

*Chapter 3*

# Mass Relationships in Chemical Reactions



NASA

# Atomic mass

Micro World  
atoms & molecules



Macro World  
grams

**Atomic mass** is the mass of an atom in atomic mass units (**amu**)

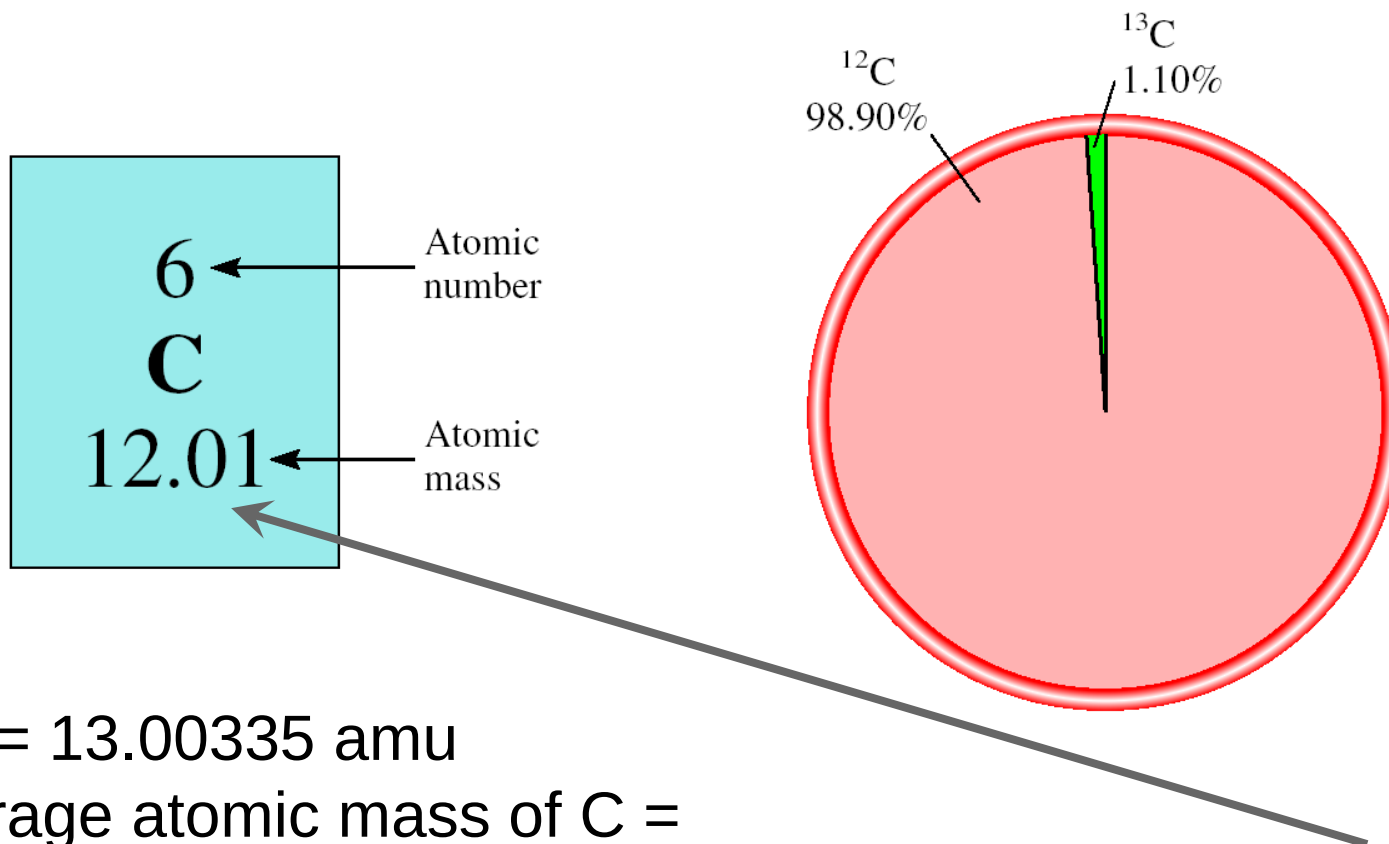
**amu** definition: the mass exactly equal to **1/12** the mass of one  $^{12}\text{C}$  atom

$$^{12}\text{C} = 6p, 6n = 12.00 \text{ amu} \quad m_{e^-} = 0$$

**Experiment** shows one atom  $^1\text{H} = 8.400\%$  of  $^{12}\text{C}$  atom thus; mass of one atom  $^1\text{H} = 1.008 \text{ amu}$   
( $12.00 \times .08400$ )

$$^{16}\text{O} = 16.00 \text{ amu}, \quad ^{26}\text{Fe} = 55.85 \text{ amu}$$

The ***average atomic mass*** is the weighted average of all the naturally occurring isotopes of the element.



$$^{13}\text{C} = 13.00335 \text{ amu}$$

average atomic mass of C =

$$(0.9890 \times 12.00000 \text{ amu}) + (0.0110 \times 13.00335) = \mathbf{12.01 \text{ amu}}$$

Naturally occurring lithium is:

7.42%  ${}^6\text{Li}$  (6.015 amu)

92.58%  ${}^7\text{Li}$  (7.016 amu)

***Average atomic mass*** of lithium:

$$\frac{(7.42 \times 6.015) + (92.58 \times 7.016)}{100} = 6.941 \text{ amu}$$

## EXAMPLE 3.1

Copper, a metal known since ancient times, is used in electrical cables and pennies, among other things. The atomic masses of its two stable isotopes,  $^{63}_{29}\text{Cu}$  (69.09 percent) and  $^{65}_{29}\text{Cu}$  (30.91 percent), are 62.93 amu and 64.9278 amu, respectively. Calculate the average atomic mass of copper. The relative abundances are given in parentheses.

**Strategy** Each isotope contributes to the average atomic mass based on its relative abundance. Multiplying the mass of an isotope by its fractional abundance (not percent) will give the contribution to the average atomic mass of that particular isotope.

**Solution** First the percents are converted to fractions: 69.09 percent to 69.09/100 or 0.6909 and 30.91 percent to 30.91/100 or 0.3091. We find the contribution to the average atomic mass for each isotope, then add the contributions together to obtain the average atomic mass.

$$(0.6909)(62.93 \text{ amu}) + (0.3091)(64.9278 \text{ amu}) = 63.55 \text{ amu}$$

