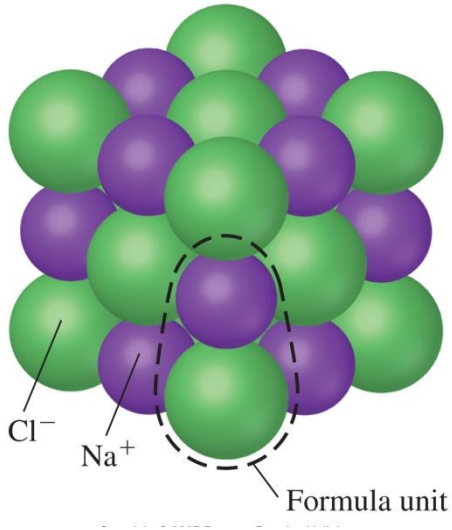
GENERAL CHEMISTRY I



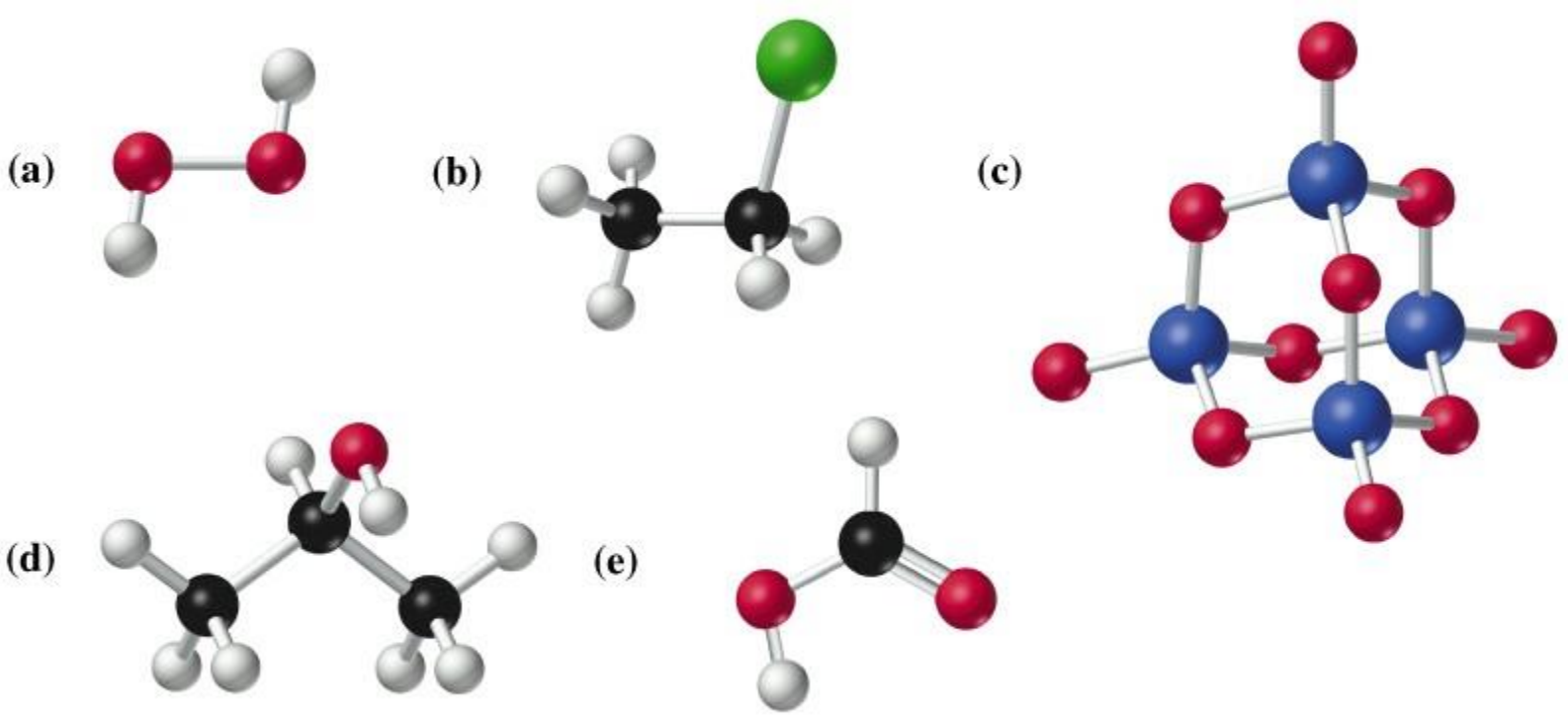
Chapter 3
Chemical Reactions and Reaction stoichiometry

Contents

Color Chart for Common Elements

Some Organic and Inorganic Molecules

H_2O_2 CH_3CH_2Cl P_4O_{10}



$CH_3CH(OH)CH_3$ HCO_2H

Copper Penny Reacting with Nitric Acid in a Test Tube

$$Cu\ (s) + \mathbf{4}\ HNO_3\ (l) \rightarrow Cu(NO_3)_2 + \mathbf{2}\ H_2O\ (l) + \mathbf{2}\ NO_2\ (g)$$

https://www.youtube.com/watch?v=uOa2v0Y0IeU

As reactants are converted to products we observe:

- Color change
- Precipitate formation
- Gas evolution
- Heat absorption or evolution

Chemical evidence may be necessary.

Stoichiometry

Antoine Lavoisier
(1743 – 1794)

- Stoichiometry is built on an understanding of
- atomic masses,
- chemical formulas,
- the law of conservation of mass.

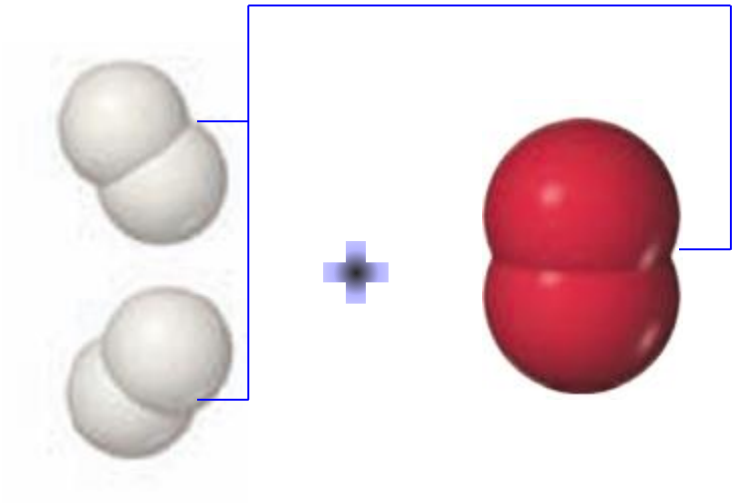
"We may lay it down as an incontestable axiom that, in all the operations of art and nature, ***nothing is created; an equal quantity of matter exists both before and after the experiment****. Upon this principle, the whole art of performing chemical experiments depends."*

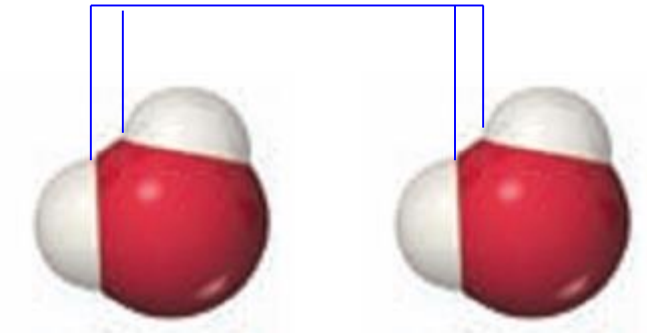
3-1 Chemical Equations

Hydrogen + Oxygen → Water

These covalent bonds break

New covalent bonds form





4 H 2O

same numbers and kinds of atoms on both side of the arrow

4H 2O

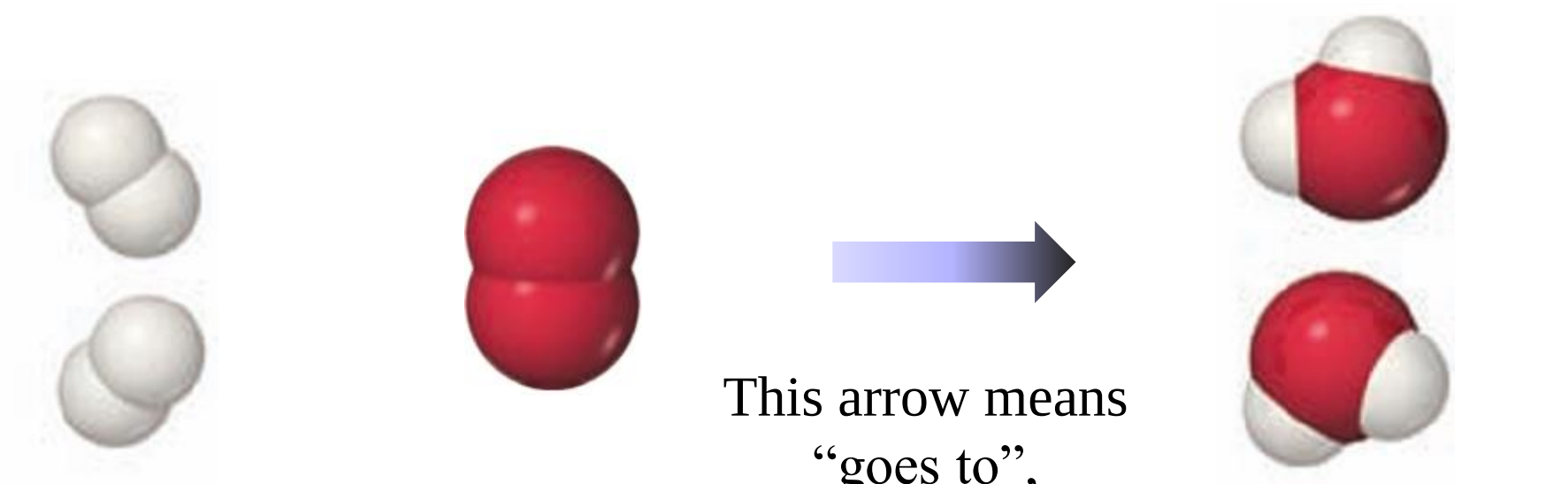
the coefficient

$2\ H_2\ (g) \quad + \quad O_2\ (g)$ → special conditions (like heat or light) → $2\ H_2O\ (l)$

physical state (for H_2 and O_2)

the coefficient (for H_2O)

physical state (for H_2O)



This arrow means "goes to", "yields", or "produces"

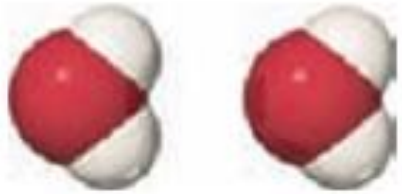
reactants

products

Two molecules of hydrogen ***react with*** one molecule of oxygen ***produces*** two molecules of water

H_2O

Changing coefficient changes amount → $2\ H_2O$



Two molecules water (contain four H atoms and two O atoms)

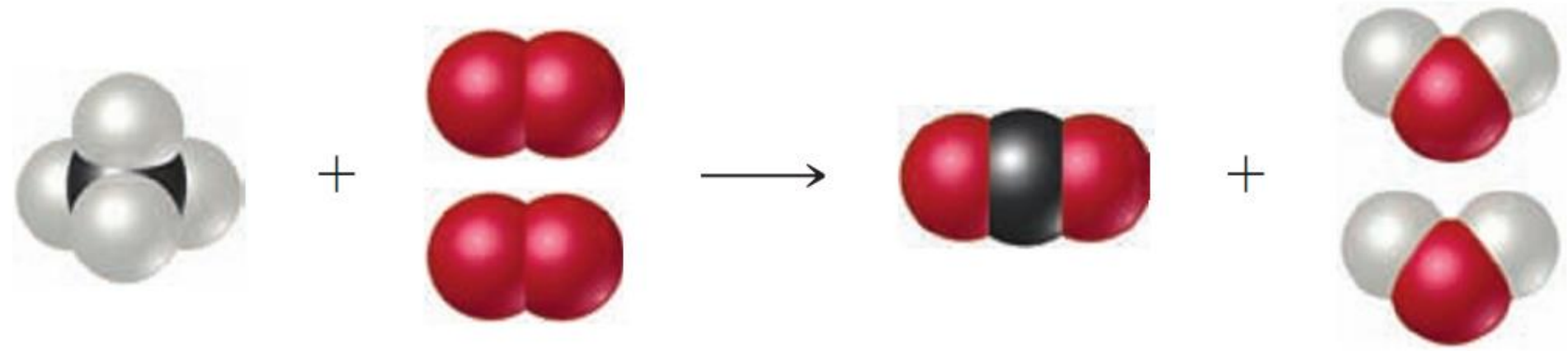
Changing subscript changes identity and properties → H_2O_2

One molecule hydrogen peroxide (contains two H atoms and two O atoms)

Balancing Equations

When balancing an equation always make sure the ***type*** and ***number*** of atoms on both sides of the arrow are equal.

