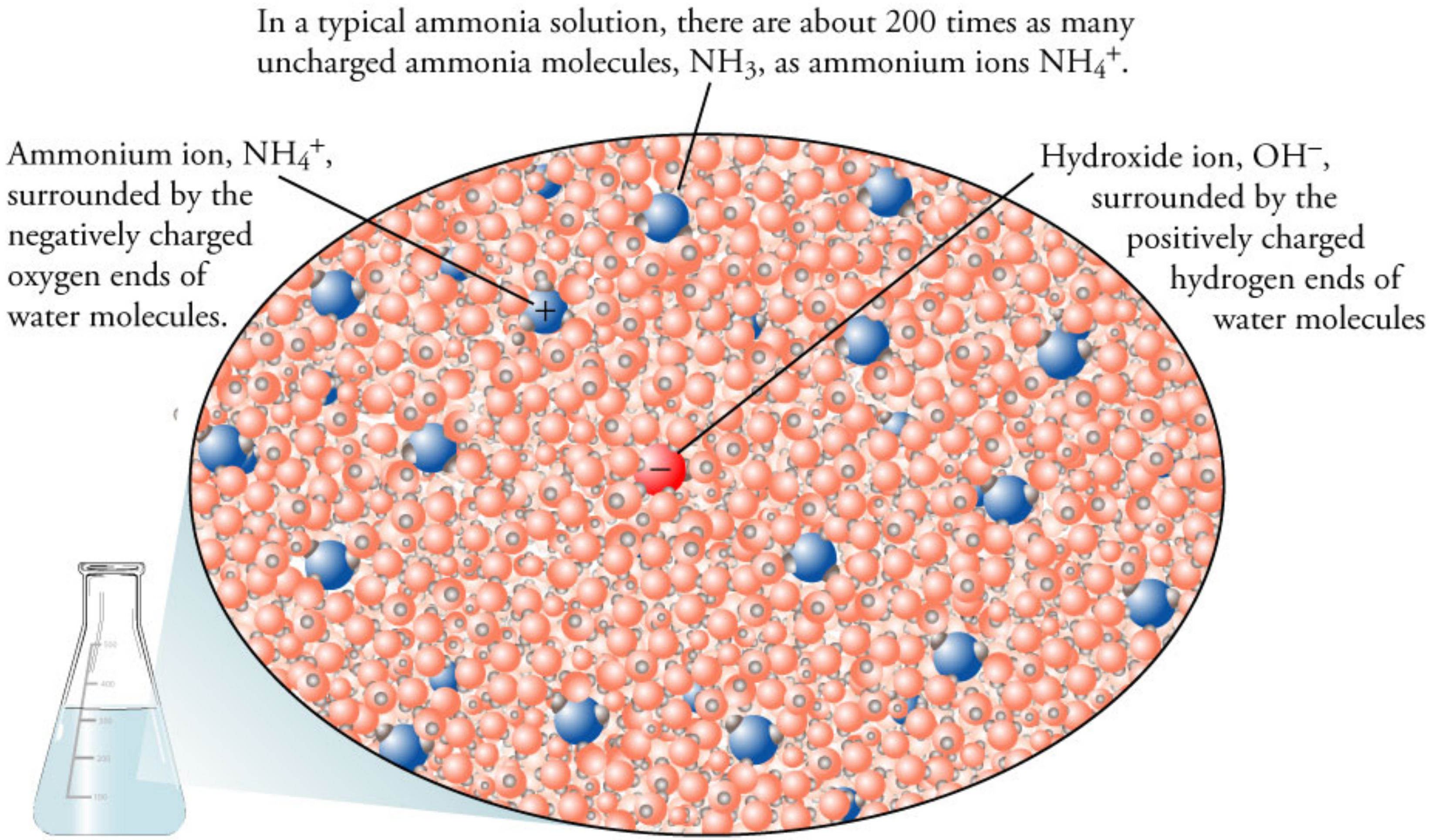


$$NH_3(aq) + H_2O(l) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$$

Weak Base

- ***Weak Base*** = due to a reversible reaction with water, generates significantly less than one OH^- for each formula unit of base added to water.
  - Ammonia and ionic compounds that contain CO_3^{2-} or HCO_3^- are weak bases.