|                                      |                                       |                                       |                                            |                                      |                                         |                                       |                                       |                                         |                                           |                                          |                                     |                                      |                                       |                                       |                                       |                                      |                                     |  |
|--------------------------------------|---------------------------------------|---------------------------------------|--------------------------------------------|--------------------------------------|-----------------------------------------|---------------------------------------|---------------------------------------|-----------------------------------------|-------------------------------------------|------------------------------------------|-------------------------------------|--------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|--------------------------------------|-------------------------------------|--|
| 1A                                   |                                       |                                       |                                            |                                      |                                         |                                       |                                       |                                         |                                           |                                          |                                     |                                      |                                       |                                       |                                       |                                      | 18A                                 |  |
| 1<br><b>H</b><br>Hydrogen<br>1.008   | 2<br>2A                               |                                       |                                            |                                      |                                         |                                       |                                       |                                         |                                           |                                          |                                     | 13<br>3A                             | 14<br>4A                              | 15<br>5A                              | 16<br>6A                              | 17<br>7A                             | 2<br><b>He</b><br>Helium<br>4.003   |  |
| 3<br><b>Li</b><br>Lithium<br>6.941   | 4<br><b>Be</b><br>Beryllium<br>9.012  |                                       |                                            |                                      |                                         |                                       |                                       |                                         |                                           |                                          |                                     | 5<br><b>B</b><br>Boron<br>10.81      | 6<br><b>C</b><br>Carbon<br>12.01      | 7<br><b>N</b><br>Nitrogen<br>14.01    | 8<br><b>O</b><br>Oxygen<br>16.00      | 9<br><b>F</b><br>Fluorine<br>19.00   | 10<br><b>Ne</b><br>Neon<br>20.18    |  |
| 11<br><b>Na</b><br>Sodium<br>22.99   | 12<br><b>Mg</b><br>Magnesium<br>24.31 | 3<br>3B                               | 4<br>4B                                    | 5<br>5B                              | 6<br>6B                                 | 7<br>7B                               | 8<br>8B                               | 9<br>8B                                 | 10<br>8B                                  | 11<br>1B                                 | 12<br>2B                            | 13<br><b>Al</b><br>Aluminum<br>26.98 | 14<br><b>Si</b><br>Silicon<br>28.09   | 15<br><b>P</b><br>Phosphorus<br>30.97 | 16<br><b>S</b><br>Sulfur<br>32.07     | 17<br><b>Cl</b><br>Chlorine<br>35.45 | 18<br><b>Ar</b><br>Argon<br>39.95   |  |
| 19<br><b>K</b><br>Potassium<br>39.10 | 20<br><b>Ca</b><br>Calcium<br>40.08   | 21<br><b>Sc</b><br>Scandium<br>44.96  | 22<br><b>Ti</b><br>Titanium<br>47.88       | 23<br><b>V</b><br>Vanadium<br>50.94  | 24<br><b>Cr</b><br>Chromium<br>52.00    | 25<br><b>Mn</b><br>Manganese<br>54.94 | 26<br><b>Fe</b><br>Iron<br>55.85      | 27<br><b>Co</b><br>Cobalt<br>58.93      | 28<br><b>Ni</b><br>Nickel<br>58.69        | 29<br><b>Cu</b><br>Copper<br>63.55       | 30<br><b>Zn</b><br>Zinc<br>65.39    | 31<br><b>Ga</b><br>Gallium<br>69.72  | 32<br><b>Ge</b><br>Germanium<br>72.59 | 33<br><b>As</b><br>Arsenic<br>74.92   | 34<br><b>Se</b><br>Selenium<br>78.96  | 35<br><b>Br</b><br>Bromine<br>79.90  | 36<br><b>Kr</b><br>Krypton<br>83.80 |  |
| 37<br><b>Rb</b><br>Rubidium<br>85.47 | 38<br><b>Sr</b><br>Strontium<br>87.62 | 39<br><b>Y</b><br>Yttrium<br>88.91    | 40<br><b>Zr</b><br>Zirconium<br>91.22      | 41<br><b>Nb</b><br>Niobium<br>92.91  | 42<br><b>Mo</b><br>Molybdenum<br>95.94  | 43<br><b>Tc</b><br>Technetium<br>(98) | 44<br><b>Ru</b><br>Ruthenium<br>101.1 | 45<br><b>Rh</b><br>Rhodium<br>102.9     | 46<br><b>Pd</b><br>Palladium<br>106.4     | 47<br><b>Ag</b><br>Silver<br>107.9       | 48<br><b>Cd</b><br>Cadmium<br>112.4 | 49<br><b>In</b><br>Indium<br>114.8   | 50<br><b>Sn</b><br>Tin<br>118.7       | 51<br><b>Sb</b><br>Antimony<br>121.8  | 52<br><b>Te</b><br>Tellurium<br>127.6 | 53<br><b>I</b><br>Iodine<br>126.9    | 54<br><b>Xe</b><br>Xenon<br>131.3   |  |
| 55<br><b>Cs</b><br>Cesium<br>132.9   | 56<br><b>Ba</b><br>Barium<br>137.3    | 57<br><b>La</b><br>Lanthanum<br>138.9 | 72<br><b>Hf</b><br>Hafnium<br>178.5        | 73<br><b>Ta</b><br>Tantalum<br>180.9 | 74<br><b>W</b><br>Tungsten<br>183.9     | 75<br><b>Re</b><br>Rhenium<br>186.2   | 76<br><b>Os</b><br>Osmium<br>190.2    | 77<br><b>Ir</b><br>Iridium<br>192.2     | 78<br><b>Pt</b><br>Platinum<br>195.1      | 79<br><b>Au</b><br>Gold<br>197.0         | 80<br><b>Hg</b><br>Mercury<br>200.6 | 81<br><b>Tl</b><br>Thallium<br>204.4 | 82<br><b>Pb</b><br>Lead<br>207.2      | 83<br><b>Bi</b><br>Bismuth<br>209.0   | 84<br><b>Po</b><br>Polonium<br>(210)  | 85<br><b>At</b><br>Astatine<br>(210) | 86<br><b>Rn</b><br>Radon<br>(222)   |  |
| 87<br><b>Fr</b><br>Francium<br>(223) | 88<br><b>Ra</b><br>Radium<br>(226)    | 89<br><b>Ac</b><br>Actinium<br>(227)  | 104<br><b>Rf</b><br>Rutherfordium<br>(257) | 105<br><b>Db</b><br>Dubnium<br>(260) | 106<br><b>Sg</b><br>Seaborgium<br>(263) | 107<br><b>Bh</b><br>Bohrium<br>(262)  | 108<br><b>Hs</b><br>Hassium<br>(265)  | 109<br><b>Mt</b><br>Meitnerium<br>(266) | 110<br><b>Ds</b><br>Darmstadtium<br>(269) | 111<br><b>Rg</b><br>Roentgenium<br>(272) | 112                                 | 113                                  | 114                                   | 115                                   | 116                                   | (117)                                | 118                                 |  |

10  
**Ne**  
Neon  
20.18

Atomic number

Atomic mass

Average atomic mass (6.941)

10  
**Ne**  
Neon  
20.18

Atomic number

Atomic mass

Average atomic mass (6.941)

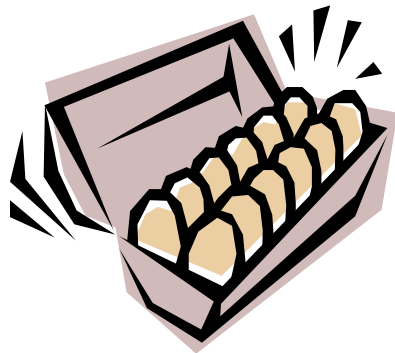
|  |            |
|--|------------|
|  | Metals     |
|  | Metalloids |
|  | Nonmetals  |

|                                     |                                          |                                       |                                        |                                       |                                       |                                        |                                       |                                         |                                         |                                      |                                          |                                       |                                         |
|-------------------------------------|------------------------------------------|---------------------------------------|----------------------------------------|---------------------------------------|---------------------------------------|----------------------------------------|---------------------------------------|-----------------------------------------|-----------------------------------------|--------------------------------------|------------------------------------------|---------------------------------------|-----------------------------------------|
| 58<br><b>Ce</b><br>Cerium<br>140.1  | 59<br><b>Pr</b><br>Praseodymium<br>140.9 | 60<br><b>Nd</b><br>Neodymium<br>144.2 | 61<br><b>Pm</b><br>Promethium<br>(147) | 62<br><b>Sm</b><br>Samarium<br>150.4  | 63<br><b>Eu</b><br>Europium<br>152.0  | 64<br><b>Gd</b><br>Gadolinium<br>157.3 | 65<br><b>Tb</b><br>Terbium<br>158.9   | 66<br><b>Dy</b><br>Dysprosium<br>162.5  | 67<br><b>Ho</b><br>Holmium<br>164.9     | 68<br><b>Er</b><br>Erbium<br>167.3   | 69<br><b>Tm</b><br>Thulium<br>168.9      | 70<br><b>Yb</b><br>Ytterbium<br>173.0 | 71<br><b>Lu</b><br>Lutetium<br>175.0    |
| 90<br><b>Th</b><br>Thorium<br>232.0 | 91<br><b>Pa</b><br>Protactinium<br>(231) | 92<br><b>U</b><br>Uranium<br>238.0    | 93<br><b>Np</b><br>Neptunium<br>(237)  | 94<br><b>Pu</b><br>Plutonium<br>(242) | 95<br><b>Am</b><br>Americium<br>(243) | 96<br><b>Cm</b><br>Curium<br>(247)     | 97<br><b>Bk</b><br>Berkelium<br>(247) | 98<br><b>Cf</b><br>Californium<br>(249) | 99<br><b>Es</b><br>Einsteinium<br>(254) | 100<br><b>Fm</b><br>Fermium<br>(253) | 101<br><b>Md</b><br>Mendelevium<br>(256) | 102<br><b>No</b><br>Nobelium<br>(254) | 103<br><b>Lr</b><br>Lawrencium<br>(257) |

