Chapter 9: Stoichiometry

The Mathematics of Chemistry

(a)

Chapter Topics:

Atomic Mass and Isotopic Abundances (weighted averages) Revisited

Avogadro's Number and the Mole

Molar Mass

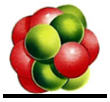
Mole-Mass Conversions

Standard Molar Volume (STP) and Density

Percent Composition and Empirical Formulas

Molecular and Empirical Formulas

Atomic Mass and Isotopic Abundances (weighted averages) Revisited



12

1amu (u) = 1/12 the mass of a C-12 isotope

(about the mass of a proton/neutron)

Numerically equivalent to 1.660538×10^{-24} grams

Mass of C-12 = 12amu exactly

The atomic masses of the other elements are determined *relative* to C-12

Ex. An oxygen atom is 1.33times the mass of C-12 or 12(1.33) = 16.00u

The Mole

The mole (abbreviated mol) is a counting unit in chemistry

By definition, its value is equal to the number of atoms in exactly 12g of the C-12 isotope, which turns out to be 6.022×10^{23}

This number is known as Avogadro's number (N_A), and is the quantity in one mole of *anything*, in the same way that a dozen is 12 of anything.

$$N_A = 1\text{mole} = 6.022 \times 10^{23}$$

Because of the relationship of how the atomic mass unit is defined, and how the mole is defined:

$^{24.30}_{12}Mg$

If mass number of an element on the periodic table:

a) is taken in u (atomic mass units), you get the mass of one atom of that element

b) is taken in g (grams), you get the mass of one mole (6.022×10^{23}) of atoms of that element

i.e.

24.30u = 1 atom of magnesium

24.30g = 1 mole of magnesium

(1u = 1.660538×10^{-24} grams)

The Periodic Table of Sports Balls

$^{550.8}Go$	$^{680.4}Te$	^{1710}Ba	$^{32,640}Bo$
			

Masses in g/doz

Vs.

The Periodic Table of the Elements

$^{12.011}C$	$^{24.31}Mg$	$^{40.08}Ca$	$^{55.85}Fe$
			

Masses in g/mol

Example: How many grams of tennis balls (680.4g/doz) gives the same quantity as there are in 40,800g of bowling balls(32,640g/doz)? How many of each type of ball are there?

Answer:
40,800g (1 doz / 32,640g)(680.4g tennis balls / 1doz) = 850.5g

40,800g (1 doz / 32,640g)(12 b.balls / 1 doz) = 15 balls

Example: How many grams of magnesium (24.31g/mol) gives the same quantity as there are in 167.55g of iron (55.85g/mol)? How many atoms of iron does this represent?

Answer:
167.55g Fe (1mol / 55.85g Fe)(1mol Mg / 1mol Fe)(24.31g Mg / 1mol) = 72.93g

167.55g Fe (1mol / 55.85g Fe)(6.022x10^{23} iron atom / 1mol) = 1.807x10^{24} atoms

How Big is a Mole???

If one mole of pennies were divided up among the Earth's population, each person would receive 1 x 10^{14} pennies. Personal spending at the rate of one million dollars a day would use up each persons wealth in about three thousand years. Life would not be comfortable because the surface of the Earth would be covered in copper coins to a depth of at least 400 meters.

A mole of pennies stacked on top of one another could reach to the sun and back (93 million miles) almost 500 million times!

Counting at an average rate of 1 number per second (24hours a day) it would take a person with an average life span of 80 years 238,700,000,000,000 (238.7 trillion) lifetimes!

A mole of marshmallows would cover the United States to a depth of 600 miles.

A mole of sheets of paper would cover the Earth 71,227,814 times.

To determine the molar mass of a compound:

Add the molar masses of the individual elements that the compound contains.

Ex. The molar mass of H_2O = 16.000g/mol + 2(1.008g/mol) = 18.016g/mol

This means that if you measure out 18.016g of water, your sample would contain 6.022x10^{23} water molecules.

The mole is the bridge between mass and quantity. (See page pp31-33 in your lab manual)

Grams ⟷ (multiply by MM) / (divide by MM) ⟷ **Moles** ⟷ (divide by N_A) / (multiply by N_A) ⟷ **Basic Units** (atoms, molecules, formula units, etc.)