Ammonia Solution



Carbonate Bases

$$Na_2CO_3(s) \rightarrow 2Na^+(aq) + CO_3^{2-}(aq)$$

$$CO_3^{2-}(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + OH^-(aq)$$

$$NaHCO_3(s) \rightarrow Na^+(aq) + HCO_3^-(aq)$$

$$HCO_3^-(aq) + H_2O(l) \rightleftharpoons H_2CO_3(aq) + OH^-(aq)$$

Arrhenius Bases

	Strong	**Weak**
Ionic Compounds	Metal hydroxides	Ionic compounds with CO_3^{2-} and HCO_3^-
Certain Uncharged molecules	None	NH_3

Acidic and Basic Solutions

- The pH scale describes the acidity and basicity of dilute acid and base solutions.
- In pure water, there are proton transfers between water molecules that form hydronium ions and hydroxide ions.

$$2H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$$

- The reaction is reversible, and at equilibrium, the product of the hydronium ion and hydroxide ion concentrations expressed in mol/L is about 10^{-14}.

$$[H_3O^+][OH^-] = 10^{-14}$$

$[H_3O^+][OH^-] = 10^{-14}$

- We consider acidic and basic solutions to be dilute if they have a concentrations of 1 mol/L or less.
- Because the product of the concentrations of H_3O^+ and OH^- is 10^{-14}, as the concentration of H_3O^+ decreases from 1 mol/L to 10^{-14} mol/L, the concentration of OH^- increases from 10^{-14} mol/L to 1 mol/L.
- See the table at the right.

$[H_3O^+]$ (mol/L)	$[OH^-]$ (mol/L)
1	10^{-14}
10^{-1}	10^{-13}
10^{-2}	10^{-12}
10^{-3}	10^{-11}
10^{-4}	10^{-10}
10^{-5}	10^{-9}
10^{-6}	10^{-8}
10^{-7}	10^{-7}
10^{-8}	10^{-6}
10^{-9}	10^{-5}
10^{-10}	10^{-4}
10^{-11}	10^{-3}
10^{-12}	10^{-2}
10^{-13}	10^{-1}
10^{-14}	1

$[H_3O^+][OH^-] = 10^{-14}$

- When the H_3O^+ concentration is greater than the OH^- concentration, the solution is acidic. (Note that even in a dilute solution of acid, there are some hydroxide ions.)
- When the OH^- concentration is greater than the H_3O^+ concentration, the solution is basic.
- When the concentrations are equal, both 10^{-7} mol/L, we say the solution is neutral in the acid/base sense.

$[H_3O^+]$ (mol/L)	$[OH^-]$ (mol/L)
1	10^{-14}
10^{-1}	10^{-13}
10^{-2}	10^{-12}
10^{-3}	10^{-11}
10^{-4}	10^{-10}
10^{-5}	10^{-9}
10^{-6}	10^{-8}
10^{-7}	10^{-7}
10^{-8}	10^{-6}
10^{-9}	10^{-5}
10^{-10}	10^{-4}
10^{-11}	10^{-3}
10^{-12}	10^{-2}
10^{-13}	10^{-1}
10^{-14}	1

pH

- To avoid the small numbers associated with describing acidic and basic solutions in terms of mol/L, pH is defined as

  $$pH = -\log[H_3O^+]$$

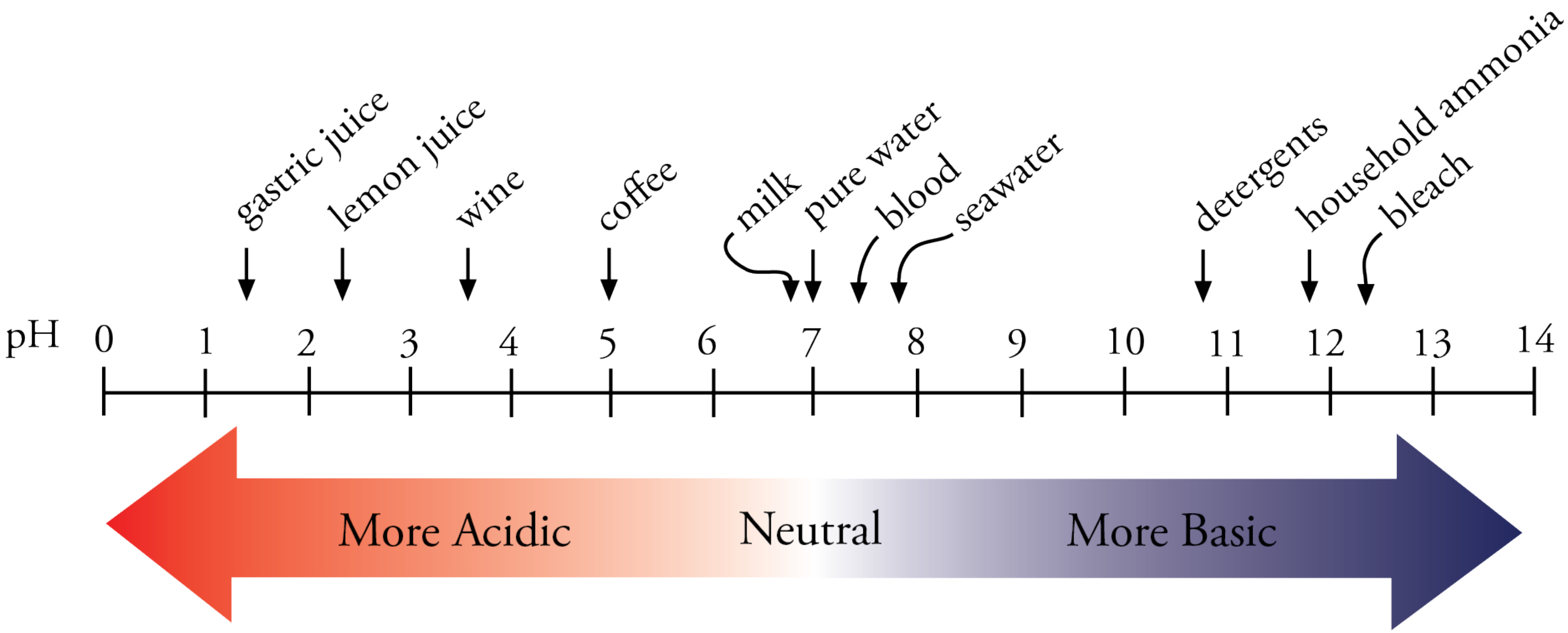
- An acidic solution that has an H_3O^+ concentration of 10^{-3} mol/L has a pH of 3 ($-\log 10^{-3} = 3$).
- A basic solution that has an OH^- concentration of 10^{-3} mol/L, and therefore an H_3O^+ concentration of 10^{-11} mol/L, has a pH of 11 ($-\log 10^{-11} = 11$).