# The Mole

The Mole (mol): A unit to count numbers of particles

Dozen = 12



Pair = 2



The ***mole (mol)*** is the amount of a substance that contains as many elementary entities as there are atoms in exactly 12.00 grams of  $^{12}\text{C}$

$$1 \text{ mol} = N_A = 6.0221367 \times 10^{23}$$

Avogadro's number ( $N_A$ )

***Molar mass*** is the mass of 1 mole of eggs  
shoes  
marbles  
atoms in grams

$$1 \text{ mole } ^{12}\text{C atoms} = 6.022 \times 10^{23} \text{ atoms} = 12.00 \text{ g}$$

$$1 \text{ } ^{12}\text{C atom} = 12.00 \text{ amu}$$

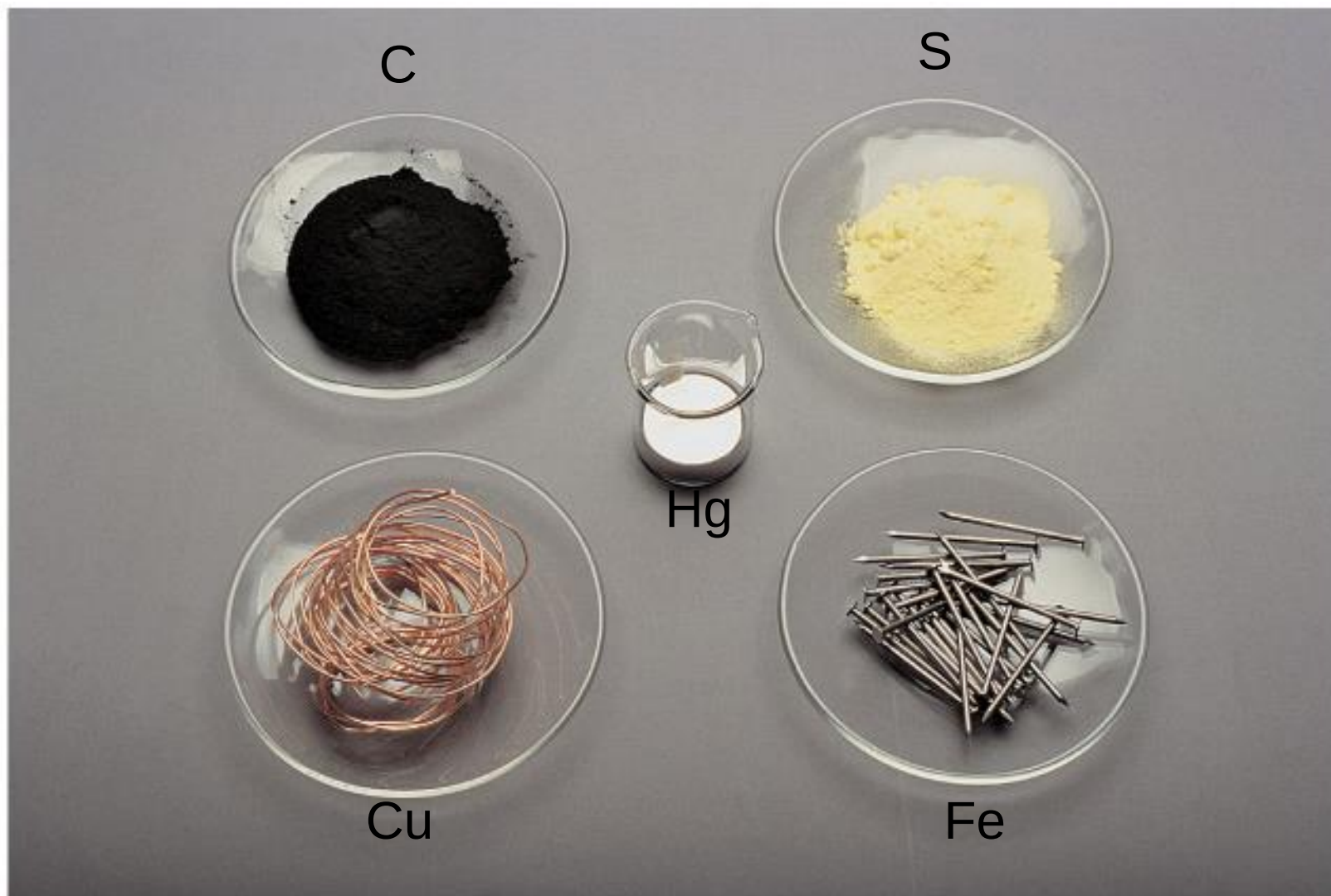
$$1 \text{ mole } ^{12}\text{C atoms} = 12.00 \text{ g } ^{12}\text{C}$$

$$1 \text{ mole lithium atoms} = 6.941 \text{ g of Li}$$

For any element  
atomic mass (amu) = molar mass (grams)



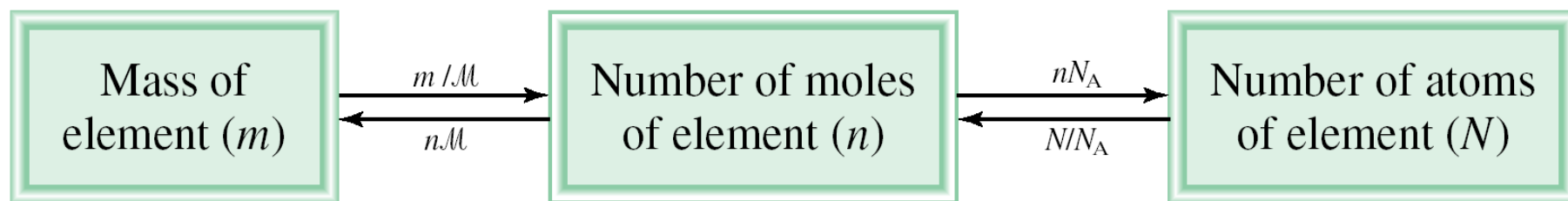
# One Mole of:



# Conversion Between Mass and Atoms

$$\frac{1 \text{ }^{12}\text{C} \text{ atom}}{12.00 \text{ amu}} \times \frac{12.00 \text{ g}}{6.022 \times 10^{23} \text{ }^{12}\text{C} \text{ atoms}} = \frac{1.66 \times 10^{-24} \text{ g}}{1 \text{ amu}}$$

$$1 \text{ amu} = 1.66 \times 10^{-24} \text{ g} \quad \text{or} \quad 1 \text{ g} = 6.022 \times 10^{23} \text{ amu}$$



$M$  = molar mass in (g/mol)

$N_A$  = Avogadro's number

How many atoms are in 0.551 g of potassium (K) ?

$$1 \text{ mol K} = 39.10 \text{ g K}$$

$$1 \text{ mol K} = 6.022 \times 10^{23} \text{ atoms K}$$

$$0.551 \text{ g K} \times \frac{1 \text{ mol K}}{39.10 \text{ g K}} \times \frac{6.022 \times 10^{23} \text{ atoms K}}{1 \text{ mol K}} =$$

$$8.49 \times 10^{21} \text{ atoms K}$$

## EXAMPLE 3.2

Helium (He) is a valuable gas used in industry, low-temperature research, deep-sea diving tanks, and balloons. How many moles of He atoms are in 6.46 g of He?