How many C, H, and O atoms are present on the reactant side?
Are the same number of each type of atom present on the product side?



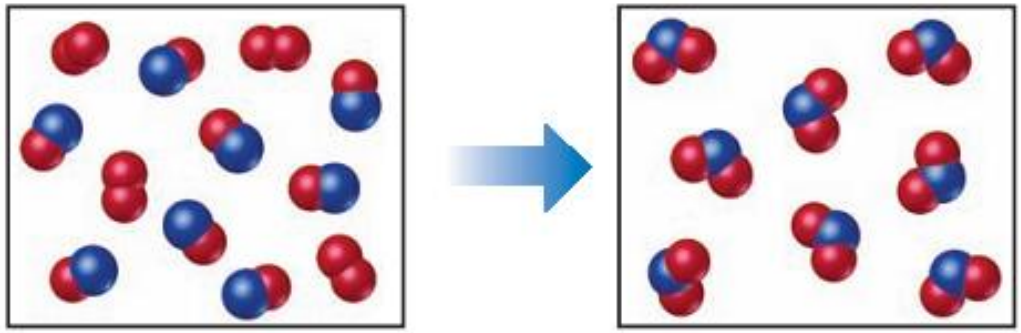
$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O$

1 C, 4 H, 4 O

1 C, 4 H, 4 O

EXAMPLE

The following diagram represents a chemical reaction in which the red spheres are oxygen atoms and the blue spheres are nitrogen atoms. The reactants and products are in gaseous state.



(a) Write the chemical formulas for the reactants and products.

Reactants: NO and O_2 Product: NO_2

(b) Write a balanced equation for the reaction.

$2\ NO + O_2 \rightarrow 2\ NO_2$

(c) Is the diagram consistent with the law of conservation of mass?

Yes, it is. Therr are 16 O and 8 N on both side

PRACTICE EXERCISE 1

In the following diagram, the white spheres represent hydrogen atoms and the blue spheres represent nitrogen atoms.

The two reactants combine to form a single product, ammonia, NH_3, which is not shown.

Write a balanced chemical equation for the reaction. Based on the equation and the contents of the left (reactants) box, find how many NH_3 molecules should be shown in the right (products) box.

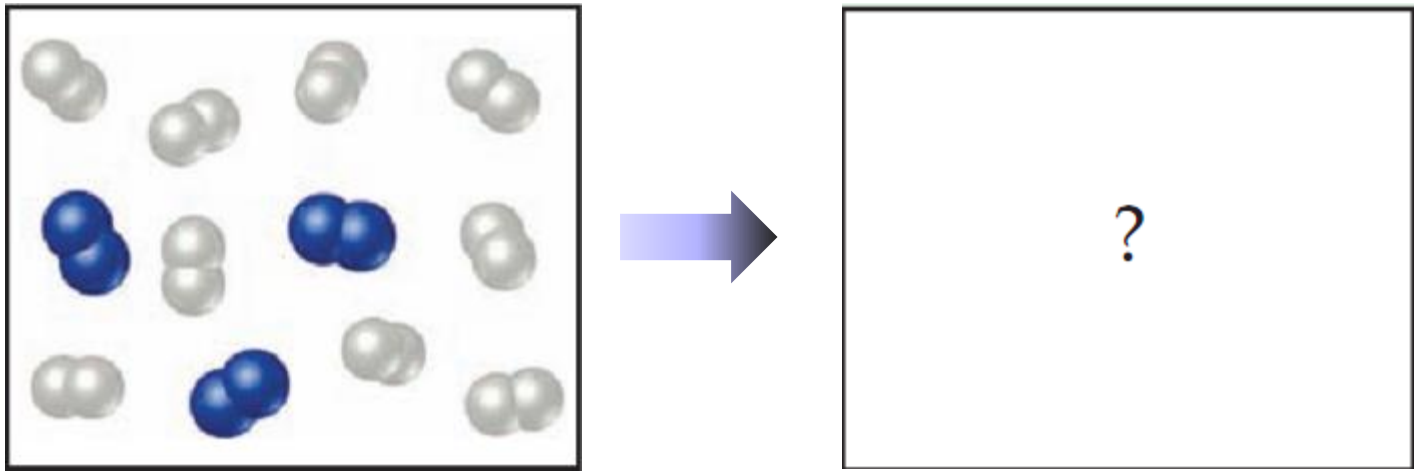
(a) 2

(b) 3

(c) 4

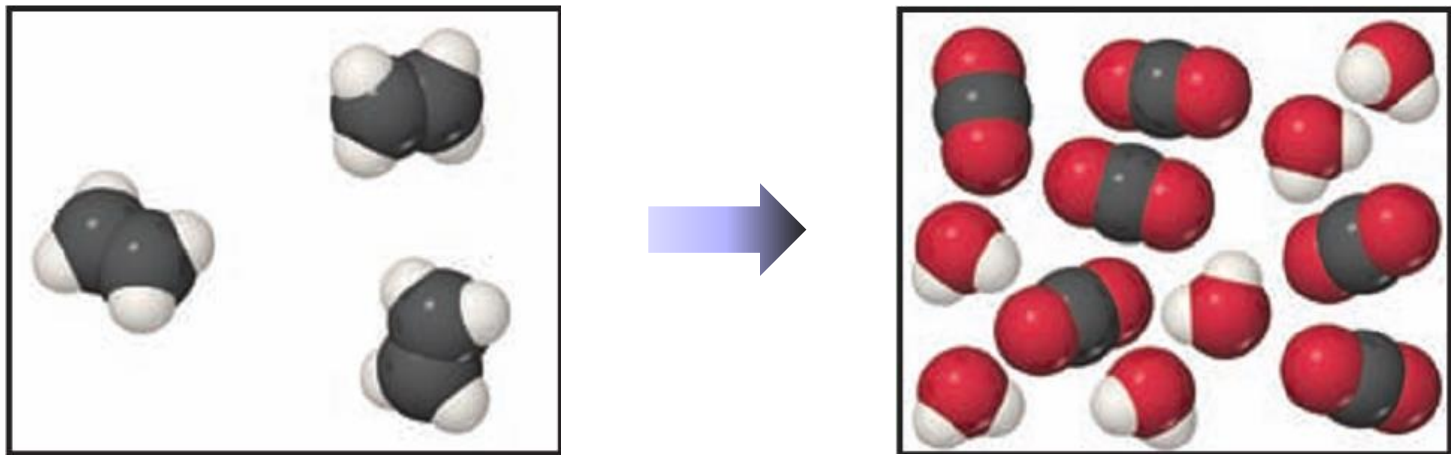
(d) 6

(e) 9



PRACTICE EXERCISE 2

In the following diagram, the white spheres represent hydrogen atoms, the black spheres carbon atoms, and the red spheres oxygen atoms.



(a) Write a balanced chemical equation for the reaction.

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$$

(b) Determine the number of O2 molecules that should be shown in the left (reactants) box.

$$3C_2H_4 + 9O_2 \rightarrow 6CO_2 + 6H_2O$$

Indicating the States of Reactants and Products

This indicates a special condition

$$2\ H_2O\ (l) \xrightarrow{\text{electric current}} 2\ H_2\ (g) + O_2\ (g)$$

This indicates the continuous addition of heat

$$2\ KClO_3\ (s) \xrightarrow{\Delta} 2\ KCl\ (s) + 3\ O_2\ (g)$$

(g)	gases
(l)	liquids
(s	solids
(aq)	dissolved in aqueous (water) solution

EXAMPLE

Balance the equation

$$Na\ (s) + H_2O\ (l) \rightarrow NaOH\ (aq) + H_2\ (g)$$

$$Na\ (s) + \mathbf{2}\ H_2O\ (l) \rightarrow NaOH\ (aq) + H_2\ (g)$$

$$Na\ (s) + \mathbf{2}\ H_2O\ (l) \rightarrow \mathbf{2}\ NaOH\ (aq) + H_2\ (g)$$

$$\mathbf{2}\ Na\ (s) + \mathbf{2}\ H_2O\ (l) \rightarrow \mathbf{2}\ NaOH\ (aq) + H_2\ (g)$$

For the online quiz where typing subscription might be impossible, especially **on a smartphone,** I'm okay with putting the molecule in parenthesis.

For example, instead of filling in the blank with

$$2\ NO + O_2 \rightarrow 2\ NO_2$$

You can use

2(NO)+O2->2(NO2)

For the online quiz, do not add space to the equations!

It's time for a quiz!

PRACTICE EXERCISE 1

The unbalanced equation for the reaction between methane and bromine is

$$\_\_\ CH_4\ (g)\ +\ \_\_\ Br_2\ (l)\ \rightarrow\ \_\_\ CBr_4\ (s)\ +\ \_\_\ HBr\ (g)$$

Once this equation is balanced what is the value of the coefficient in front of bromine Br_2?

