Section 13: pH Calculation

The following maps the videos in this section to the Texas Essential Knowledge and Skills for Science TAC §112.35(c).

13.01 Arrhenius Acids and Bases

- Chemistry (10)(G)

13.02 Bronsted-Lowry Acids and Bases

- Chemistry (10)(G)

13.03 Auto-Ionization of Water and pH

- Chemistry (10)(I)

13.04 Strength of Acids and Bases

- Chemistry (10)(J)

Note: Unless stated otherwise, any sample data is fictitious and used solely for the purpose of instruction.

Safety Note: Any chemicals mentioned in these videos are potentially harmful and should be handled with the appropriate safety precautions.

13.01

Arrhenius Acids and Bases

Chemists have known the properties of acids and bases for many years. In the late 19th century, ***Svante Arrhenius*** proposed a new way of defining acids and bases.

- An ***Arrhenius acid*** is a hydrogen-containing compound that dissociates to yield hydrogen ions (H^+) in aqueous solution.
  - Acids give foods a tart or sour taste, like we find in lemon juice and vinegar.
  - Acids vary in the number of ionizable hydrogens:
    - If an acid has one ionizable hydrogen, it is classified as a ***monoprotic acid***.
    - If an acid has two ionizable hydrogens, it is classified as a ***diprotic acid***.
    - If an acid has three ionizable hydrogens, it is classified as a ***triprotic acid***.
- In an aqueous solution, hydrogen ions are not really present because they react with water molecules to form hydronium.
  - A ***hydronium ion (H_3O^+)*** is an ion that forms when a water molecule gains a hydrogen ion.
  - Below is an example of a reaction that forms an Arrhenius acid in aqueous solution:

$$HCl + H_2O \rightarrow H_3O^+ + Cl^-$$

- Not all compounds that contain hydrogen are acids. Only a hydrogen that is bonded to a very electronegative element can be released as an ion. Even though CH_3COOH looks like it has four ionizable hydrogens, only the hydrogen bonded to the oxygen atom is ionizable.
- An ***Arrhenius base*** is a compound that dissociates to yield hydroxide ions (OH^-) in aqueous solution.
  - Bases typically have a bitter taste and slippery feel.
  - Below is an example of a reaction that forms an Arrhenius base in aqueous solution:

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

1. Which of the following is an Arrhenius acid?

   A. KOH
   B. CH_3CH_3
   C. $Ca(OH)_2$
   D. H_2SO_4

13.02

Brønsted-Lowry Acids and Bases

The Arrhenius definition of acids and bases is not a very broad one. Some substances have acidic and basic properties that are excluded from this definition. To account for these other substances, two chemists in the early 20th century proposed a broader definition of acids and bases, known as the ***Brønsted-Lowry acid-base theory***.

A ***Brønsted-Lowry acid*** is a molecule or ion that acts as a hydrogen ion donor.

A ***Brønsted-Lowry base*** is a molecule or ion that acts as a hydrogen ion acceptor.

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

Brønsted-Lowry acids and bases also include all acids and bases that Arrhenius defined.

In a Brønsted-Lowry acid and base reaction, the products of the forward reaction are distinguished from the reactants by the term *conjugate*.

- A ***conjugate base*** is the ion or molecule that remains after an acid loses a hydrogen ion.
- A ***conjugate acid*** is the ion or molecule formed when a base gains a hydrogen ion.
- A ***conjugate acid-base pair*** consists of two ions or molecules related by the loss or gain of one hydrogen ion.

An ***amphoteric*** substance is capable of either accepting or donating a hydrogen ion.

1. Write the formula for the conjugate acid of HCO_3^-.

2. Write the formula for the conjugate base of HCO_3^-.

3. Identify the Brønsted-Lowry acid for the reaction below:

$$H_2PO_4^-(aq) + HCO_3^-(aq) \rightleftharpoons H_2CO_3(aq) + HPO_4^{2-}(aq)$$

A. HCO_3^-
B. $H_2PO_4^-$
C. HPO_4^{2-}
D. H_2CO_3

4. Which of the following does not represent a conjugate acid-base pair?

A. HCN and CN^-
B. HBr and Br^-
C. HCO_3^- and H_2CO_3
D. PO_4^{3-} and H_3PO_4

13.03
Autoionization of Water and pH

Autoionization – The reaction in which water molecules produce ions (sometimes called ***self-ionization***)

$$H_2O \;+\; H_2O \;\rightleftharpoons\; H_3O^+ \;+\; OH^-$$

The autoionization of water occurs to a very small extent. In pure water, at 25 °C, the number of H_3O^+ and OH^- ions are equal. Pure water is a neutral solution, so the $[H_3O^+]$ and $[OH^-]$ are equal.