**Solution** The conversion factor needed to convert between grams and moles is the molar mass. In the periodic table (see inside front cover) we see that the molar mass of He is 4.003 g. This can be expressed as

$$1 \text{ mol He} = 4.003 \text{ g He}$$

From this equality, we can write two conversion factors

$$\frac{1 \text{ mol He}}{4.003 \text{ g He}} \quad \text{and} \quad \frac{4.003 \text{ g He}}{1 \text{ mol He}}$$

The conversion factor on the left is the correct one. Grams will cancel, leaving the unit mol for the answer, that is,

$$6.46 \text{ g He} \times \frac{1 \text{ mol He}}{4.003 \text{ g He}} = 1.61 \text{ mol He}$$

Thus, there are 1.61 moles of He atoms in 6.46 g of He.

### EXAMPLE 3.3

Zinc (Zn) is a silvery metal that is used in making brass (with copper) and in plating iron to prevent corrosion. How many grams of Zn are in 0.356 mole of Zn?

**Solution** The conversion factor needed to convert between moles and grams is the molar mass. In the periodic table (see inside front cover) we see the molar mass of Zn is 65.39 g. This can be expressed as

$$1 \text{ mol Zn} = 65.39 \text{ g Zn}$$

From this equality, we can write two conversion factors

$$\frac{1 \text{ mol Zn}}{65.39 \text{ g Zn}} \quad \text{and} \quad \frac{65.39 \text{ g Zn}}{1 \text{ mol Zn}}$$

The conversion factor on the right is the correct one. Moles will cancel, leaving unit of grams for the answer. The number of grams of Zn is

$$0.356 \cancel{\text{ mol Zn}} \times \frac{65.39 \text{ g Zn}}{1 \cancel{\text{ mol Zn}}} = 23.3 \text{ g Zn}$$

Thus, there are 23.3 g of Zn in 0.356 mole of Zn.

### EXAMPLE 3.4

Sulfur (S) is a nonmetallic element that is present in coal. When coal is burned, sulfur is converted to sulfur dioxide and eventually to sulfuric acid that gives rise to the acid rain phenomenon. How many atoms are in 16.3 g of S?

**Solution** We need two conversions: first from grams to moles and then from moles to number of particles (atoms). The first step is similar to Example 3.2. Because

$$1 \text{ mol S} = 32.07 \text{ g S}$$

the conversion factor is

$$\frac{1 \text{ mol S}}{32.07 \text{ g S}}$$

Avogadro's number is the key to the second step. We have

$$1 \text{ mol} = 6.022 \times 10^{23} \text{ particles (atoms)}$$

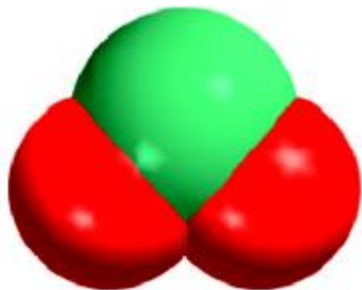
and the conversion factors are

$$\frac{6.022 \times 10^{23} \text{ S atoms}}{1 \text{ mol S}} \quad \text{and} \quad \frac{1 \text{ mol S}}{6.022 \times 10^{23} \text{ S atoms}}$$

$$16.3 \text{ g S} \times \frac{1 \text{ mol S}}{32.07 \text{ g S}} \times \frac{6.022 \times 10^{23} \text{ S atoms}}{1 \text{ mol S}} = 3.06 \times 10^{23} \text{ S atoms}$$

# Molecular Mass

**Molecular mass** (or molecular weight) is the sum of the atomic masses (in amu) in a molecule.



$$\begin{array}{rcl} 1\text{S} & & 32.07 \text{ amu} \\ 2\text{O} & + (2 \times 16.00 \text{ amu}) & \\ \hline \text{SO}_2 & & 64.07 \text{ amu} \end{array}$$

For any molecule  
molecular mass (amu) = molar mass (grams)

$$1 \text{ molecule SO}_2 = 64.07 \text{ amu}$$

$$1 \text{ mole SO}_2 = 64.07 \text{ g SO}_2$$

### EXAMPLE 3.6

Methane ( $\text{CH}_4$ ) is the principal component of natural gas. How many moles of  $\text{CH}_4$  are present in 6.07 g of  $\text{CH}_4$ ?

**Solution** The conversion factor needed to convert between grams and moles is the molar mass. First we need to calculate the molar mass of  $\text{CH}_4$ , following the procedure in Example 3.5:

$$\begin{aligned}\text{molar mass of CH}_4 &= 12.01 \text{ g} + 4(1.008 \text{ g}) \\ &= 16.04 \text{ g}\end{aligned}$$

Because

$$1 \text{ mol CH}_4 = 16.04 \text{ g CH}_4$$

the conversion factor we need should have grams in the denominator so that the unit g will cancel, leaving the unit mol in the numerator:

$$\frac{1 \text{ mol CH}_4}{16.04 \text{ g CH}_4}$$

We now write

$$6.07 \text{ g } \cancel{\text{CH}_4} \times \frac{1 \text{ mol CH}_4}{16.04 \text{ g } \cancel{\text{CH}_4}} = 0.378 \text{ mol CH}_4$$

Thus, there is 0.378 mole of  $\text{CH}_4$  in 6.07 g of  $\text{CH}_4$ .



How many H atoms are in 72.5 g of C<sub>3</sub>H<sub>8</sub>O?

$$1 \text{ mol C}_3\text{H}_8\text{O} = (3 \times 12) + (8 \times 1) + 16 = 60 \text{ g C}_3\text{H}_8\text{O}$$

$$1 \text{ mol C}_3\text{H}_8\text{O molecules} = 8 \text{ mol H atoms}$$

$$1 \text{ mol H} = 6.022 \times 10^{23} \text{ atoms H}$$

$$72.5 \text{ g C}_3\text{H}_8\text{O} \times \frac{1 \text{ mol C}_3\text{H}_8\text{O}}{60 \text{ g C}_3\text{H}_8\text{O}} \times \frac{8 \text{ mol H atoms}}{1 \text{ mol C}_3\text{H}_8\text{O}} \times \frac{6.022 \times 10^{23} \text{ H atoms}}{1 \text{ mol H atoms}} =$$

$$\mathbf{5.82 \times 10^{24} \text{ atoms H}}$$

## EXAMPLE 3.7

How many hydrogen atoms are present in 25.6 g of urea  $[(\text{NH}_2)_2\text{CO}]$ , which is used as a fertilizer, in animal feed, and in the manufacture of polymers? The molar mass of urea is 60.06 g.

**Solution** To calculate the number of H atoms, we first must convert grams of urea to moles of urea using the molar mass of urea. This part is similar to Example 3.2. The molecular formula of urea shows there are four moles of H atoms in one mole of urea molecule, so the mole ratio is 4:1. Finally, knowing the number of moles of H atoms, we can calculate the number of H atoms using Avogadro's number. We need two conversion factors: molar mass and Avogadro's number. We can combine these conversions

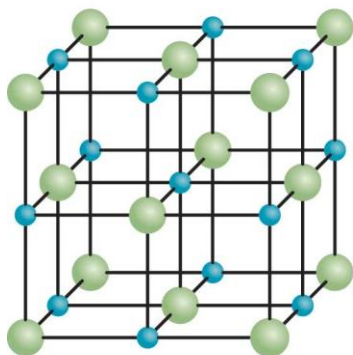
grams of urea  $\longrightarrow$  moles of urea  $\longrightarrow$  moles of H  $\longrightarrow$  atoms of H

into one step:

$$25.6 \text{ g } (\text{NH}_2)_2\text{CO} \times \frac{1 \text{ mol } (\text{NH}_2)_2\text{CO}}{60.06 \text{ g } (\text{NH}_2)_2\text{CO}} \times \frac{4 \text{ mol H}}{1 \text{ mol } (\text{NH}_2)_2\text{CO}} \times \frac{6.022 \times 10^{23} \text{ H atoms}}{1 \text{ mol H}} = 1.03 \times 10^{24} \text{ H atoms}$$