PRACTICE EXERCISE 2

Balance these equations by providing the missing coefficients:

(a) __ Fe *(s)* + __O_2 *(g)* → __Fe_2O_3 *(s)*

(b) __ Al *(s)* + __ HCl *(aq)* → __ $AlCl_3$ *(aq)* + __ H_2 *(g)*

(c) __ $CaCO_3$ *(s)* + __ HCl *(aq)* → __ $CaCl_2$ *(aq)* + __ CO_2 *(g)* + __ H_2O *(l)*

3-2 Simple Patterns of Chemical Reactivity

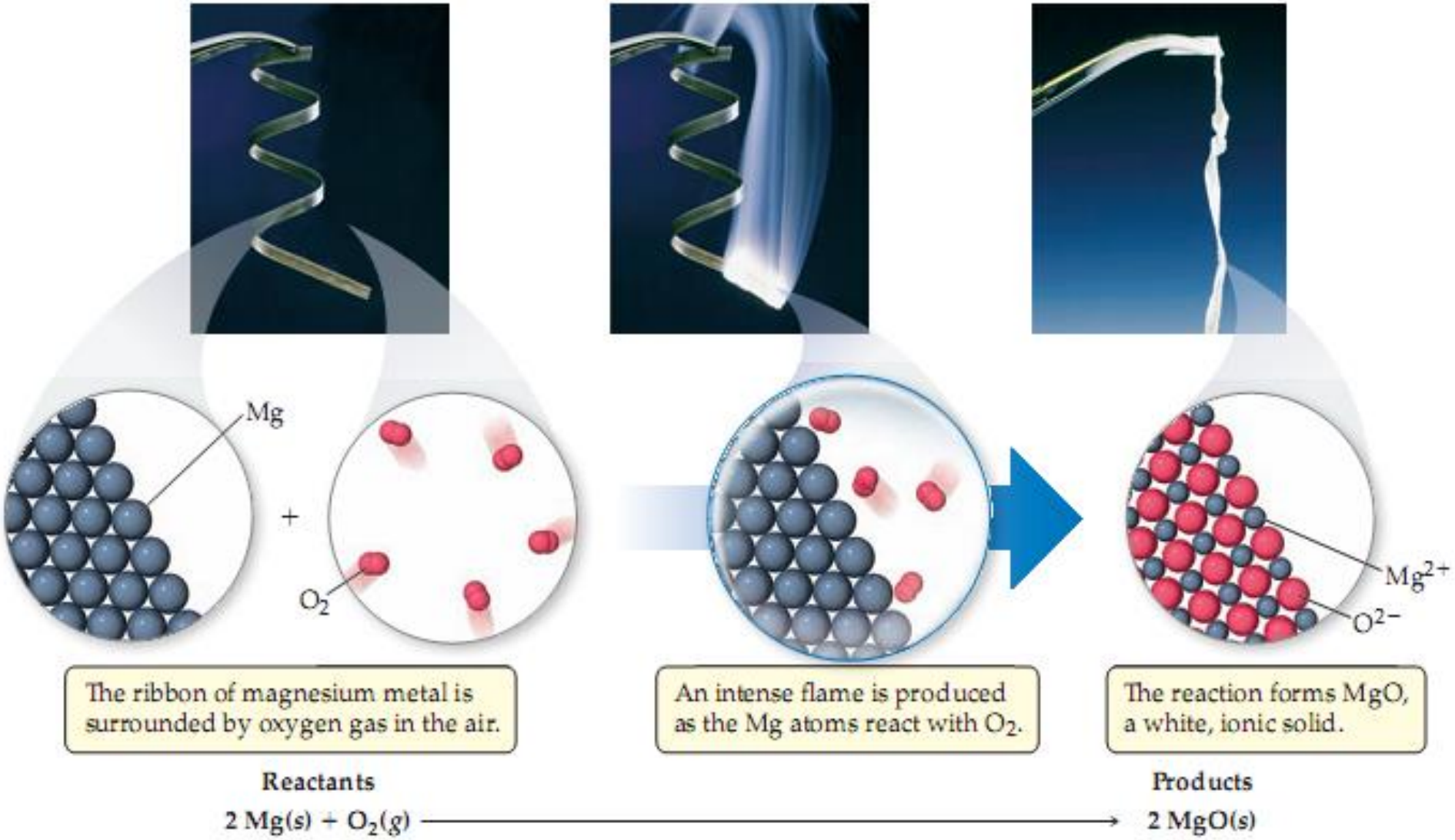
1. Synthesis (Combination)
2. Decomposition
3. Single replacement
4. Double replacement
5. Combustion

Combination Reactions

Two or more reactants combine to form a single product.

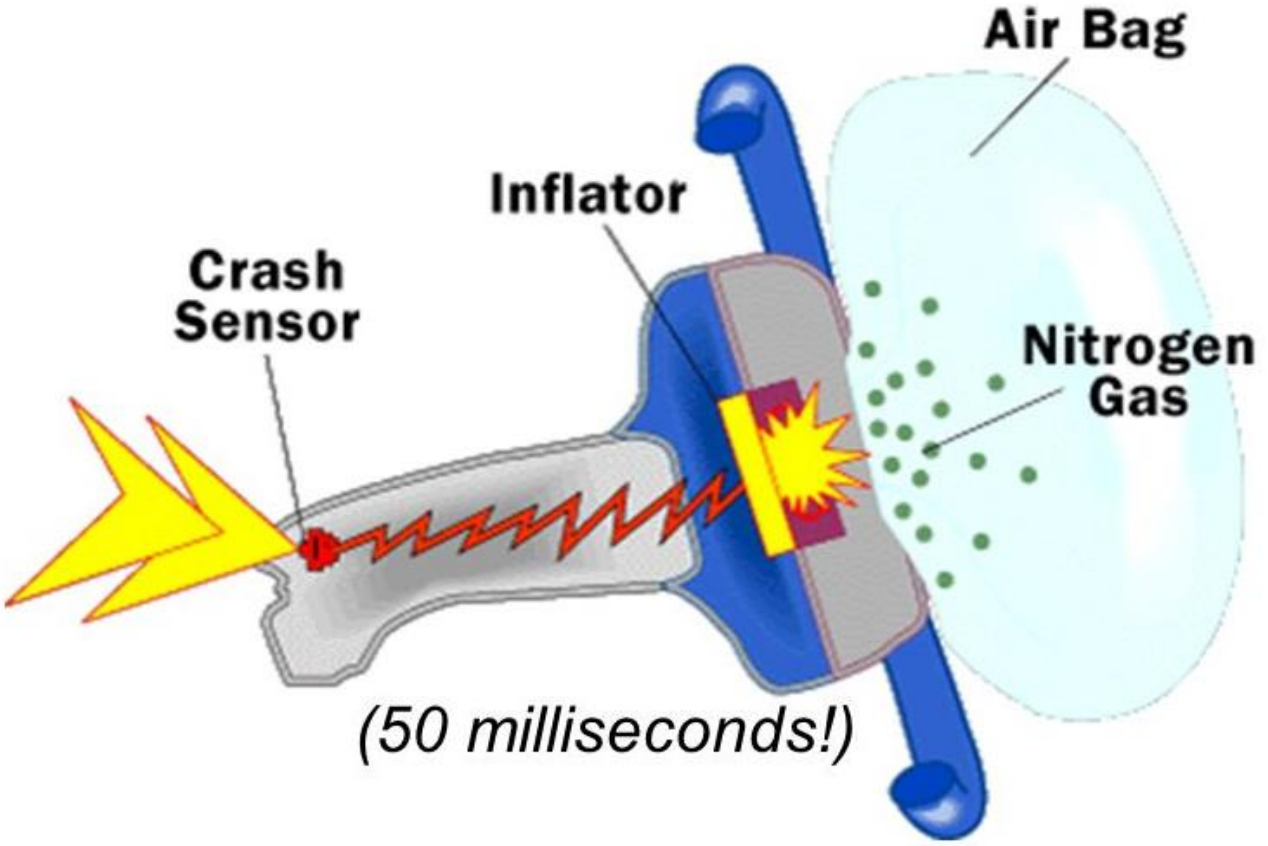
It was such a great combination of brass and bamboo!

Combustion of magnesium metal in air, a combination reaction



Decomposition Reactions

A single reactant undergoes a reaction to produce two or more other substances



Combination Reactions
$A + B \longrightarrow C$
$C(s) + O_2(g) \longrightarrow CO_2(g)$
$N_2(g) + 3\,H_2(g) \longrightarrow 2\,NH_3(g)$
$CaO(s) + H_2O(l) \longrightarrow Ca(OH)_2(aq)$
Decomposition Reactions
$C \longrightarrow A + B$
$2\,KClO_3(s) \longrightarrow 2\,KCl(s) + 3\,O_2(g)$
$PbCO_3(s) \longrightarrow PbO(s) + CO_2(g)$
$Cu(OH)_2(s) \longrightarrow CuO(s) + H_2O(g)$

EXAMPLE

Write a balanced equation for

(a) the combination reaction between lithium metal and fluorine gas

$$2Li\ (s) + F_2\ (g) \rightarrow 2\ LiF\ (s)$$

(b) the decomposition reaction that occurs when solid barium carbonate is heated (two products form, a solid and a gas).

$$BaCO_3\ (s) \rightarrow BaO\ (s) + CO_2\ (g)$$

PRACTICE 1

Which of the following reactions is the balanced equation that represents the decomposition reaction that occurs when silver (I) oxide is heated?

(a) $AgO\ (s) \rightarrow Ag\ (s) + O\ (g)$

(b) $2\ AgO\ (s) \rightarrow 2\ Ag\ (s) + O_2\ (g)$

(c) $Ag_2O \rightarrow 2\ Ag\ (s) + O\ (g)$

(d) $2\ Ag_2O \rightarrow 4\ Ag\ (s) + O_2\ (g)$

(e) $Ag_2O \rightarrow 2\ Ag\ (s) + O_2\ (g)$

PRACTICE 2

Write a balanced equation for

(a) solid mercury(II) sulfide decomposing into its component elements when heated

$$HgS\ (s) \rightarrow Hg\ (l) + S\ (s)$$

(b) aluminum metal combining with oxygen in the air.

$$4Al + 3O_2 \rightarrow 2Al_2O_3$$

Combustion Reactions

Combustion reactions are rapid reactions that produce a flame. Most combustion reactions we observe involve O_2 from air as a reactant.

pure methanol vs pure ethanol
in combustion

Why?

PRACTICE

Write the balanced equation for the reaction that occurs when

(a) methanol, CH_3OH *(l)*, is burned in air.

$$2\ CH_3OH + O_2 \rightarrow 2\ CO_2 + 4\ H_2O$$

(b) ethylene glycol, $C_2H_4(OH)_2$ *(l)*, burns in air.

$$2\ C_2H_4(OH)_2 + 5\ O_2 \rightarrow 4\ CO_2 + 6\ H_2O$$

(c) ethanol, C_2H_5OH *(l)*, burns in air.