$[H_3O^+][OH^-] = 10^{-14}$

- Dilute acidic solutions with H_3O^+ concentrations of 1 to 10^{-6} mol/L have a pHs of 0 to 6.
- Dilute basic solutions with OH^- concentrations of 10^{-6} to 1 mol/L have H_3O^+ concentrations of 10^{-8} to 10^{-14} mol/L and pHs of 8-14.
- Neutral solutions with H_3O^+ and OH^- concentrations 10^{-7} mol/L have a pH of 7.

$[H_3O^+]$ (mol/L)	$[OH^-]$ (mol/L)	pH
1	10^{-14}	0
10^{-1}	10^{-13}	1
10^{-2}	10^{-12}	2
10^{-3}	10^{-11}	3
10^{-4}	10^{-10}	4
10^{-5}	10^{-9}	5
10^{-6}	10^{-8}	6
10^{-7}	10^{-7}	7
10^{-8}	10^{-6}	8
10^{-9}	10^{-5}	9
10^{-10}	10^{-4}	10
10^{-11}	10^{-3}	11
10^{-12}	10^{-2}	12
10^{-13}	10^{-1}	13
10^{-14}	1	14

pH Range



Acidic solutions have pH values less than 7.

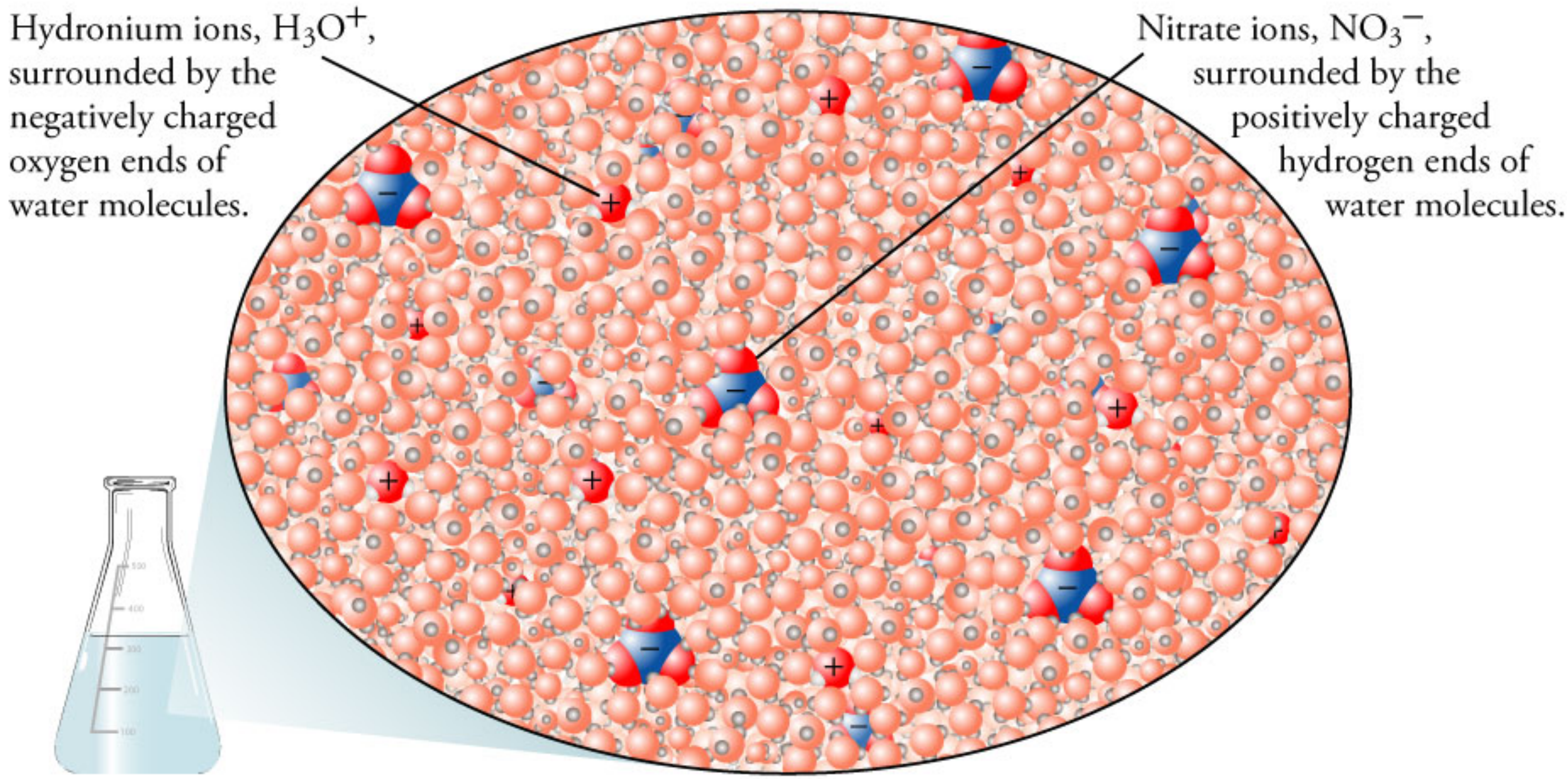
Basic solutions have pH values greater than 7.