# Formula Mass

**Formula mass** is the sum of the atomic masses (in amu) in a formula unit of an ionic compound.



|      |      |                   |
|------|------|-------------------|
|      | 1 Na | 22.99 amu         |
| NaCl | 1 Cl | <u>+35.45 amu</u> |
| NaCl |      | 58.44 amu         |

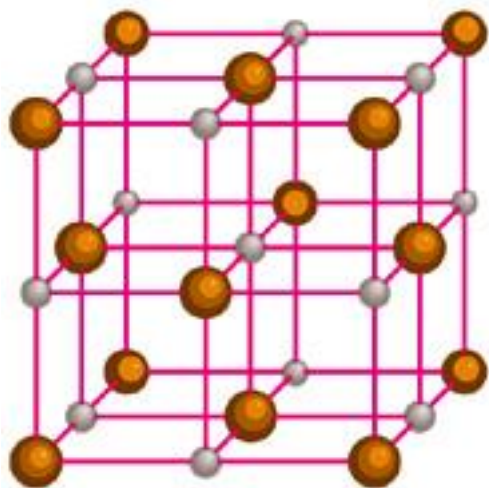
For any ionic compound

formula mass (amu) = molar mass (grams)

1 formula unit NaCl = 58.44 amu

1 mole NaCl = 58.44 g NaCl

**Formula mass** is the sum of the atomic masses (in amu) in a formula unit of an ionic compound.



Cl

$$\begin{array}{r} 22.99 \text{ amu} \\ 1\text{Cl} \quad + \quad 35.45 \text{ amu} \\ \hline \text{NaCl} \quad 58.44 \text{ amu} \end{array}$$

For any ionic compound  
formula mass (amu) = molar mass (grams)

1 formula unit NaCl = 58.44 amu

1 mole NaCl = 58.44 g NaCl

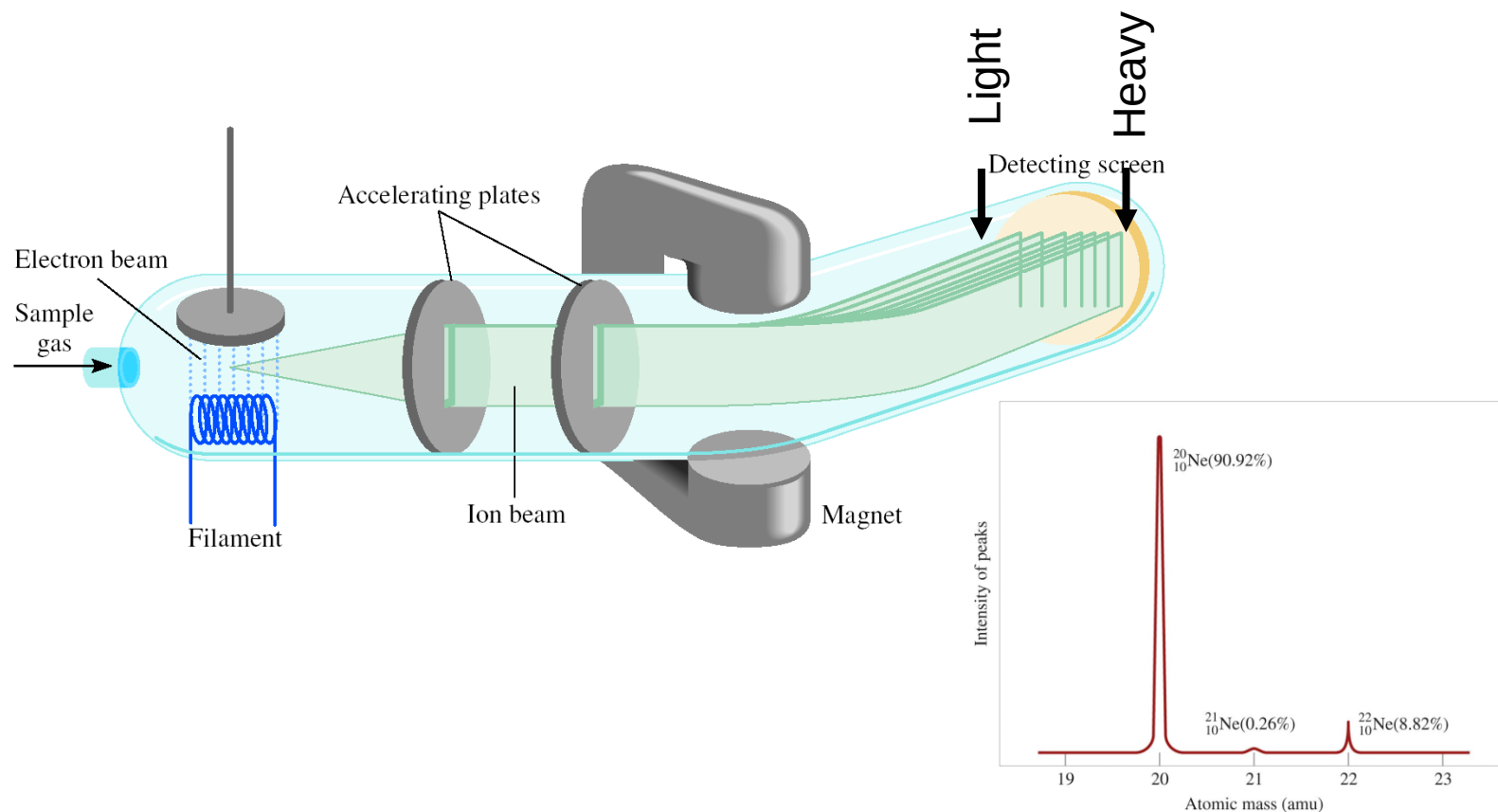
What is the formula mass of  $\text{Ca}_3(\text{PO}_4)_2$ ?

1 formula unit of  $\text{Ca}_3(\text{PO}_4)_2$

|      |             |            |
|------|-------------|------------|
| 3 Ca | 3 x 40.08   |            |
| 2 P  | 2 x 30.97   |            |
| 8 O  | + 8 x 16.00 |            |
|      | <hr/>       |            |
|      |             | 310.18 amu |

# Mass Spectrometer

The most direct and most accurate method for determining atomic and molecular masses is mass spectrometry

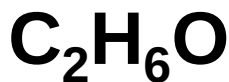
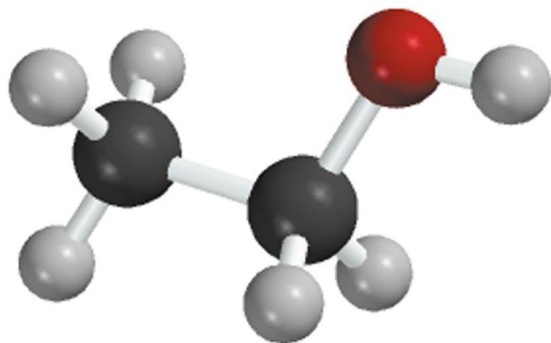


Mass Spectrum of Ne

**Percent composition** of an element in a compound =

$$\frac{n \times \text{molar mass of element}}{\text{molar mass of compound}} \times 100\%$$

***n*** is the number of moles of the element in **1 mole** of the compound



$$\%C = \frac{2 \times (12.01 \text{ g})}{46.07 \text{ g}} \times 100\% = 52.14\%$$

$$\%H = \frac{6 \times (1.008 \text{ g})}{46.07 \text{ g}} \times 100\% = 13.13\%$$

$$\%O = \frac{1 \times (16.00 \text{ g})}{46.07 \text{ g}} \times 100\% = 34.73\%$$

$$52.14\% + 13.13\% + 34.73\% = \mathbf{100.0\%}$$

## Examples

What is the mass of H ,Cl in 10 g HCl?