$$C_2H_5OH + 2\ O_2 \rightarrow CO_2 + 3\ H_2O$$

Behind the fireworks

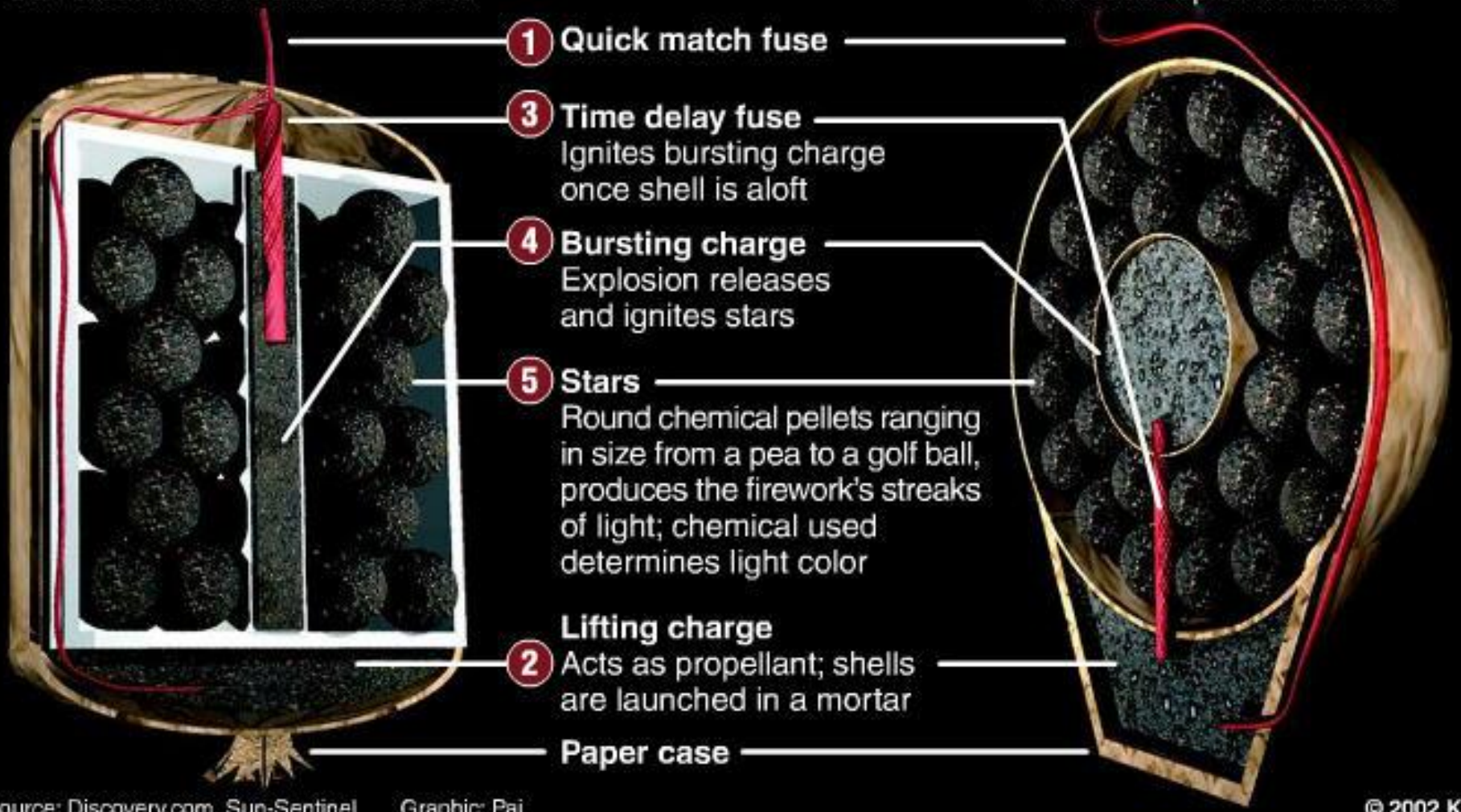
Two main types of aerial shells used for fireworks shows:

Italian-style shell

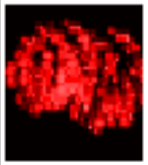
Can create more elaborate effects

Oriental-style shell

Produces spherical bursts



Source: Discovery.com, Sun-Sentinel Graphic: Pai

	Color	Compound	Wavelength (nm)
	red	strontium salts, lithium salts lithium carbonate, Li_2CO_3 = deep red strontium carbonate, $SrCO_3$ = bright red	650
	orange	calcium salts calcium chloride, $CaCl_2$	670
	yellow	sodium salts sodium chloride, NaCl	610-620
	green	barium compounds + chlorine producer barium chloride, $BaCl_2$	590
	blue	copper compounds + chlorine producer copper(I) chloride, CuCl	500-535
	purple	mixture of strontium (red) and copper (blue) compounds	420-460
	silver	burning metallic aluminum, titanium, or magnesium	all

Chemical Reactions in the Black Powder

- Black powder (bursting and lifting charges): 75% potassium nitrate, 15% charcoal, and 10% sulfur

  - Decompostion reaction of the oxidizers to produce oxygen

$$4\ KNO_3\ (s) \rightarrow\ 2\ K_2O\ (s) +\ 2\ N_2\ (g) +\ 5\ O_2\ (g)$$

  - Combination reactions of oxygen with reducing agents to produce hot, rapidly expanding gasses

$$O_2\ (g) + C\ (s) \rightarrow CO_2\ (g)$$

$$O_2\ (g) + S\ (s) \rightarrow SO_2\ (g)$$

Chemical Reactions in the Stars

- Stars: potassium perclorate or amonium perclorate, charcoal, sulfur, and metal salts

  - Decompostion reaction of the oxidizers to produce oxygen

$$KClO_4 \rightarrow KCl + O_2$$

$$4\ NH_4ClO_4 \rightarrow 4\ HCl + 2\ N_2 + 5\ O_2 + 6\ H_2O$$

  - Combination reactions of oxygen with reducing agents to produce hot, rapidly expanding gasses

$$O_2\,(g) + C\,(s) \rightarrow CO_2\,(g)$$

$$O_2\,(g) + S\,(s) \rightarrow SO_2\,(g)$$ white sparks

$$O_2\,(g) + Mg\,(s) \rightarrow MgO\,(s)$$

Chemical Reactions in the Stars

- Stars: potassium perclorate or amonium perclorate, charcoal, sulfur, and metal salts
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3-3 Formula Weights

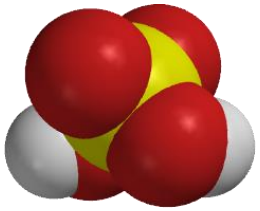
The **formula weight** (FW) of a substance is the **sum** of the **atomic weights** (AW) of the atoms in the chemical formula of the substance.

- If the chemical formula is the chemical symbol of an element,

  FW = AW

  FW of Na = AW of Na = 23.0 amu

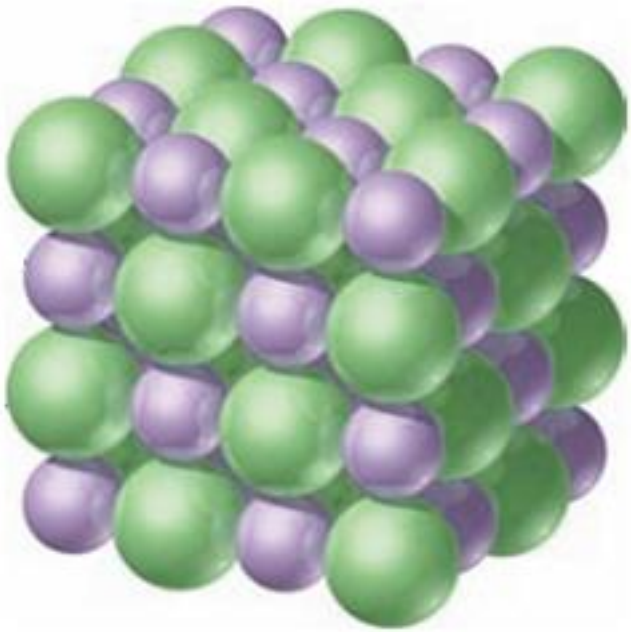
- If the chemical formula is that of a molecule, the formula weight is also called the **molecular weight** (MW)



FW of H_2SO_4 = 2 (AW of H) + (AW of S) + 4 (AW of O)

= 2(1.0 amu) + 32.1 amu + 4(16.0 amu)

= 98.1 amu



It is inappropriate to speak of molecules of **ionic substances** the **empirical formula** is used as the formula unit.

FW of NaCl = (AW of Na) + (AW of Cl)
= 23.0 amu + 35.5 amu
= 58.5 amu

EXAMPLE

Calculate the formula weight of

(a) sucrose, $C_{12}H_{22}O_{11}$ (table sugar);

$$\begin{aligned} 12\,\text{C atoms} &= 12(12.0\,\text{amu}) = 144.0\,\text{amu} \\ 22\,\text{H atoms} &= 22(1.0\,\text{amu}) = 22.0\,\text{amu} \\ 11\,\text{O atoms} &= 11(16.0\,\text{amu}) = \underline{176.0\,\text{amu}} \\ & \qquad\qquad\qquad\qquad\quad 342.0\,\text{amu} \end{aligned}$$

(b) calcium nitrate, $Ca(NO_3)_2$.

$$\begin{aligned} 1\,\text{Ca atom} &= 1(40.1\,\text{amu}) = 40.1\,\text{amu} \\ 2\,\text{N atoms} &= 2(14.0\,\text{amu}) = 28.0\,\text{amu} \\ 6\,\text{O atoms} &= 6(16.0\,\text{amu}) = \underline{96.0\,\text{amu}} \\ & \qquad\qquad\qquad\qquad\quad 164.1\,\text{amu} \end{aligned}$$

PRACTICE 1

Which of the following is the correct formula weight for calcium phosphate?

(a) 310.17 amu,

(b) 135.11 amu,

(c) 182.22 amu,

(d) 278.25 amu,

(e) 175.11 amu.

$Ca_3(PO_4)_2$

PRACTICE 2

Calculate the formula weight of

(a) $Al(OH)_3$,

(b) CH_3OH

(c) TaON

Percentage Composition from Chemical Formulas

$$\%\ \text{composition of element} = \frac{\left(\begin{array}{c}\text{number of atoms}\\ \text{of element}\end{array}\right)\left(\begin{array}{c}\text{atomic weight}\\ \text{of element}\end{array}\right)}{\text{formula weight of substance}} \times 100\%$$

$C_{12}H_{22}O_{11}$

$$\%C = \frac{(12)(12.0\ \text{amu})}{342.0\ \text{amu}} \times 100\% = 42.1\%$$

$$\%H = \frac{(22)(1.0\ \text{amu})}{342.0\ \text{amu}} \times 100\% = 6.4\%$$

$$\%O = \frac{(11)(16.0\ \text{amu})}{342.0\ \text{amu}} \times 100\% = 51.5\%$$

PRACTICE

1. What is the percentage of nitrogen, by mass, in calcium nitrate?

(a) 8.54%,

(b) 17.1%,

(c) 13.7%,

(d) 24.4%,

(e) 82.9%

2. Calculate the percentage of potassium, by mass, in K_2PtCl_6.

3-4 Avogadro's Number and the Mole

Amedeo Avogadro
(1776-1856)

Avogadro's law:
"Equal volumes of gases under the same conditions of temperature and pressure will contain equal numbers of molecules"

A teaspoon of water contains about 2×10^{23} water molecules

a so large number!

➔ Need a chemical unit for the amount of a substance

Mole

- number of atoms in exactly 12 g of isotopically pure ^{12}C
- **Avogadro's number,** N_A **,** $6.02214129 \times 10^{23}$

  - We use **atoms** when dealing with a single, individual element.
  - We use **molecules** or **particles** when dealing with more than one element or a compound

.

6.022×10^{23} atoms of Fe ⇌ **1 mole of Fe** ⇌ **55.85 amu**

EXAMPLE

Without using a calculator, arrange these samples in order of increasing numbers of carbon atoms: 12 g ^{12}C, 1 mol C_2H_2, 9 x 10^{23} molecules of CO_2

- 12 g of ^{12}C contains 1 mol of C atoms = 6.02 x 10^{23} C atoms
- 1 mol of C_2H_2 contains 6.02 x10^{23} C_2H_2 molecules, 2 x 6.02 x10^{23} C atoms
- 9 x 10^{23} molecules of CO_2 contains 9 x 10^{23} C atoms

The order is 12 g of ^{12}C (6.02 x 10^{23} C atoms) < 9 x 10^{23} molecules of CO_2 (9 x 10^{23} C atoms) < 1 mol of C_2H_2 (12.04 x10^{23} C atoms)

PRACTICE

1. Determine which of the following samples contains the fewest sodium atoms?

(a) 1 mol sodium oxide,

(b) 45 g sodium fluoride,

(c) 50 g sodium chloride,

(d) 1 mol sodium nitrate?

2. Without using a calculator, arrange these samples in order of increasing numbers of O atoms: 1 mol H_2O, 1 mol CO_2, 3 x 10^{23} molecules of O_3.