Remember: The mole is a *counting* unit, whereas the gram is a *mass* unit!

Mass – Mole – Particle Analogy

Particles

Mole

Mass of jelly bean bag = 270.0g

Mass: One bag (mole) of jelly beans (6.022x10^{23} molecules) has a mass of 270.0g (molar mass)

On Your Own:

1. **Determine the number of moles of Fe in 80.5g of that element.**
2. **How many atoms of Fe are there in question 1?**
3. **What mass of Fe (in grams) would be required to have .0500mol of Fe?**

Answers:

1. **80.5g Fe (1mol Fe/55.85g Fe) = 1.44mol Fe**
2. **1.44mol Fe (6.022x10^{23}atoms Fe/1mol Fe) = 8.68x10^{23}atoms Fe**
3. **.0500mol Fe (55.85g Fe/1mol Fe) = 2.79g**

On Your Own:

1. **Determine the molar mass of sucrose (table sugar, $C_{12}H_{22}O_{11}$).**
2. **Determine the number of grams in .575mol of calcium nitrate.**
3. **Determine the number of oxygen atoms in 50.0g of sucrose.**

On Your Own:

1. **Determine the molar mass of sucrose (table sugar, $C_{12}H_{22}O_{11}$).**
2. **Determine the number of grams in .575mol of calcium nitrate.**
3. **Determine the number of oxygen atoms in 50.0g of sucrose.**

Answers:

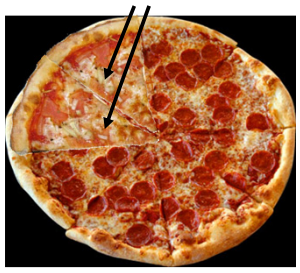
1. 12(12.011g/mol) + 22(1.008g/mol) + 11(16.00g/mol) = **342.31g/mol**

2. The formula for calcium nitrate is $Ca(NO_3)_2$

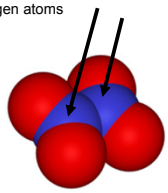
   1(40.08g/mol) + 2(14.01g/mol) + 6(16.00g/mol) = 164.09g/mol
   .575mol (164.09g/mol) = **94.4g**

3. 50.0g(1mol/342.31g)(6.022x10^{23}molecules/mol)(11atoms O /molecule) = **9.68x10^{23}atoms O**

Don't think of these as being 2 eighths of a pizza, think of each pizza as having 2 slices of this type



In the same way, when going from molecules of dinitrogen tetroxide to atoms, don't think of the nitrogen atoms as being 2-sixths of the molecule, think of each molecule as having 2 nitrogen atoms



When going from molecules to atoms, multiply by the subscript in the formula, don't divide!

Hydrated Compounds:

Compounds that attract water molecules such as $CuSO_4 \cdot 5H_2O$ (cupric sulfate pentahydrate) are known as hydrates

NOTE: The dot does not mean multiplication. It means in addition to each $CuSO_4$, there are 5 water molecules "hanging on" that must be included in the determination of the molar mass.

The molar mass of $CuSO_4 \cdot 5H_2O$ is 249.685g/mol
Which consists of 1 copper, 1 sulfur, 10 hydrogens and 9 oxygens.

Molar Volume

- At standard temperature and pressure, 1 mole of *any* gas occupies 22.4 L.
- The volume occupied by 1 mole of gas (22.4 L) is called the ***molar volume***.
- Standard temperature and pressure are 0 °C and 1 atm.

Molar Volume of Gases

- We now have a new unit factor equation:
- 1 mole gas = 6.02 x 10^{23} molecules gas = 22.4 L gas

TABLE 9.1 MOLE RELATIONSHIPS FOR SELECTED GASES

GAS	NO. OF MOLES	NO. OF MOLECULES	MOLAR MASS	MOLAR VOLUME AT STP
hydrogen, H_2	1.00	6.02×10^{23}	2.02 g/mol	22.4 L/mol
oxygen, O_2	1.00	6.02×10^{23}	32.00 g/mol	22.4 L/mol
carbon dioxide, CO_2	1.00	6.02×10^{23}	44.01 g/mol	22.4 L/mol
ammonia, NH_3	1.00	6.02×10^{23}	17.04 g/mol	22.4 L/mol
argon, Ar*	1.00	6.02×10^{23}	39.95 g/mol	22.4 L/mol

*Argon gas is composed of atoms rather than molecules.