What is % composition of the elements C in  $\text{CH}_3\text{COOH}$ ?

What is % composition of the elements in 25.00 g  $\text{H}_2\text{SO}_4$   
if  $m_{\text{H}} = 0.5142$  g and  $m_{\text{O}} = 16.3239$  g and  $m_{\text{S}} = 8.1619$  g ?



# Percent Composition and Empirical Formulas

Mass  
percent

↓  
Convert to grams and  
divide by molar mass

Moles of  
each element

↓  
Divide by the smallest  
number of moles

Mole ratios  
of elements

↓  
Change to  
integer subscripts

Empirical  
formula

Determine the empirical formula of a compound that has the following percent composition by mass:  
K 24.75, Mn 34.77, O 40.51 percent.

$$n_{\text{K}} = 24.75 \text{ g K} \times \frac{1 \text{ mol K}}{39.10 \text{ g K}} = 0.6330 \text{ mol K}$$

$$n_{\text{Mn}} = 34.77 \text{ g Mn} \times \frac{1 \text{ mol Mn}}{54.94 \text{ g Mn}} = 0.6329 \text{ mol Mn}$$

$$n_{\text{O}} = 40.51 \text{ g O} \times \frac{1 \text{ mol O}}{16.00 \text{ g O}} = 2.532 \text{ mol O}$$

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Empirical  
formula

$$n_{\text{K}} = 0.6330, n_{\text{Mn}} = 0.6329, n_{\text{O}} = 2.532$$

$$\text{K} : \frac{0.6330}{0.6329} \approx 1.0$$

$$\text{Mn} : \frac{0.6329}{0.6329} = 1.0$$

$$\text{O} : \frac{2.532}{0.6329} \approx 4.0$$



### EXAMPLE 3.9

Ascorbic acid (vitamin C) cures scurvy. It is composed of 40.92 percent carbon (C), 4.58 percent hydrogen (H), and 54.50 percent oxygen (O) by mass. Determine its empirical formula.

#### Solution

$$n_{\text{C}} = 40.92 \text{ g } \cancel{\text{C}} \times \frac{1 \text{ mol C}}{12.01 \text{ g } \cancel{\text{C}}} = 3.407 \text{ mol C}$$

$$n_{\text{H}} = 4.58 \text{ g } \cancel{\text{H}} \times \frac{1 \text{ mol H}}{1.008 \text{ g } \cancel{\text{H}}} = 4.54 \text{ mol H}$$

$$n_{\text{O}} = 54.50 \text{ g } \cancel{\text{O}} \times \frac{1 \text{ mol O}}{16.00 \text{ g } \cancel{\text{O}}} = 3.406 \text{ mol O}$$

$$\text{C: } \frac{3.407}{3.406} \approx 1 \quad \text{H: } \frac{4.54}{3.406} = 1.33 \quad \text{O: } \frac{3.406}{3.406} = 1$$

$$1.33 \times 1 = 1.33$$

$$1.33 \times 2 = 2.66$$

$$1.33 \times 3 = 3.99 \approx 4$$

Because  $1.33 \times 3$  gives us an integer (4), we multiply all the subscripts by 3 and obtain  $\text{C}_3\text{H}_4\text{O}_3$  as the empirical formula for ascorbic acid.

## EXAMPLE 3.10

Chalcopyrite ( $\text{CuFeS}_2$ ) is a principal mineral of copper. Calculate the number of kilograms of Cu in  $3.71 \times 10^3$  kg of chalcopyrite.

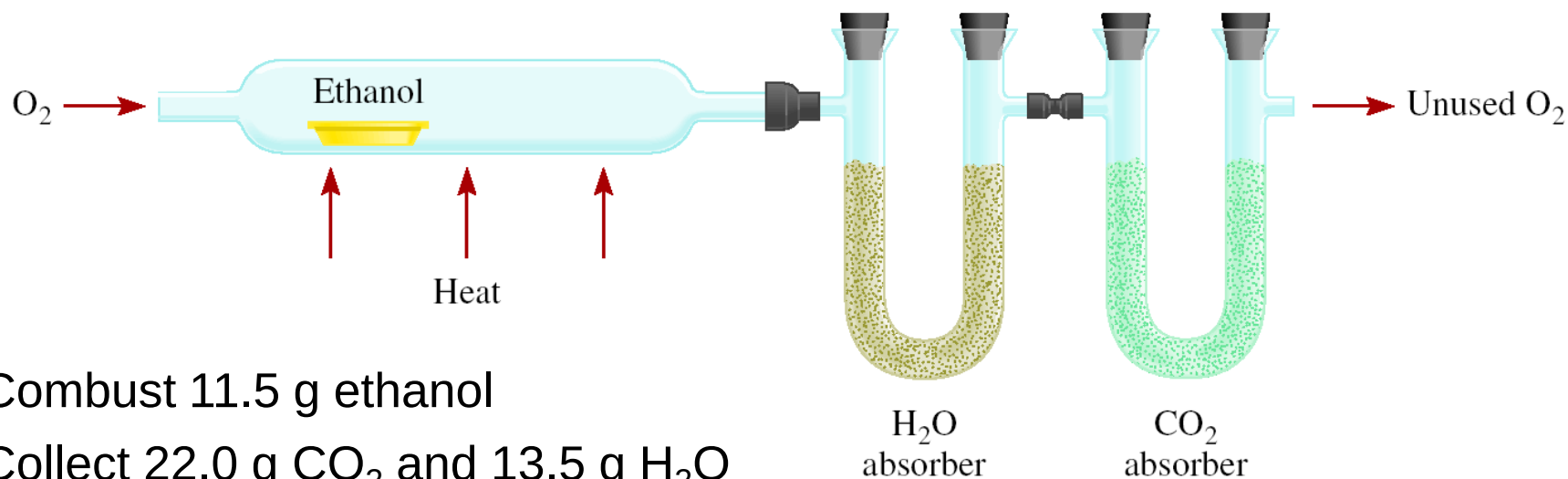
**Strategy** Chalcopyrite is composed of Cu, Fe, and S. The mass due to Cu is based on its percentage by mass in the compound. How do we calculate mass percent of an element?

**Solution** The molar masses of Cu and  $\text{CuFeS}_2$  are 63.55 g and 183.5 g, respectively. The mass percent of Cu is therefore

$$\begin{aligned}\% \text{Cu} &= \frac{\text{molar mass of Cu}}{\text{molar mass of CuFeS}_2} \times 100\% \\ &= \frac{63.55 \text{ g}}{183.5 \text{ g}} \times 100\% = 34.63\%\end{aligned}$$

To calculate the mass of Cu in a  $3.71 \times 10^3$  kg sample of  $\text{CuFeS}_2$ , we need to convert the percentage to a fraction (that is, convert 34.63 percent to 34.63/100, or 0.3463) and write

$$\text{mass of Cu in CuFeS}_2 = 0.3463 \times (3.71 \times 10^3 \text{ kg}) = 1.28 \times 10^3 \text{ kg}$$



Combust 11.5 g ethanol

Collect 22.0 g CO<sub>2</sub> and 13.5 g H<sub>2</sub>O

g CO<sub>2</sub>  $\longrightarrow$  mol CO<sub>2</sub>  $\longrightarrow$  mol C  $\longrightarrow$  g C    6.0 g C = 0.5 mol C

g H<sub>2</sub>O  $\longrightarrow$  mol H<sub>2</sub>O  $\longrightarrow$  mol H  $\longrightarrow$  g H    1.5 g H = 1.5 mol H

g of O = g of sample – (g of C + g of H)    4.0 g O = 0.25 mol O

Empirical formula C<sub>0.5</sub>H<sub>1.5</sub>O<sub>0.25</sub>

Divide by smallest subscript (0.25)

**Empirical formula C<sub>2</sub>H<sub>6</sub>O**

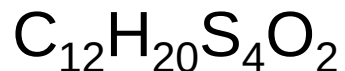
# Molecular Formulas

Molecular weight of the compound should be known

$$X = \frac{\mathcal{M}_{\text{actual}}}{\mathcal{M}_{\text{empirical}}}$$

Multiply the empirical formula by the integer x

A compound has empirical formula  $\text{C}_6\text{H}_{10}\text{S}_2\text{O}$  but its molecular weight is 324 g/mol !