EXAMPLE

Calculate the number of H atoms in 0.350 mol of $C_6H_{12}O_6$.

Moles $C_6H_{12}O_6$ → # molecules $C_6H_{12}O$ → # atoms H

$$\text{H atoms} = (0.350 \text{ mol } C_6H_{12}O_6)\left(\frac{6.02 \times 10^{23} \text{ molecules } C_6H_{12}O_6}{1 \text{ mol } C_6H_{12}O_6}\right)\left(\frac{12 \text{ H atoms}}{1 \text{ molecule } C_6H_{12}O_6}\right)$$

$$= 2.53 \times 10^{24} \text{ H atoms}$$

PRACTICE

1. How many sulfur atoms are in

(a) 0.45 mol $BaSO_4$

(b) 1.10 mol of aluminum sulfide

2. How many oxygen atoms are in

(a) 0.25 mol $Ca(NO_3)_2$

(b) 1.50 mol of sodium carbonate

Molar Mass

^{12}C has an atomic weight of 12 amu
1 mole of ^{12}C has a mass of 12 g

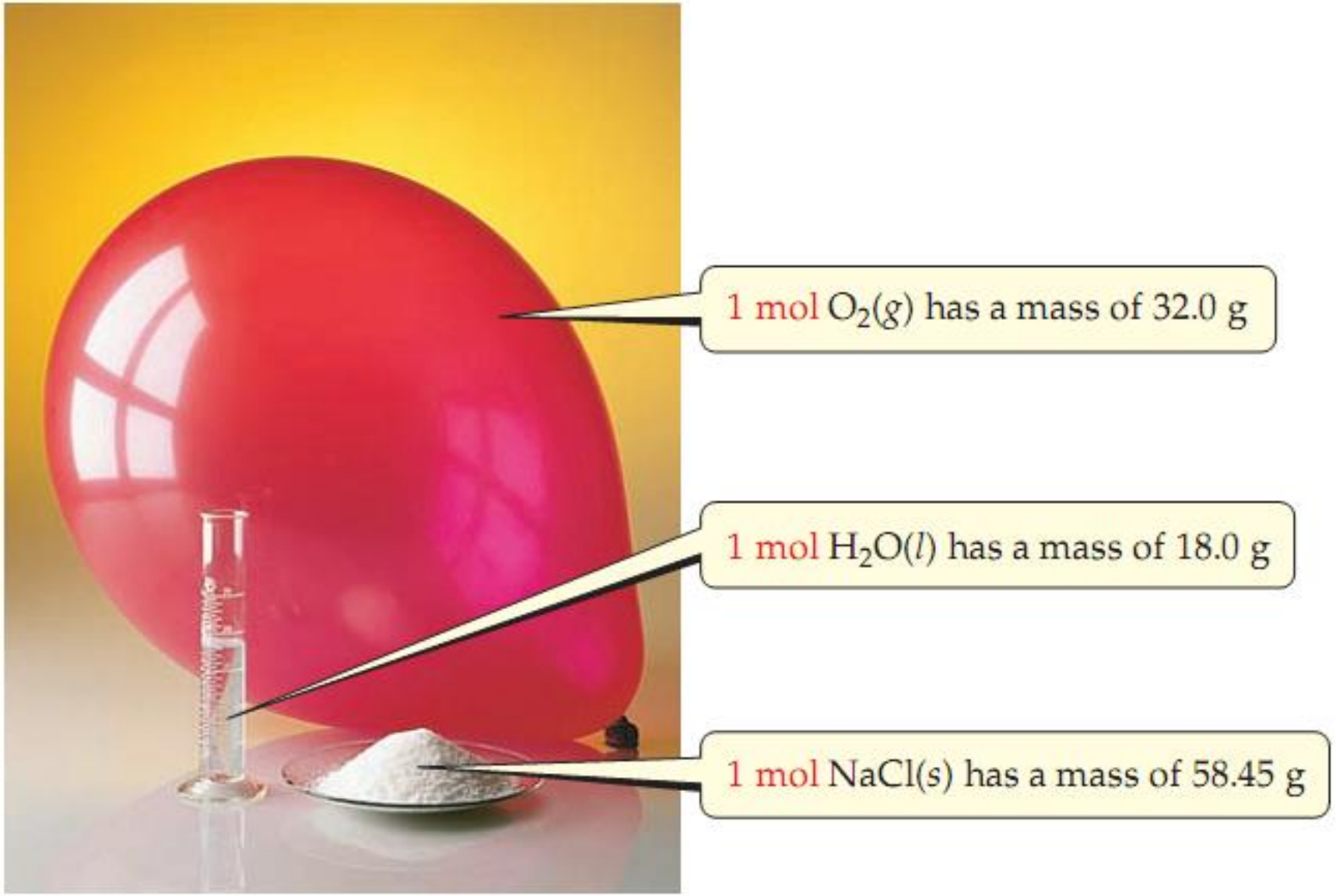
The **atomic weight** of an element in atomic mass units is **numerically equal to** the mass in grams of 1 mol of that element

How about 1 mole of Cl and 1 mole of NaCl?

Cl has an atomic weight of 35.5 amu ➔ mol Cl has a mass of 35.5 g.
Au has an atomic weight of 197 amu ➔ mol Au has a mass of 197 g.

H_2O has a formula weight of 18.0 amu ➔ mol H_2O has a mass of 18.0 g
NaCl has a formula weight of 58.5 amu ➔ mol NaCl has a mass of 58.5 g

Name of Substance	Formula	Formula Weight (amu)	Molar Mass (g/mol)	Number and Kind of Particles in One Mole
Atomic nitrogen	N	14.0	14.0	6.02×10^{23} N atoms
Molecular nitrogen	N_2	28.0	28.0	6.02×10^{23} N_2 molecules $2(6.02 \times 10^{23})$ N atoms
Silver	Ag	107.9	107.9	6.02×10^{23} Ag atoms
Silver ions	Ag^+	107.9[a]	107.9	6.02×10^{23} Ag^+ ions
Barium chloride	$BaCl_2$	208.2	208.2	6.02×10^{23} $BaCl_2$ formula units 6.02×10^{23} Ba^{2+} ions $2(6.02 \times 10^{23})$ Cl^- ions


1 mol $O_2(g)$ has a mass of 32.0 g
1 mol $H_2O(l)$ has a mass of 18.0 g
1 mol NaCl(s) has a mass of 58.45 g

EXAMPLE

What is the molar mass of glucose, $C_6H_{12}O_6$.

$$\begin{aligned} 6\,\text{C atoms} &= 6(12.0\ \text{amu}) = 72.0\ \text{amu} \\ 12\,\text{H atoms} &= 12(1.0\ \text{amu}) = 12.0\ \text{amu} \\ 6\,\text{O atoms} &= 6(16.0\ \text{amu}) = 96.0\ \text{amu} \\ &\qquad\qquad\qquad\qquad 180.0\ \text{amu} \end{aligned}$$

$C_6H_{12}O_6$ has a formula weight of 180.0 amu, 1 mol of this substance (6.02×10^{23} molecules) has a mass of 180.0 g.

➔ Glucose has a molar mass of 180.0 g/mol

PRACTICE

1. A sample of an ionic compound containing iron and chlorine is analyzed and found to have a molar mass of 126.8 g/mol. What is the charge of the iron in this compound?

(a) 1+

(b) 2+

(c) 3+

(d) 4+

2. Calculate the molar mass of $Ca(NO_3)_2$.

Converting Mass to Mole

Calculate the number of moles of glucose ($C_6H_{12}O_6$) in 5.380 g of $C_6H_{12}O_6$

4 significant figures

1 mol $C_6H_{12}O_6$ = 180.0 g $C_6H_{12}O_6$

$$\text{Moles } C_6H_{12}O_6 = (5.380 \text{ g } C_6H_{12}O_6)\left(\frac{1 \text{ mol } C_6H_{12}O_6}{180.0 \text{ g } C_6H_{12}O_6}\right)$$

$$= 0.02989 \text{ mol } C_6H_{12}O_6$$

4 significant figures

PRACTICE

1. How many moles of sodium bicarbonate ($NaHCO_3$) are in 508 g of $NaHCO_3$?

2. How many moles of water are in 1.00 L of water, whose density is 1.00 g/mL?

Converting Mole to Mass

Calculate the mass, in grams, of 0.433 mol of calcium nitrate

3 significant figures

1 mol $Ca(NO_3)_2$ = 164.1 g $Ca(NO_3)_2$

$$\text{Grams } Ca(NO_3)_2 = (0.433 \text{ mol } Ca(NO_3)_2)\left(\frac{164.1 \text{ g } Ca(NO_3)_2}{1 \text{ mol } Ca(NO_3)_2}\right)$$

$$= 71.1 \text{ g } Ca(NO_3)_2$$

3 significant figures

PRACTICE

1. What is the mass, in grams, of

(a) 6.33 mol of $NaHCO_3$

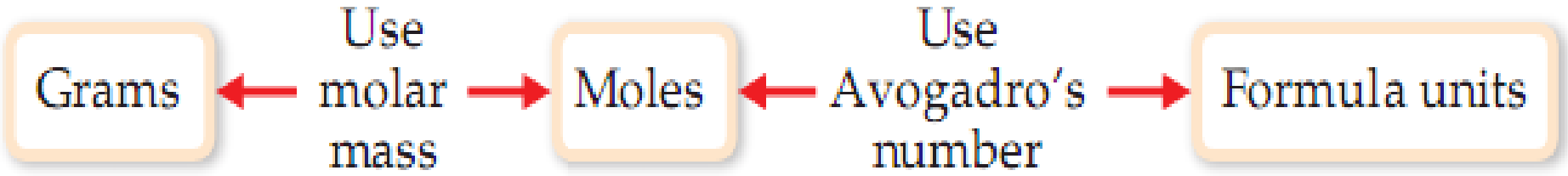
(b) 3.0×10^{-5} mol of sulfuric acid?

2. What is the mass, in grams, of

(a) 0.50 mol of diamond (C)

(b) 0.155 mol of ammonium chloride?

Interconverting Masses and Numbers of Particles



Example: Calculate the number of copper atoms in 3 g of copper

$$\text{Cu atoms} = (3\ \text{g}\ \cancel{\text{Cu}})\left(\frac{1\ \cancel{\text{mol Cu}}}{63.5\ \cancel{\text{g Cu}}}\right)\left(\frac{6.02 \times 10^{23}\ \text{Cu atoms}}{1\ \cancel{\text{mol Cu}}}\right)$$

$$= 3 \times 10^{22}\ \text{Cu atoms}$$

PRACTICE

1. How many chlorine atoms are in 12.2 g of CCl_4?

(a) 4.77×10^{22}

(b) 7.34×10^{24}

(c) 1.91×10^{23}

(d) 2.07×10^{23}

2. For 4.20 g of HNO_3,

(a) How many nitric acid molecules are in this sample?