Neutralization Reactions

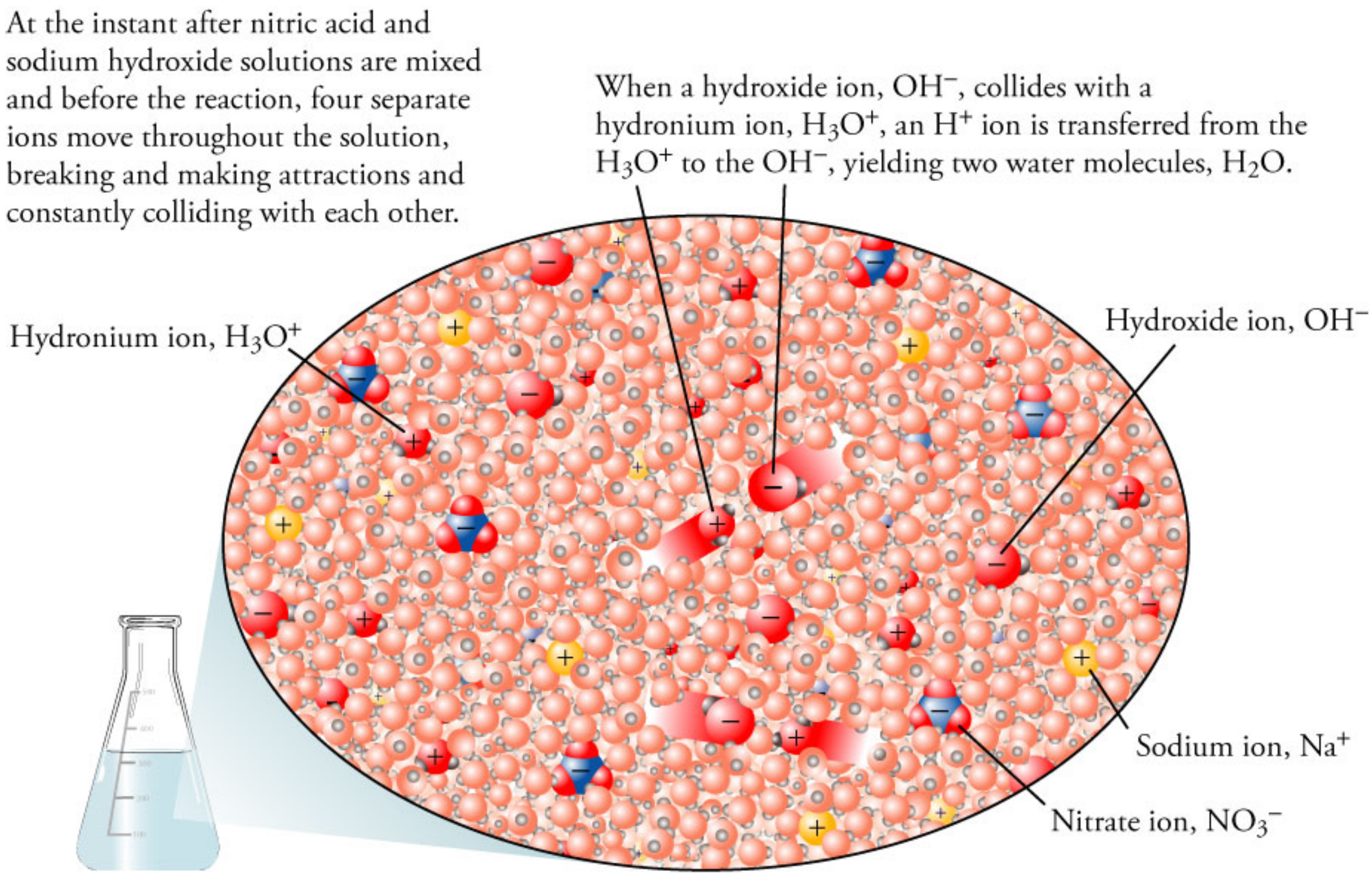
- Reactions between Arrhenius acids and Arrhenius bases are called ***neutralization reactions***.