Calculate the number of grams of Al in 371 g of  $\text{Al}_2\text{O}_3$ ?

196.5 g

### EXAMPLE 3.11

A sample of a compound contains 1.52 g of nitrogen (N) and 3.47 g of oxygen (O). The molar mass of this compound is between 90 g and 95 g. Determine the molecular formula and the accurate molar mass of the compound.

**Solution** We are given grams of N and O. Use molar mass as a conversion factor to convert grams to moles of each element. Let  $n$  represent the number of moles of each element. We write

$$n_{\text{N}} = 1.52 \text{ g N} \times \frac{1 \text{ mol N}}{14.01 \text{ g N}} = 0.108 \text{ mol N}$$
$$n_{\text{O}} = 3.47 \text{ g O} \times \frac{1 \text{ mol O}}{16.00 \text{ g O}} = 0.217 \text{ mol O}$$

Thus, we arrive at the formula  $\text{N}_{0.108}\text{O}_{0.217}$ , which gives the identity and the ratios of atoms present. However, chemical formulas are written with whole numbers. Try to convert to whole numbers by dividing the subscripts by the smaller subscript (0.108). After rounding off, we obtain  $\text{NO}_2$  as the empirical formula.

$$\text{empirical molar mass} = 14.01 \text{ g} + 2(16.00 \text{ g}) = 46.01 \text{ g}$$

Next, we determine the ratio between the molar mass and the empirical molar mass

$$\frac{\text{molar mass}}{\text{empirical molar mass}} = \frac{90 \text{ g}}{46.01 \text{ g}} \approx 2$$

The molar mass is twice the empirical molar mass. This means that there are two  $\text{NO}_2$  units in each molecule of the compound, and the molecular formula is  $(\text{NO}_2)_2$  or  $\text{N}_2\text{O}_4$ .

The actual molar mass of the compound is two times the empirical molar mass, that is,  $2(46.01 \text{ g})$  or  $92.02 \text{ g}$ , which is between 90 g and 95 g.

# Chemical Reaction

A process in which one or more substances is changed into one or more new substances is a **chemical reaction**

A **chemical equation** uses chemical symbols to show what happens during a chemical reaction

reactants  $\longrightarrow$  products

3 ways of representing the reaction of  $\text{H}_2$  with  $\text{O}_2$  to form  $\text{H}_2\text{O}$

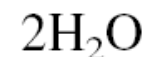
Two hydrogen molecules + One oxygen molecule  $\longrightarrow$  Two water molecules



+



$\longrightarrow$



+



$\longrightarrow$





# How to “Read” Chemical Equations



2 atoms Mg + 1 molecule O<sub>2</sub> makes 2 formula units MgO

2 moles Mg + 1 mole O<sub>2</sub> makes 2 moles MgO

48.6 grams Mg + 32.0 grams O<sub>2</sub> makes 80.6 g MgO

**NOT**

~~2 grams Mg + 1 gram O<sub>2</sub> makes 2 g MgO~~

# Balancing Chemical Equations

1. Write the **correct** formula(s) for the reactants on the left side and the **correct** formula(s) for the product(s) on the right side of the equation.

Ethane reacts with oxygen to form carbon dioxide and water

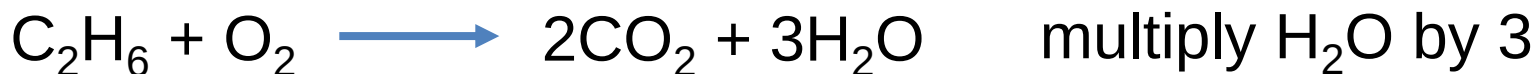
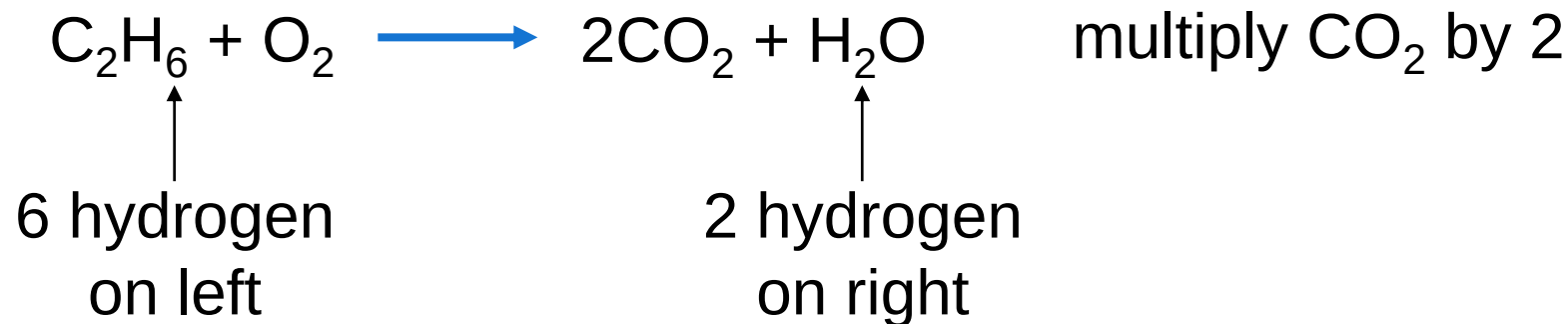
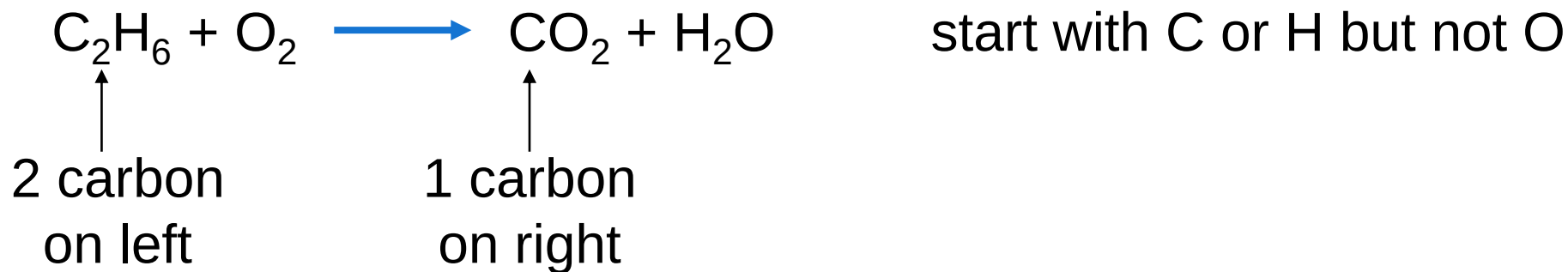


2. Change the numbers in front of the formulas (***coefficients***) to make the number of atoms of each element the same on both sides of the equation. Do not change the subscripts.