One Mole of a Gas at STP

- The box below has a volume of 22.4 L, which is the volume occupied by 1 mole of a gas at STP.

Gas Density

- The density of gases is much less than that of liquids.
- We can easily calculate the density of any gas at STP.
- The formula for ***gas density*** at STP is as follows:

$$\frac{\text{molar mass in grams}}{\text{molar volume in liters}} = \text{density, g/L}$$

Percent Composition:

Gives (as a mass percentage)

Mass % = (Total mass of element in compound/Mass of compound) x 100

Example: Determine the mass percentage of oxygen in carbon dioxide.

Answer: Carbon dioxide is CO_2

Mass % O = $(2O/CO_2)$ = (32.0/44.01) x 100 = 72.7% oxygen

Percent Composition Analysis:

Used to determine the empirical formula for a compound.
Based on the mass percentage of each element in a compound.

Steps:

1. Assume 100g sample (if given as a percentage)
2. Convert grams to moles for each element
3. Use moles to determine the mole ratios (subscripts) of the elements in the compound
   - Use the moles as temporary subscripts
   - Divide subscripts through by smallest number of moles in the set
   - Check to make sure subscripts are integer numbers. (If not, multiply through by an integer that makes them such)

Percent Composition Analysis:

Example: A sample of a substance is analyzed and found to contain 78.14% boron and 21.86% hydrogen.

a) Determine the empirical formula for the compound.

b) The substance is analyzed with a mass spectrometer and found to have a molar mass between 25.0 and 30.0g. Determine the actual molecular formula for the compound.

Percent Composition Analysis:

ANSWER

Example: A sample of a substance is analyzed and found to contain 78.14% boron and 21.86% hydrogen.

a) Determine the empirical formula for the compound.

Assuming a 100g sample you get:
78.14g B and 21.86g H
Converting to moles: 78.14gB/(10.81g/mol) = 7.228mol B
21.86g H/(1.008g/mol) = 21.69mol H
$B_{7.23}H_{21.69}$ But you can't leave it as a fraction so,
$B_{7.228/7.228}H_{21.69/7.228}$ = BH_3

b) The substance is analyzed with a mass spectrometer and found to have a molar mass between 25.0 and 30.0g. Determine the actual molecular formula for the compound.

The empirical mass of BH_3 is 13.83g/mol which goes into the above range twice. So the actual molecular formula is B_2H_6

Percent Composition Analysis (Level 2 Difficulty):

A 5.000g sample of a substance is analyzed and found to contain 2.182g of phosphorus and 2.818g of oxygen.

a) Determine the empirical formula for the compound.

b) Assuming the empirical formula is also the molecular formula, name the compound.

Percent Composition Analysis (Level 2 Difficulty):

ANSWER:

A 5.000g sample of a substance is analyzed and found to contain 2.182g of phosphorus and 2.818g of oxygen.

a) Determine the empirical formula for the compound.

mol P = 2.182g (1mol P / 30.97g) = .07046mol P
mol O = 2.818g (1mol O / 16.00g) = .1761mol O
$P_{.07046/.07046}O_{.1761/.07046} = P_1O_{2.5}$
Since subscripts can't be fractional, multiplying through by 2 gives:
P_2O_5

b) Assuming the empirical formula is also the molecular formula, name the compound.
diphosphorus pentoxide

Molecular Formulas

- The empirical formula for acetylene is CH. This represents the ratio of C to H atoms on acetylene.
- The actual ***molecular formula*** is some multiple of the empirical formula, $(CH)_n$.
- Acetylene has a molar mass of 26 g/mol. Find *n* to find the molecular formula:

$$\frac{(CH)_n}{CH} = \frac{26\ \text{g/mol}}{13\ \text{g/mol}}$$

$n = 2$ and the molecular formula is C_2H_2.

Chapter Summary, Continued

- The ***percent composition*** of a substance is the mass percent of each element in that substance.
- The ***empirical formula*** of a substance is the simplest whole number ratio of the elements in the formula.
- The ***molecular formula*** is a multiple of the empirical formula.