$$HNO_3(aq) + NaOH(aq)$$
$$\rightarrow H_2O(l) + NaNO_3(aq)$$

Aqueous Nitric Acid

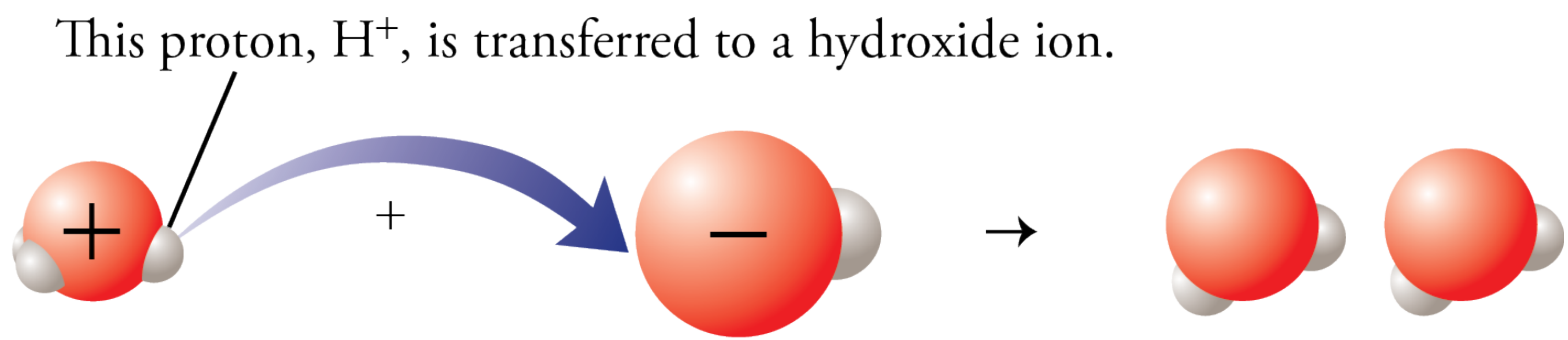


Mixture of HNO_3 and NaOH Before Reaction



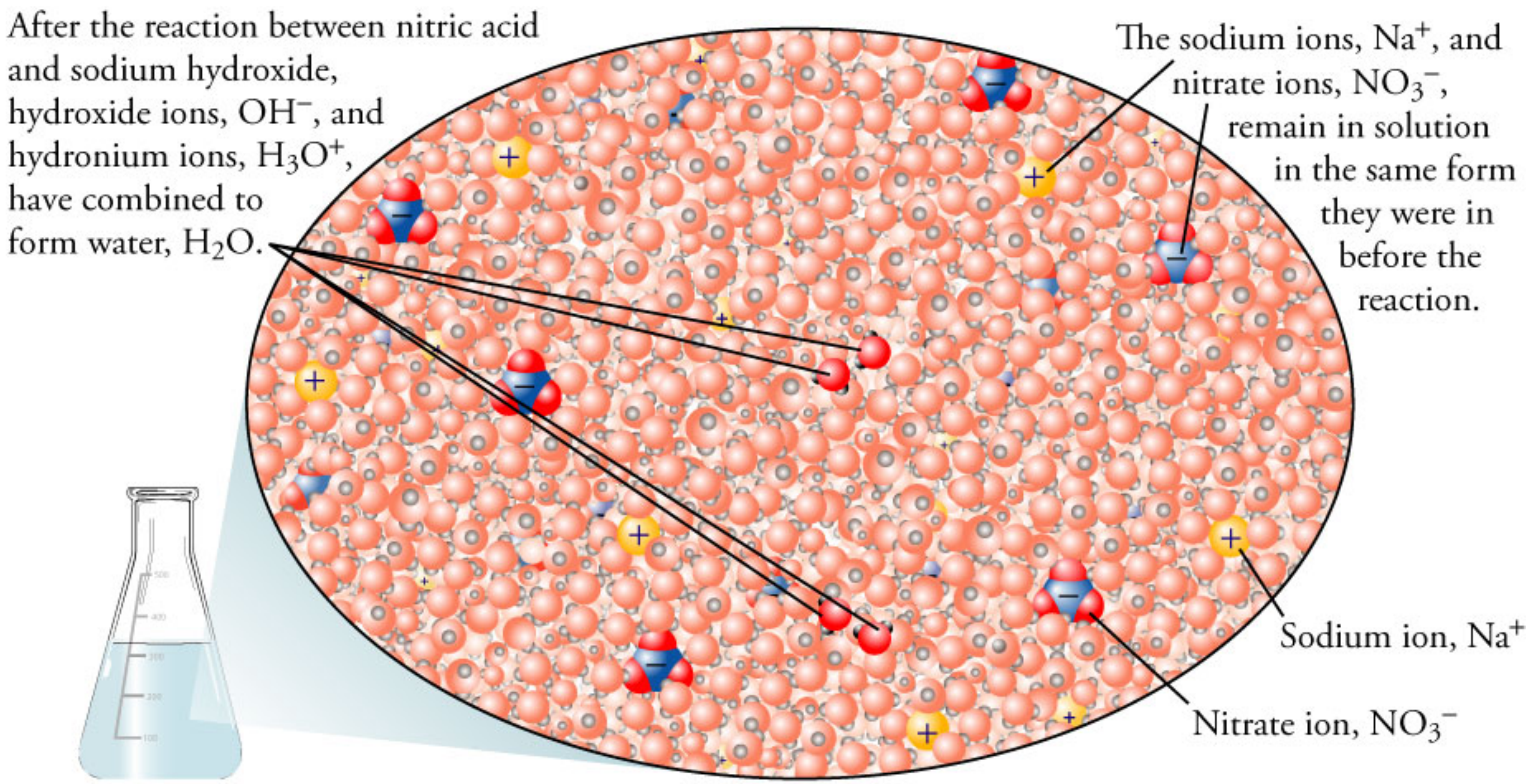
Strong Acid and Strong Base Reaction

The hydronium ion, H_3O^+, from the strong acid reacts with the hydroxide ion, OH^-, from the strong base to form water, H_2O.



$$H_3O^+(aq) + OH^-(aq) \rightarrow 2H_2O(l)$$

Mixture of HNO_3 and NaOH After the Reaction



https://preparatorychemistry.com/neutralization_Canvas.html

Reaction between an Acid and a Hydroxide Base.

- If you have an Arrhenius acid combined with an Arrhenius base, they will react in an acid-base reaction.
- The reactions we will see have the double displacement form.

$$AB(aq) + CD(aq\ or\ s) \rightarrow H_2O(l) + CB(aq)$$

  - The positive part of the acid is H^+.
- The hydroxide base can be soluble or insoluble.
- The products are water and a water-soluble ionic compound.

Reaction between an Acid and a Carbonate Base

- The reaction of an acid with a base containing the carbonate ion or the hydrogen carbonate ion has the double displacement form.

$$AB(aq) + CD(aq\ or\ s) \rightarrow H_2O(l) + CO_2(g) + CB(aq)$$

  - The positive part of the acid is H^+.
- The products are water, carbon dioxide, and a water-soluble ionic compound. The H_2O and the CO_2 come from the decomposition of the initial product H_2CO_3.

Steps for Writing Acid-Base Equations

- Write the formulas for the given reactants separate by a "+" and followed by a single arrow. The acid formula will be followed by an (aq), and the base formula will followed by (aq) if it is water soluble or (s) if it is insoluble.

$$AB(aq) + CD(aq \text{ or } s) \rightarrow$$

Steps for Writing Acid-Base Equations

- Follow these steps to determine the formulas for the products.