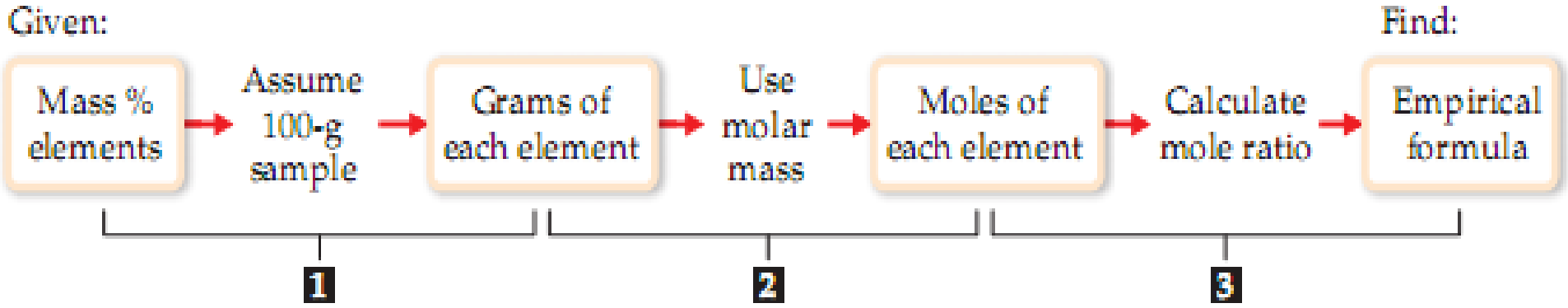
(b) How many O atoms are in this sample?

3-5 Empirical Formulas from Analyses

The **empirical formula** for a substance tells us the **relative number of atoms** of each element in the substance.

H_2O shows that water contains two H atoms for each O atom
1 mol of H_2O contains 2 mol of H atoms and 1 mol of O atoms

The **ratio of the numbers of moles** of all elements in a compound gives the **subscript**s in the compound's empirical formula



EXAMPLE

Ascorbic acid (vitamin C) contains 40.92% C, 4.58% H, and 54.50% O by mass. What is the empirical formula of ascorbic acid?

$C_3H_4O_3$

(1) For simplicity, assume that we have exactly 100 g of material

(2) Calculate the number of moles of each element

$$\text{Moles C} = (40.92\ \text{g C})\left(\frac{1\ \text{mol C}}{12.01\ \text{g C}}\right) = 3.407\ \text{mol C}$$

$$\text{Moles H} = (4.58\ \text{g H})\left(\frac{1\ \text{mol C}}{1.008\ \text{g H}}\right) = 4.54\ \text{mol H}$$

$$\text{Moles O} = (54.50\ \text{g O})\left(\frac{1\ \text{mol O}}{16.00\ \text{g O}}\right) = 3.406\ \text{mol O}$$

(3) Determine the simplest whole-number ratio of moles by dividing each number of moles by the smallest number of moles.

$$\text{C}: \frac{3.407}{3.406} = 1.000 \quad \text{H}: \frac{4.54}{3.406} = 1.33 \quad \text{O}: \frac{3.406}{3.406} = 1.000 \qquad C:H:O = (3 \times 1 : 3 \times 1.33 : 3 \times 1) = (3:4:3)$$

PRACTICE

1. A 2.144-g sample of phosgene, a compound used as a chemical warfare agent during World War I, contains 0.260 g of carbon, 0.347 g of oxygen, and 1.537 g of chlorine. What is the empirical formula of this substance?

(a) CO_2Cl_6,

(b) $COCl_2$,

(c) $C_{0.022}O_{0.022}Cl_{0.044}$,

(d) C_2OCl

PRACTICE

2. A 5.325-g sample of methyl benzoate, a compound used in the manufacture of perfumes, contains 3.758 g of carbon, 0.316 g of hydrogen, and 1.251 g of oxygen. What is the empirical formula of this substance?

Molecular Formulas from Empirical Formulas

The **subscripts in the molecular formula** of a substance are always **whole-number multiples of the subscripts** in its empirical formula

$$\text{Whole-number multiple} = \frac{\text{molecular weight}}{\text{empirical formula weight}}$$

Example:

Empirical formula of ascorbic acid is **$C_3H_4O_3$**

Empirical formula weight of ascorbic acid is **88.0 amu**

Molecular weight of ascorbic acid is **176 amu**

$$\text{Whole-number multiple} = \frac{\text{molecular weight}}{\text{empirical formula weight}} = \frac{176 \text{ amu}}{88.0 \text{ amu}} = 2$$

The molecular formula of ascorbic acid is **$C_6H_8O_6$.**

EXAMPLE

Mesitylene, a hydrocarbon found in crude oil, has an empirical formula of C_3H_4 and an experimentally determined molecular weight of 121 amu. What is its molecular formula?

(1) Calculate the formula weight of the empirical formula C_3H_4

$$3(12.0\,\text{amu}) + 4(1.0\,\text{amu}) = 40.0\,\text{amu}$$

(2) Calculate the whole number multiple

$$\text{Whole-number multiple} = \frac{\text{molecular weight}}{\text{empirical formula weight}} = \frac{121}{40.0} = 3.03$$

The molecular formula of mesitylene is **C_9H_{12}**

PRACTICE

1. Cyclohexane, a commonly used organic solvent, is 85.6% C and 14.4% H by mass with a molar mass of 84.2 g/mol. What is its molecular formula?

(a) C_6H,

(b) CH_2,

(c) C_5H_{24},

(d) C_6H_{12},

(e) C_4H_8.

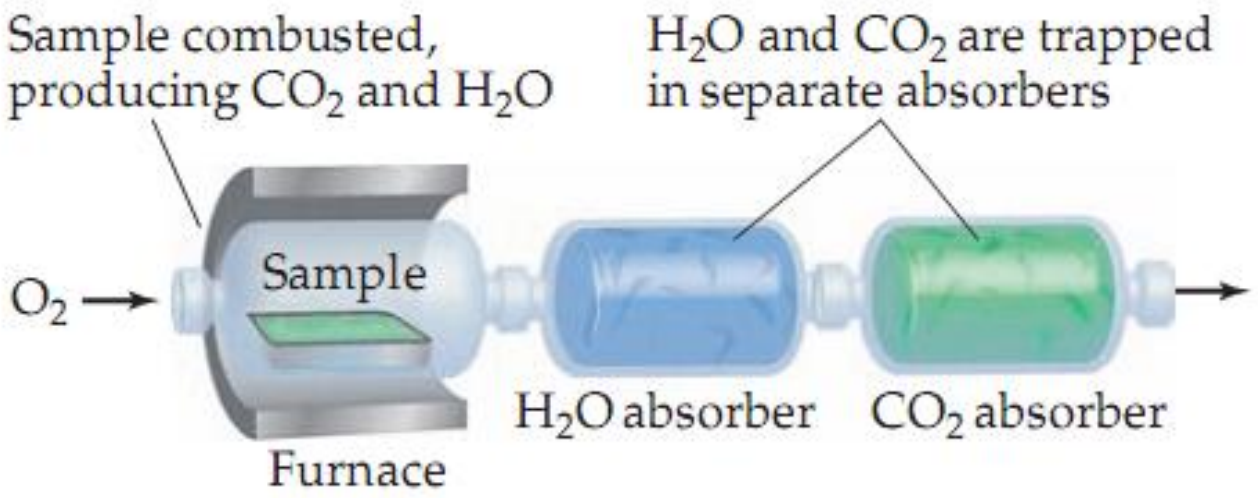
PRACTICE

2. Ethylene glycol, used in automobile antifreeze, is 38.7% C, 9.7% H, and 51.6% O by mass. Its molar mass is 62.1 g/mol.

(a) What is the empirical formula of ethylene glycol?

(b) What is its molecular formula?

Combustion Analysis



Mass gained by each absorber corresponds to mass of CO_2 or H_2O produced

Mass CO_2 produced → Molar mass CO_2 44.0 g/mol → Moles CO_2 produced → 1 C atom per CO_2 molecule → Moles of C original sample → Molar mass C 12.0 g/mol → Mass C in original sample

Mass H_2O produced → Molar mass H_2O 18.0 g/mol → Moles H_2O produced → 2 H atoms per H_2O molecule → Moles H in original sample → Molar mass H 1.01 g/mol → Mass H in original sample

EXAMPLE

Isopropyl alcohol, sold as rubbing alcohol, is composed of C, H, and O. Combustion of 0.255 g of isopropyl alcohol produces 0.561 g of CO_2 and 0.306 g of H_2O. Determine the empirical formula of isopropyl alcohol.

(1) Calculate mass of carbon in the original sample

$$\text{Grams C} = (0.561\ \text{g}\cancel{\text{CO}_2})\left(\frac{1\ \text{mol}\cancel{\text{CO}_2}}{44.0\ \text{g}\cancel{\text{CO}_2}}\right)\left(\frac{1\ \text{mol C}}{1\ \text{mol}\cancel{\text{CO}_2}}\right)\left(\frac{12.0\ \text{g C}}{1\ \text{mol C}}\right)$$

$$= 0.153\ \text{g C}$$

(2) Calculate mass of hydrogen in the original sample

$$\text{Grams H} = (0.306\ \text{g}\cancel{\text{H}_2\text{O}})\left(\frac{1\ \text{mol}\cancel{\text{H}_2\text{O}}}{18.0\ \text{g}\cancel{\text{H}_2\text{O}}}\right)\left(\frac{2\ \text{mol H}}{1\ \text{mol}\cancel{\text{H}_2\text{O}}}\right)\left(\frac{1.01\ \text{g H}}{1\ \text{mol H}}\right)$$

$$= 0.0343\ \text{g H}$$

(3) Calculate mass of hydrogen in the original sample

$$\text{Mass of O} = \text{mass of sample} - (\text{mass of C} + \text{mass of H})$$

$$= 0.255\ \text{g} - (0.153\ \text{g} + 0.0343\ \text{g}) = 0.068\ \text{g O}$$

EXAMPLE

(4) Calculate the number of moles of C, H, and O in the sample

$$\text{Moles C} = (0.153\ \text{g}\cancel{\text{C}})\left(\frac{1\ \text{mol C}}{12.0\ \text{g}\cancel{\text{C}}}\right) = 0.0128\ \text{mol C}$$

$$\text{Moles H} = (0.0343\ \text{g}\cancel{\text{H}})\left(\frac{1\ \text{mol H}}{1.01\ \text{g}\cancel{\text{H}}}\right) = 0.0340\ \text{mol H}$$

$$\text{Moles O} = (0.068\ \text{g}\cancel{\text{O}})\left(\frac{1\ \text{mol O}}{16.0\ \text{g}\cancel{\text{O}}}\right) = 0.0043\ \text{mol O}$$

(5) Find the empirical formula

$$\text{C}:\frac{0.0128}{0.0043} = 3.0 \quad \text{H}:\frac{0.0340}{0.0043} = 7.9 \quad \text{O}:\frac{0.0043}{0.0043} = 1.0$$

The first two numbers are very close to the whole numbers 3 and 8, giving the empirical formula **C_3H_8O**.

PRACTICE

1. The compound dioxane, which is used as a solvent in various industrial processes, is composed of C, H, and O atoms. Combustion of a 2.203-g sample of this compound produces 4.401 g CO_2 and 1.802 g H_2O. A separate experiment shows that it has a molar mass of 88.1 g/mol. Which of the following is the correct molecular formula for dioxane?

(a) C_2H_4O,

(b) $C_4H_4O_2$,

(c) CH_2,

(d) $C_4H_8O_2$.