For aqueous solutions, the product of the hydrogen ion concentration and the hydroxide ion concentration equals 1.0×10^{-14}, which is the ***ion product constant for water (K_w)***.

$$K_w = [H_3O^+] \times [OH^-] = 1.0 \times 10^{-14}$$

Not all solutions are neutral. When some substances dissolve in water, they release hydrogen ions or form hydroxide ions. Whichever concentration is higher determines whether a solution is acidic, basic, or neutral.

- An ***acidic solution*** is a solution in which there is more $[H_3O^+]$ than $[OH^-]$.
- A ***basic solution*** is a solution in which there is less $[H_3O^+]$ than $[OH^-]$.

A more practical way of determining whether a solution is acidic, basic, or neutral is using the pH scale. The pH of a solution is the negative logarithm of the hydrogen ion concentration:

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

- An acidic solution is one with a pH less than 7.0.
- A solution with a pH of 7.0 is neutral.
- A basic solution is one with a pH greater than 7.0.

To report pH, the number of significant figures in the concentration of hydronium ions should equal the number of decimal places in the reported pH.

Two methods are used to measure pH:

- An acid-base indicator is a solution that has a certain color at one pH and a different color at another pH. Different indicators are useful for different ranges of pH values.
- A pH meter is a machine that makes continuous measurements of pH.

1. What is the pH of a solution that contains 6.8×10^{-3} M H_3O^+ at 25 °C?

   A. 4.62
   B. 9.38
   C. 2.17
   D. 2.47

2. The pH of milk of magnesia is 10.5. Which species exists in greater concentration in milk of magnesia: hydronium ion or hydroxide ion? Calculate $[H_3O^+]$ and $[OH^-]$ for milk of magnesia at a pH of 10.5.

13.04
Strengths of Acids and Bases

Acids and bases are classified as strong or weak based on the degree to which they ionize in water.

Strong acids ionize completely in aqueous solution.

- Examples include HI, HBr, HCl, $HClO_4$, HNO_3, and H_2SO_4.
- Consider the equation $HCl(g) + H_2O(l) \rightarrow H_3O^+(aq) + Cl^-(aq)$.

Initial Final

Weak acids ionize slightly in aqueous solution.

- Examples include HF, HCN, H_2CO_3, and others.
- Consider the equation $HF(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + F^-(aq)$.

Initial Final

Dissociation – The process by which a compound separates into ions when in an aqueous solution

The symbol K_a represents the ***acid dissociation constant***, or the ionization constant of an acid.

- The acid dissociation constant is the ratio of the concentration of the dissociated form of an acid to the concentration of the undissociated form. The dissociated form includes both the H_3O^+ and the conjugate base.
- The stronger an acid is, the larger its K_a value will be.

1. How many of the following are *weak* acids?

HClO HBr HNO_3 H_3PO_4 HF

A. 1
B. 2
C. 3
D. 4

A ***strong base*** dissociates completely into metal ions and hydroxide ions in aqueous solution.

- Examples include LiOH, NaOH, KOH, RbOH, CsOH, $Sr(OH)_2$, $Ba(OH)_2$, and $Ca(OH)_2$.
- Consider the equation NaOH(s) $\xrightarrow{H_2O}$ Na^+(aq) + OH^-(aq).

Initial Final

A ***weak base*** reacts with water to form the conjugate acid of the base and hydroxide ions. Generally, the amount of dissociation is relatively small.

- Examples include NH_3, CH_3NH_2, and others.
- Consider the equation NH_3(g) + H_2O(l) $\rightleftharpoons$ NH_4^+(aq) + OH^-(aq).

Initial Final

The symbol K_b represents the ***base dissociation constant***.

- The base dissociation constant is the ratio of the concentration of the conjugate acid multiplied by the ratio of the concentration of the hydroxide ion to the concentration of the base.
- The stronger a base is, the larger its K_b value will be.

2. What is the pH of a solution of 0.0085 M $Sr(OH)_2$?

A. 1.8
B. 7.89
C. 12.2
D. 12.23

PERIODIC TABLE OF THE ELEMENTS

	1A 1	2A 2	3B 3	4B 4	5B 5	6B 6	7B 7	<--- 8	8B 9	---> 10	1B 11	2B 12	3A 13	4A 14	5A 15	6A 16	7A 17	8A 18
1	1 **H** 1.008																	2 **He** 4.003
2	3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
3	11 **Na** 22.99	12 **Mg** 24.31											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
4	19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.59	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
5	37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (99)	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
6	55 **Cs** 132.9	56 **Ba** 137.3	57 **La** 138.9	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.9	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
7	87 **Fr** (223)	88 **Ra** 226.0	89 **Ac** 227.0	104 **Rf** (261)	105 **Ha** (262)	106 (263)	107 (262)	108	109									

Lanthanides	58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.2	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0	71 **Lu** 175.0
Actinides	90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** 237.0	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (260)