  - Divide the acid formula into H^+ and whatever is left after all of the H^+ ions are removed. For example, HNO_3 is divided into H^+ and NO_3^-, and H_2SO_4 is divided into H^+ and SO_4^{2-}.
  - Divide the base into its cation and whatever is left when the cations are removed. For example, NaOH is divided into Na^+ and OH^-, and K_2CO_3 is divided into K^+ and CO_3^{2-}.

Steps for Writing Acid-Base Equations (cont.)

- Follow these steps to determine the formulas for the products. (cont.)
  - If the base includes the hydroxide ion, the first product will be water.

    $$AB(aq) + CD(aq\ or\ s) \rightarrow H_2O(l) + CB(aq)$$

  - If the base includes either the carbonate ion or the hydrogen carbonate ion, the first products will be water and carbon dioxide.

    $$AB(aq) + CD(aq\ or\ s) \rightarrow H_2O(l) + CO_2(g) + CB(aq)$$

Steps for Writing Acid-Base Equations (cont.)

- Follow these steps to determine the formulas for the products. (cont.)
  - The formula for the second product is formed by combining the cation from the base and the anion from the acid. For example, Na^+ combines with NO_3^- to form the CB formula, $NaNO_3(aq)$. (Remember that even though the ions in ionic compounds dissolved in water are separated from each other, we describe them as together in the complete equation.)

$$AB(aq) + CD(aq\ or\ s) \rightarrow H_2O(l) + CB(aq)$$

or

$$AB(aq) + CD(aq\ or\ s) \rightarrow H_2O(l) + CO_2(g) + CB(aq)$$

Example 1

- Write the complete equation for the neutralization reaction that takes place when aqueous solutions of sulfuric acid, H_2SO_4, and sodium hydroxide, NaOH, are mixed. (If an acid has more than one acidic hydrogen, assume that there is enough base to remove all of them. Assume that there is enough acid to neutralize all of the basic hydroxide ions.)