PRACTICE

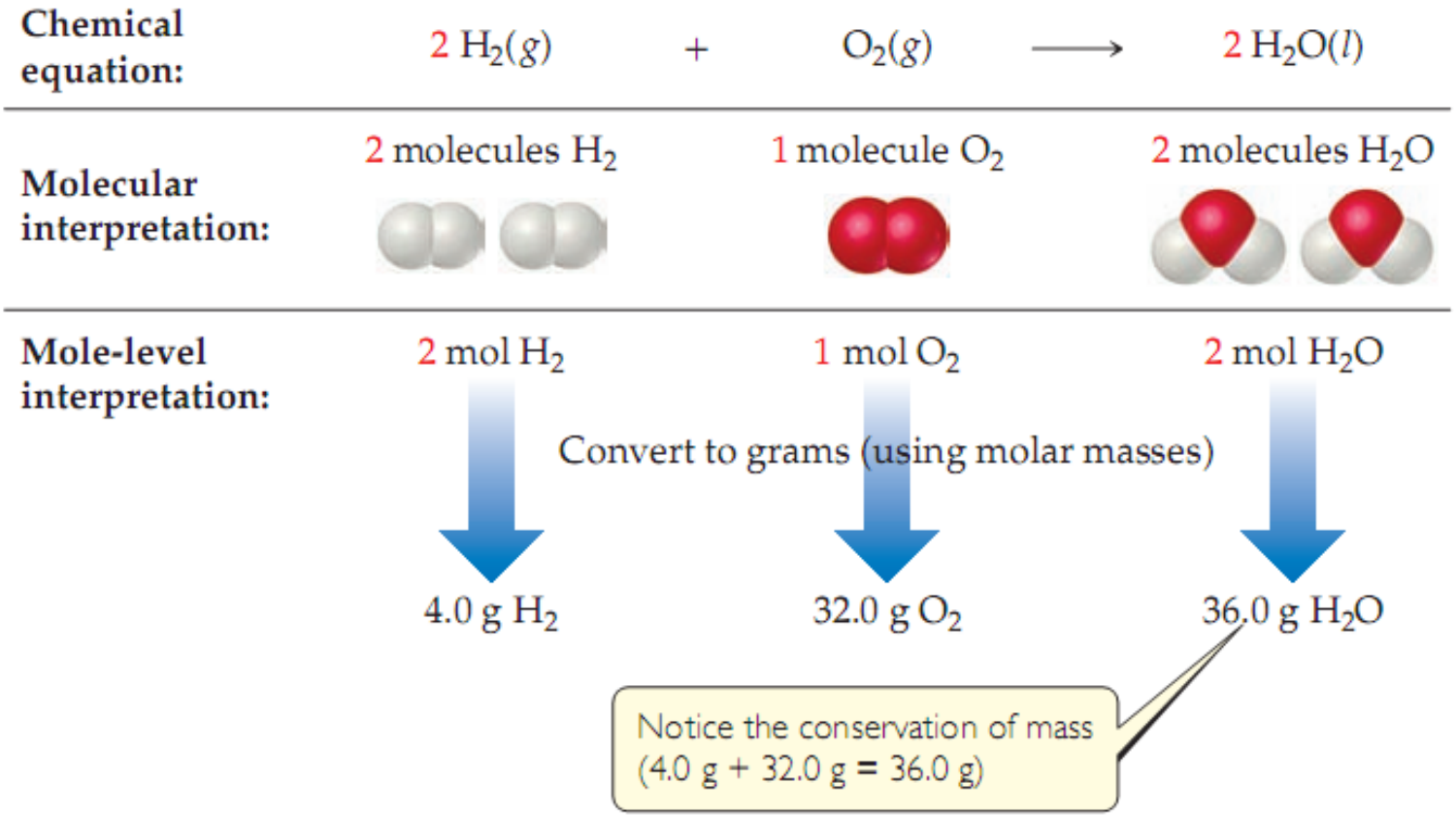
2. Caproic acid, responsible for the odor of dirty socks, is composed of C, H, and O atoms. Combustion of a 0.225-g sample of this compound produces 0.512 g CO_2 and 0.209 g H_2O. Caproic acid has a molar mass of 116 g/mol.

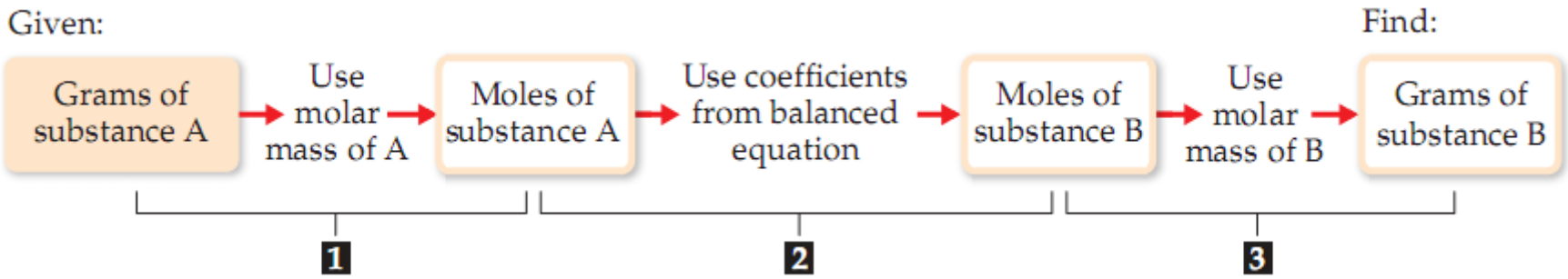
(a) What is the empirical formula of caproic acid?

(b) What is the molecular formula of caproic acid?

3-6 Quantitative Information from Balanced Equations

The **coefficients** in a balanced chemical equation indicate both the **relative numbers of molecules** (or formula units) in the reaction and the **relative numbers of moles**





Consider the combustion of 1.00 g of butane (C_4H_{10}), calculate the mass of CO_2 produced

$$2\,C_4H_{10}(l) + 13\,O_2(g) \longrightarrow 8\,CO_2(g) + 10\,H_2O(g)$$

$$\text{Moles } C_4H_{10} = (1.00\ \text{g}\,\cancel{C_4H_{10}})\left(\frac{1\ \text{mol } C_4H_{10}}{58.0\ \text{g}\,\cancel{C_4H_{10}}}\right) = 1.72 \times 10^{-2}\ \text{mol } C_4H_{10}$$

$$\text{Moles } CO_2 = (1.72 \times 10^{-2}\ \text{mol}\,\cancel{C_4H_{10}})\left(\frac{8\ \text{mol } CO_2}{2\ \text{mol}\,\cancel{C_4H_{10}}}\right) = 6.88 \times 10^{-2}\ \text{mol } CO_2$$

$$\text{Grams } CO_2 = (6.88 \times 10^{-2}\ \text{mol}\,\cancel{CO_2})\left(\frac{44.0\ \text{g } CO_2}{1\ \text{mol}\,\cancel{CO_2}}\right) = 3.03\ \text{g } CO_2$$

PRACTICE

1. Sodium hydroxide reacts with carbon dioxide to form sodium carbonate and water. How many grams of Na_2CO_3 can be prepared from 2.40 g of NaOH?

(a) 3.18 g,

(b) 6.36 g,

(c) 1.20 g,

(d) 0.0300 g

PRACTICE

Decomposition of $KClO_3$ is sometimes used to prepare small amounts of O_2 in the laboratory

$2\ KClO_3\ (s) \rightarrow 2\ KCl\ (s) + 3\ O_2\ (g)$

How many grams of O_2 can be prepared from 4.50 g of $KClO_3$?

Calculating amounts of Reactants and products

Solid lithium hydroxide is used in space vehicles to remove the carbon dioxide gas exhaled by astronauts. The hydroxide reacts with the carbon dioxide to form solid lithium carbonate and liquid water. How many grams of carbon dioxide can be absorbed by 1.00 g of lithium hydroxide?

$$2\ LiOH\ (s) + CO_2\ (g) \rightarrow Li_2CO_3(s) + H_2O(l)$$

molar mass of LiOH: 16.94 + 16.00 + 1.01 = 23.95 g/mol
molar mass of CO_2 : 12.01 + 2116.002 = 44.01 g/mol

$$(1.00\ \text{g}\ \cancel{\text{LiOH}})\left(\frac{1\ \cancel{\text{mol LiOH}}}{23.95\ \cancel{\text{g LiOH}}}\right)\left(\frac{1\ \cancel{\text{mol CO}_2}}{2\ \cancel{\text{mol LiOH}}}\right)\left(\frac{44.01\ \text{g CO}_2}{1\ \cancel{\text{mol CO}_2}}\right) = 0.919\ \text{g CO}_2$$

PRACTICE

1. Propane, C_3H_8, is a common fuel used for cooking and home heating. What mass of O_2 is consumed in the combustion of 1.00 g of propane?

(a) 5.00 g,

(b) 0.726 g,

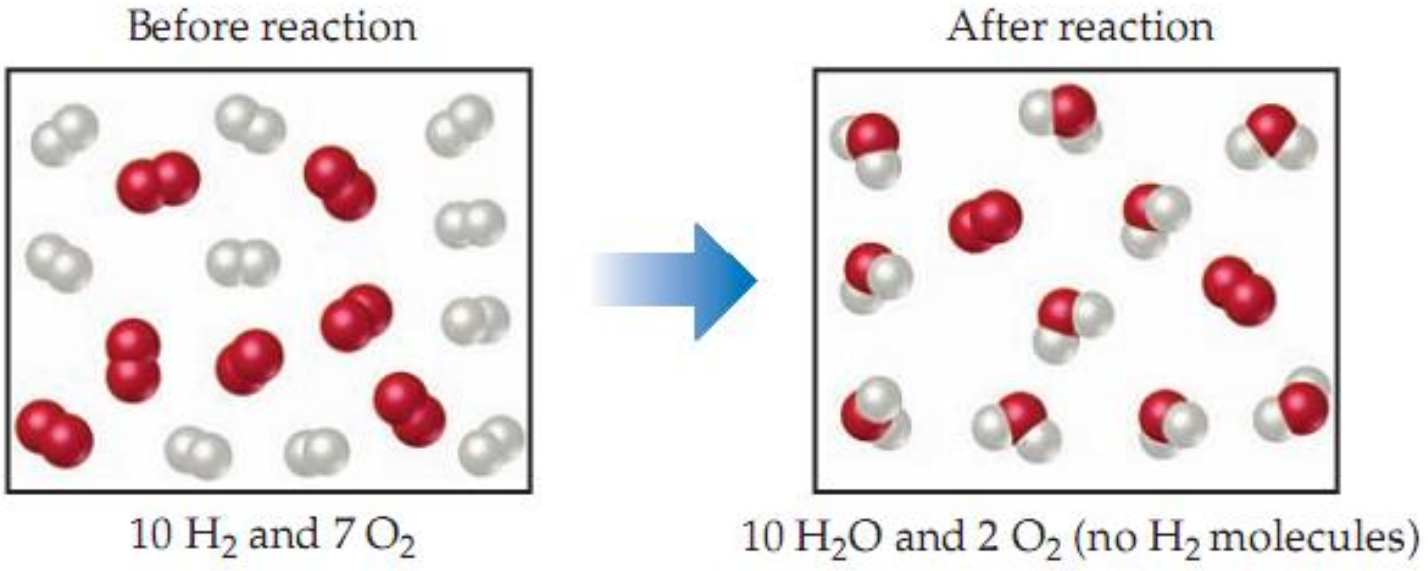
(c) 2.18 g,

(d) 3.63 g.

PRACTICE

2. Methanol, CH_3OH, reacts with oxygen from air in a combustion reaction to form water and carbon dioxide. What mass of water is produced in the combustion of 23.6 g of methanol?

3-6 Limiting Reactants



Because H_2 is completely consumed, it is the limiting reactant.
Because some O_2 is left over after the reaction is complete, it is the excess reactant.

➔ The amount of H_2O formed depends on the amount of limiting reactant, H_2

EXAMPLE

The most important commercial process for converting N_2 from the air into nitrogen-containing compounds is based on the reaction of N_2 and H_2 to form ammonia (NH_3). How many moles of NH_3 can be formed from 3.0 mol of N_2 and 6.0 mol of H_2?

$$N_2(g) + 3\ H_2(g) \rightarrow NH_3(g)$$

(1) The number of moles of H_2 needed for complete consumption of 3.0 mol of N_2 is

$$\text{Moles } H_2 = (3.0\ \cancel{\text{mol } N_2})\left(\frac{3\ \text{mol } H_2}{1\ \cancel{\text{mol } N_2}}\right) = 9.0\ \text{mol } H_2$$

(2) The quantity of NH_3 produced

$$\text{Moles } NH_3 = (6.0\ \cancel{\text{mol } H_2})\left(\frac{2\ \text{mol } NH_3}{3\ \cancel{\text{mol } H_2}}\right) = 4.0\ \text{mol } NH_3$$

PRACTICE

1. When 24 mol of methanol and 15 mol of oxygen combine in the combustion reaction $2\ CH_3OH(l) + 3\ O_2\ (g) \rightarrow 2\ CO_2(g) + 4\ H_2O(g)$, what is the excess reactant and how many moles of it remains at the end of the reaction?

(a) 9 mol CH_3OH (l),

(b) 10 mol CO_2 (g),

(c) 10 mol CH_3OH (l),

(d) 14 mol CH_3OH (l),

(e) 1 mol O_2 (g).

PRACTICE

2. When a 2.00-g strip of zinc metal is placed in an aqueous solution containing 2.50 g of silver nitrate, the reaction is

$Zn\ (s) + 2\ AgNO_3(aq) \rightarrow 2\ Ag(s) + Zn(NO_3)_2\ (aq)$

(a) Which reactant is limiting?

(b) How many grams of Ag form?

(c) How many grams of $Zn(NO_3)_2$ form?

(d) How many grams of the excess reactant are left at the end of the reaction?

Theoretical and Percent Yields

$$\text{Percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

Adipic acid, $H_2C_6H_8O_4$, used to produce nylon, is made commercially by a reaction between cyclohexane (C_6H_{12}) and O_2:

$$2\ C_6H_{12}\ (l) + 5\ O_2\ (g) \rightarrow H_2C_6H_8O_4\ (l) + 2\ H_2O\ (g)$$

(a) Assume that you carry out this reaction with 25.0 g of cyclohexane and that cyclohexane is the limiting reactant. What is the theoretical yield of adipic acid?

(b) If you obtain 33.5 g of adipic acid, what is the percent yield for the reaction?

(a) The theoretical yield is

$$\text{Grams } H_2C_6H_8O_4 = (25.0\ \text{g } C_6H_{12})\left(\frac{1\ \text{mol } C_6H_{12}}{84.0\ \text{g } C_6H_{12}}\right)\left(\frac{2\ \text{mol } H_2C_6H_8O_4}{2\ \text{mol } C_6H_{12}}\right)\left(\frac{146.0\ \text{g } H_2C_6H_8O_4}{1\ \text{mol } H_2C_6H_8O_4}\right)$$

$$= 43.5\ \text{g } H_2C_6H_8O_4$$

(b) $$\text{Percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\% = \frac{33.5\ \text{g}}{43.5\ \text{g}} \times 100\% = 77.0\%$$

PRACTICE

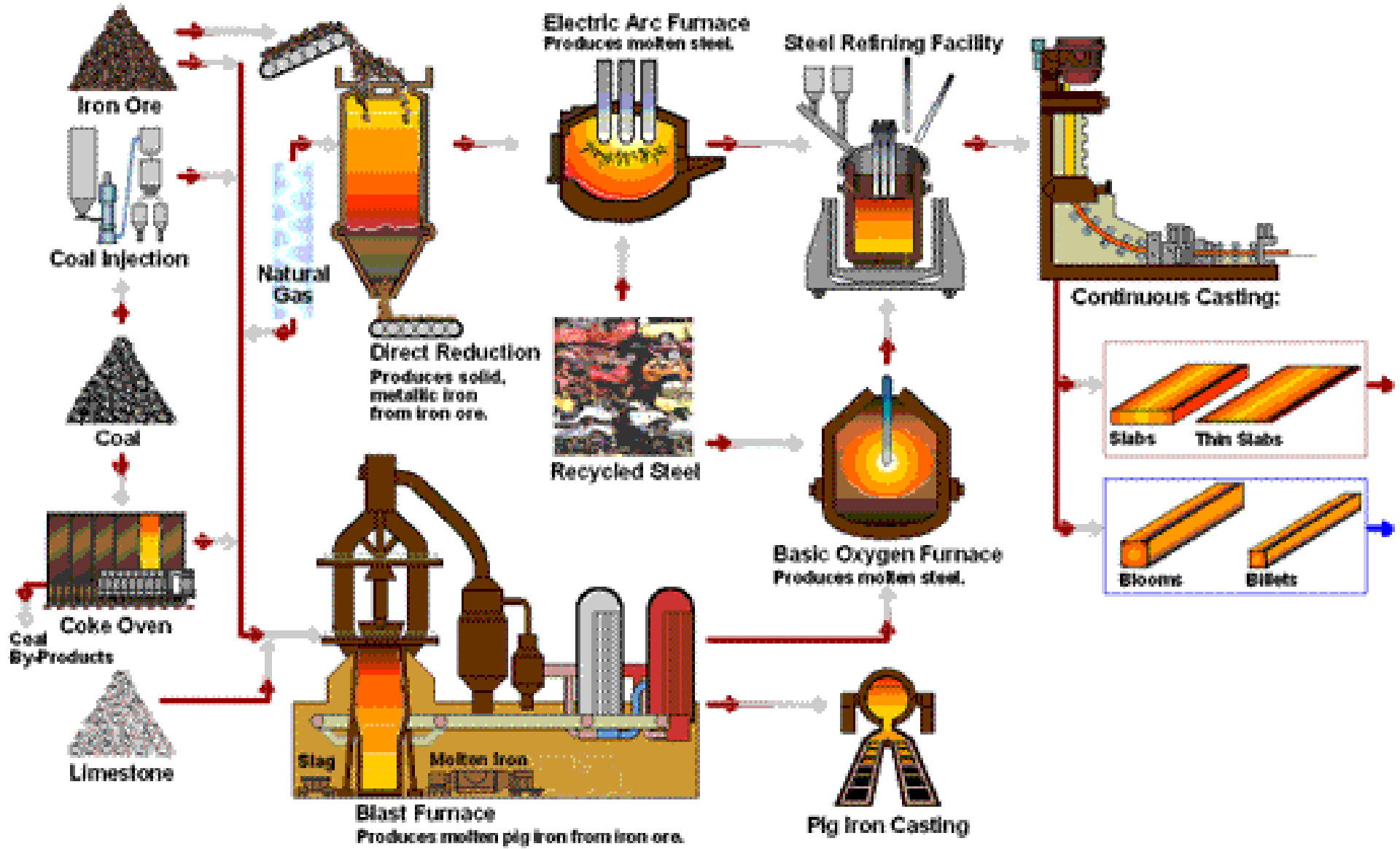
1. If 3.00 g of titanium metal is reacted with 6.00 g of chlorine gas, Cl_2, to form 7.7 g of titanium (IV) chloride in a combination reaction, what is the percent yield of the product?

(a) 65%,

(b) 96%,

(c) 48%,

(d) 86%.


Iron Ore
Coal Injection
Natural Gas
Direct Reduction
Produces solid, metallic iron from iron ore.
Electric Arc Furnace
Produces molten steel.
Steel Refining Facility
Continuous Casting:
Slabs
Thin Slabs
Blooms
Billets
Recycled Steel
Basic Oxygen Furnace
Produces molten steel.
Coal
Coke Oven
Coal By-Products
Limestone
Slag
Molten Iron
Blast Furnace
Produces molten pig iron from iron ore.
Pig Iron Casting

PRACTICE

2. Imagine you are working on ways to improve the process by which iron ore containing Fe_2O_3 is converted into iron:

Fe_2O_3 (s) + cCO (g) → 2Fe (s) + $3CO_2$ (g)

(a) If you start with 150 g of Fe_2O_3 as the limiting reactant, what is the theoretical yield of Fe?

(b) If your actual yield is 87.9 g, what is the percent yield?

Homeworks

Excercises:

3.5

3.13

3.21

3.23

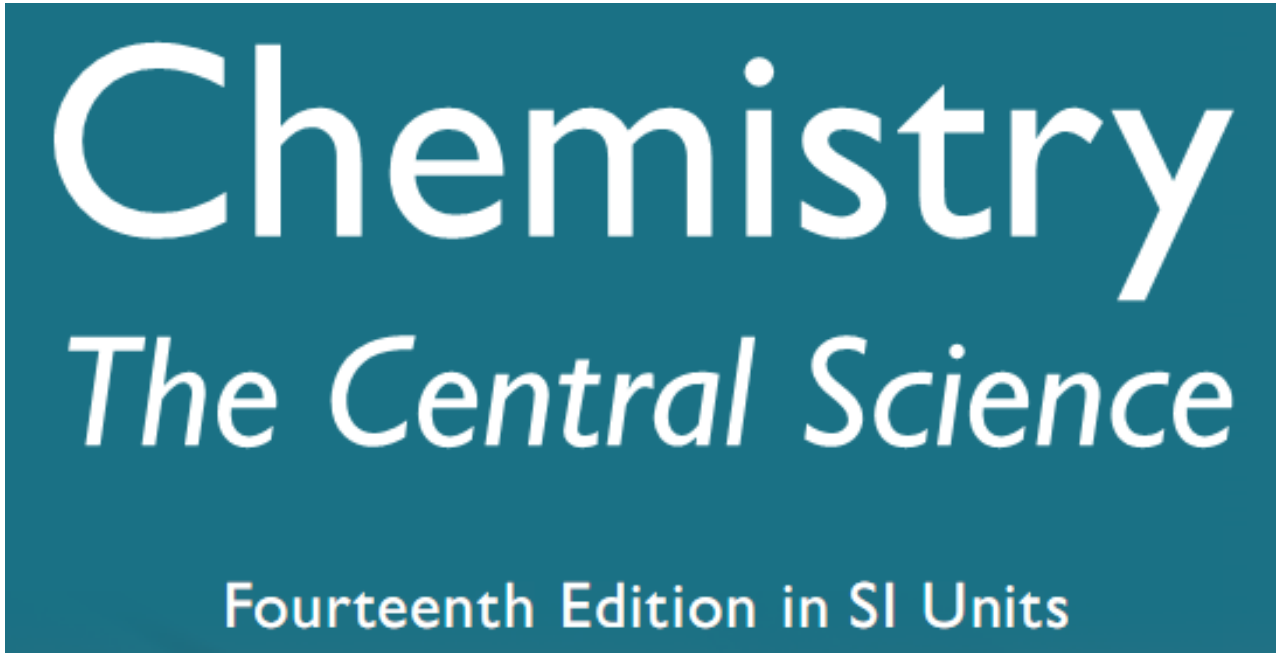
3.37

3.51

3.63

3.81

3.91



You will have a quiz next week

What are allowed?

- A pen
- A periodic table
- An A4-sized sheet of hand written notes
- A calculator

No other devices are allowed!