Example 1
Steps

- The acid-base reactions we will see are double displacement reactions.

  $AB + CD \rightarrow AD + CB$

- Write the formulas for the given reactants separated by a "+" and followed by a single arrow. The acid formula will be followed by an (aq), and the base formula will followed by (aq) if it is water soluble or (s) if it is insoluble.

  $H_2SO_4(aq) + NaOH(aq) \rightarrow$

Example 1
Steps

$H_2SO_4(aq) + NaOH(aq) \rightarrow$

- Identify A, B, C, and D.
  - For the acid H_2SO_4, A is H^+ and B is SO_4^{2-}.
  - For NaOH, C is Na^+ and D is OH^-.
- Write the formulas for the AD and CB products on the right side of the arrow. Remember to balance the charges when writing the formulas. H_2O will be followed by (l), and the ionic product will be followed by (aq).

$$H_2SO_4(aq) + NaOH(aq) \rightarrow H_2O(l) + Na_2SO_4(aq)$$

Example 1
Steps

$$H_2SO_4(aq) + NaOH(aq) \rightarrow H_2O(l) + Na_2SO_4(aq)$$

- If one of your products is H_2CO_3, eliminate it and write $H_2O(l)$ and $CO_2(g)$ in its place.
- Balance the equation.

$$H_2SO_4(aq) + 2NaOH(aq) \rightarrow 2H_2O(l) + Na_2SO_4(aq)$$

Example 2

- Write the complete equation for the neutralization reaction that takes place when aqueous solutions of hydrochloric acid, HCl(aq), and potassium carbonate, K_2CO_3, are mixed. (If an acid has more than one acidic hydrogen, assume that there is enough base to remove all of them. Assume that there is enough acid to neutralize all of the basic anions.)

Example 2
Steps

- The acid-base reactions we will see are double displacement reactions.

  AB + CD $\rightarrow$ AD + CB

- Write the formulas for the given reactants separate by a "+" and followed by a single arrow. The acid formula will be followed by an (aq), and the base formula will followed by (aq) if it is water soluble or (s) if it is insoluble.

  $HCl(aq) + K_2CO_3(aq) \rightarrow$

Example 2
Steps

$HCl(aq) + K_2CO_3(aq) \rightarrow$

- Identify A, B, C, and D.
  - For the acid HCl, A is H^+ and B is Cl^-.
  - For K_2CO_3, C is K^+ and D is CO_3^{2-}.
- Write the formulas for the AD and CB products on the right side of the arrow. Remember to balance the charges when writing the formulas. The ionic product will be followed by (aq).

$HCl(aq) + K_2CO_3(aq) \rightarrow H_2CO_3(l) + KCl(aq)$

Example 2
Steps

$HCl(aq) + K_2CO_3(aq) \rightarrow H_2CO_3(aq) + KCl(aq)$

- If one of your products is H_2CO_3, eliminate it and write $H_2O(l)$ and $CO_2(g)$ in its place.

$$HCl(aq) + K_2CO_3(aq) \rightarrow H_2O(l) + CO_2(g) + KCl(aq)$$

- Balance the equation.

$$2HCl(aq) + K_2CO_3(aq) \rightarrow H_2O(l) + CO_2(g) + 2KCl(aq)$$

Three Definitions of Acids and Bases

- **Arrhenius**
  - An acid is a substance that generates H_3O^+ in water
  - A base is a substance that generates OH^- in water
- **Brønsted-Lowry**
- **Lewis**

Arrhenius Acid-Base Reactions?

$NH_3(aq) + HF(aq) \rightleftharpoons NH_4^+(aq) + F^-(aq)$

base acid

$H_2O(l) + HF(aq) \rightleftharpoons H_3O^+(aq) + F^-(aq)$

neutral acid

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

base neutral

Acid and Base Definitions

- **Acid**
  - Arrhenius: a substance that generates H_3O^+ in water
  - Brønsted-Lowry: a proton, H^+, donor
- **Base**
  - Arrhenius: a substance that generates OH^- in water
  - Brønsted-Lowry: a proton, H^+, acceptor
- **Acid-Base Reaction**
  - Arrhenius: between an Arrhenius acid and base
  - Brønsted-Lowry: a proton (H^+) transfer

Brønsted-Lowry Acids and Bases

$NH_3(aq) + HF(aq) \rightleftharpoons NH_4^+(aq) + F^-(aq)$

base acid

$H_2O(l) + HF(aq) \rightleftharpoons H_3O^+(aq) + F^-(aq)$

base acid

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

base acid

Why Two Definitions for Acids and Bases? (1)

- Positive Aspects of Arrhenius Definitions
  - All isolated substances can be classified as acids (generate H_3O^+ in water), bases (generate OH^- in water), or neither.
  - Allows predictions, including (1) whether substances will react with a base or acid, (2) whether the pH of a solution of the substance will be less than 7 or greater than 7, and (3) whether a solution of the substance will be sour or bitter.
- Negative Aspects of Arrhenius Definitions
  - Does not include similar reactions (H^+ transfer reactions) as acid-base reactions.

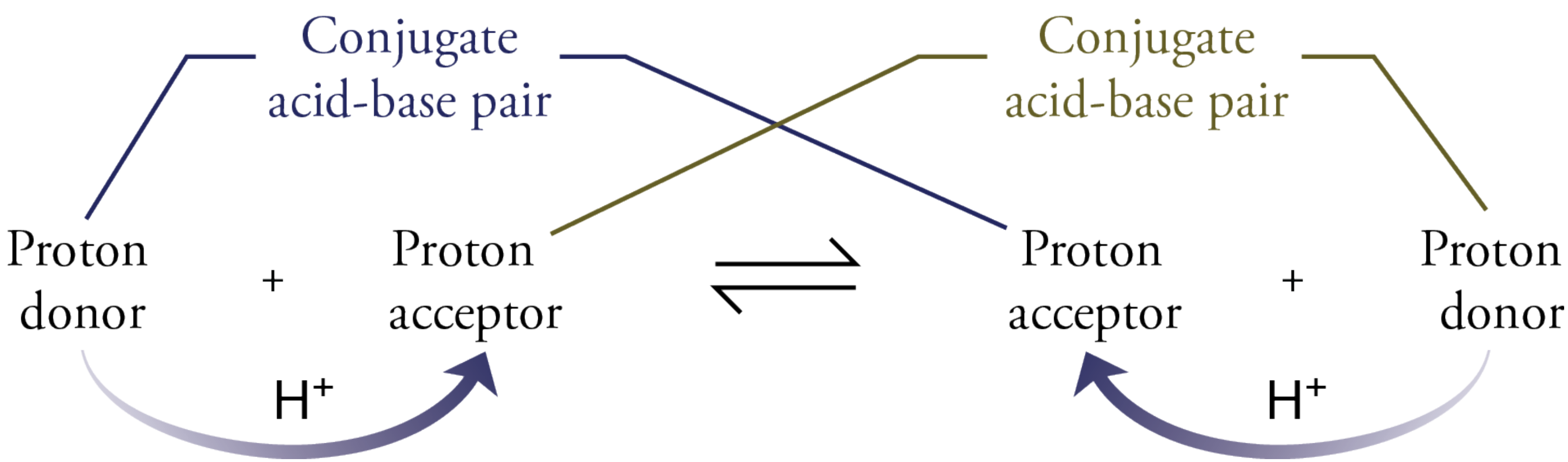
Why Two Definitions for Acids and Bases? (2)

- Positive aspects of Brønsted-Lowry model
  - Includes similar reactions (H^+ transfer reactions) as acid-base reactions.
- Negative aspects of Brønsted-Lowry model
  - Cannot classify isolated substances as acids, bases, or neither. The same substance can sometimes be an acid and sometimes a base.
  - Does not allow predictions of (1) whether substances will react with another substance, (2) whether the pH of a solution of the substance will be less than 7 or greater than 7, and (3) whether a solution will be sour or bitter.

Conjugate Acid-Base Pairs

$$NH_3(aq) + HF(aq) \rightleftharpoons NH_4^+(aq) + F^-(aq)$$

base acid acid base



Brønsted-Lowry Acids and Bases

$H_2PO_4^-(aq)$ + $HF(aq)$ ⇌ $H_3PO_4(aq)$ + $F^-(aq)$

base acid acid base

- H_3PO_4 is the conjugate acid of $H_2PO_4^-$.
- $H_2PO_4^-$ is the conjugate base of H_3PO_4.
- H_3PO_4 and $H_2PO_4^-$ are a conjugate acid-base pair.
- F^- is the conjugate base of the acid HF.
- HF is the conjugate acid of the acid F^-.
- HF and F^- are a conjugate acid-base pair.

Amphoteric Substances

Can be a Brønsted-Lowry acid in one reaction and a Brønsted-Lowry base in another?

$HCO_3^-(aq) + HF(aq) \rightleftharpoons CO_2(g) + H_2O(l) + F^-(aq)$

base acid

$HCO_3^-(aq) + OH^-(aq) \rightleftharpoons CO_3^{2-}(aq) + H_2O(l)$

acid base

$H_2PO_4^-(aq) + HF(aq) \rightleftharpoons H_3PO_4(aq) + F^-(aq)$

base acid

$H_2PO_4^-(aq) + 2OH^-(aq) \rightarrow PO_4^{3-}(aq) + 2H_2O(l)$

acid base