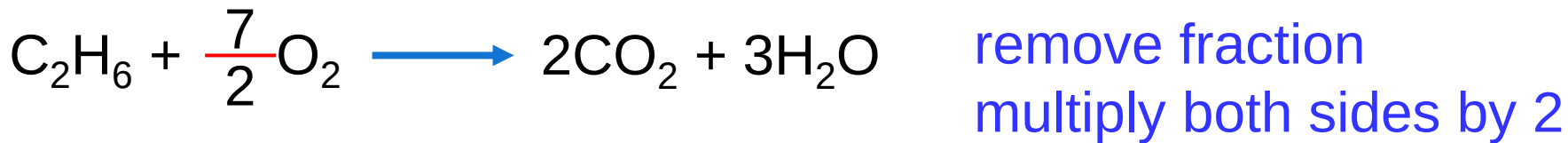
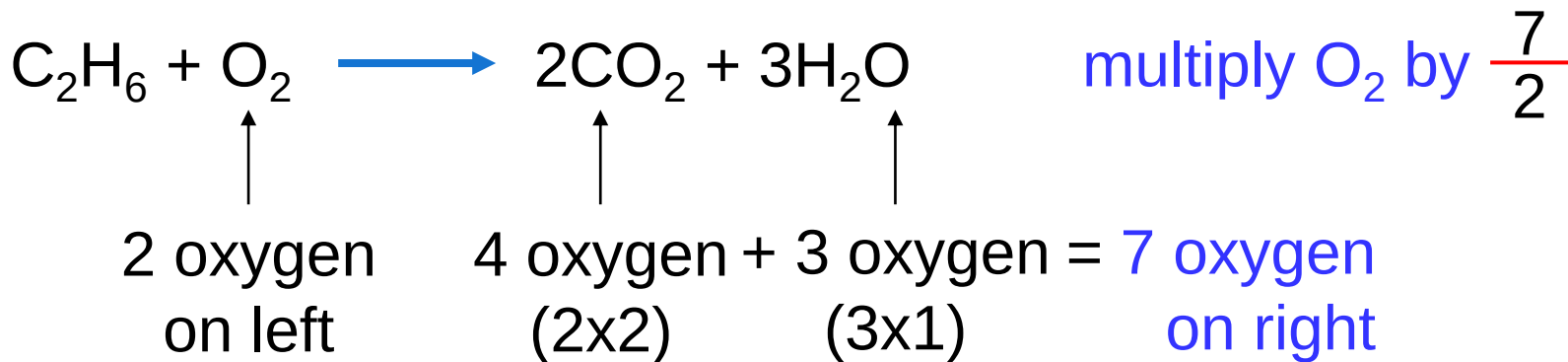
# Balancing Chemical Equations

3. Start by balancing those elements that appear in only one reactant and one product.



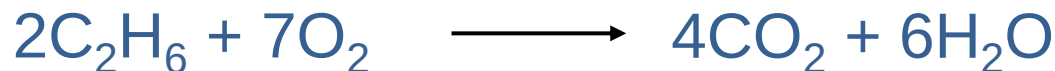
# Balancing Chemical Equations

4. Balance those elements that appear in two or more reactants or products.



# Balancing Chemical Equations

- 5. Check** to make sure that you have the same number of each type of atom on both sides of the equation.



Reactants

4 C (2 x 2)

12 H (2 x 6)

14 O (7 x 2)

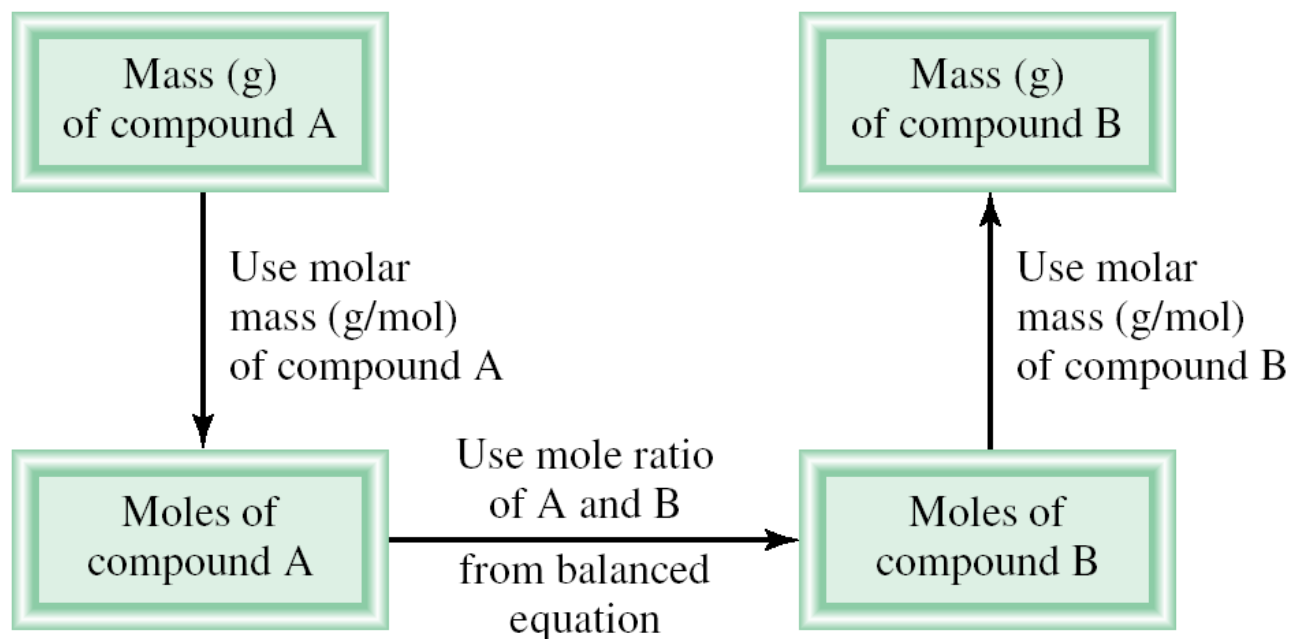
Products

4 C

12 H (6 x 2)

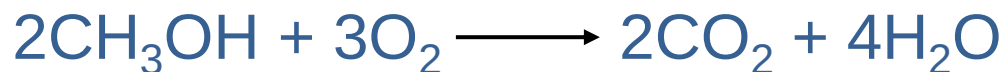
14 O (4 x 2 + 6)

# Amounts of Reactants and Products



1. Write balanced chemical equation
2. Convert quantities of known substances into moles
3. Use coefficients in balanced equation to calculate the number of moles of the sought quantity
4. Convert moles of sought quantity into desired units

Methanol burns in air according to the equation



If 209 g of methanol are used up in the combustion, what mass of water is produced?

grams  $\text{CH}_3\text{OH}$   $\longrightarrow$  moles  $\text{CH}_3\text{OH}$   $\longrightarrow$  moles  $\text{H}_2\text{O}$   $\longrightarrow$  grams  $\text{H}_2\text{O}$

molar mass  
 $\text{CH}_3\text{OH}$

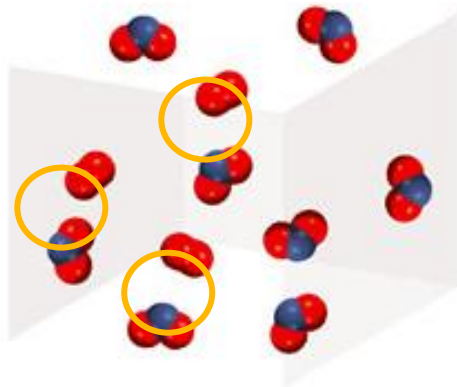
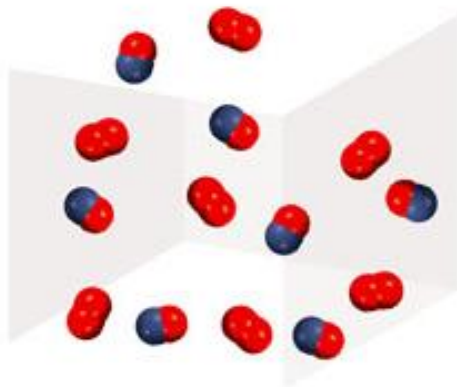
coefficients  
chemical equation

molar mass  
 $\text{H}_2\text{O}$

$$209 \text{ g } \cancel{\text{CH}_3\text{OH}} \times \frac{1 \cancel{\text{ mol CH}_3\text{OH}}}{32.0 \text{ g } \cancel{\text{CH}_3\text{OH}}} \times \frac{4 \cancel{\text{ mol H}_2\text{O}}}{2 \cancel{\text{ mol CH}_3\text{OH}}} \times \frac{18.0 \text{ g } \cancel{\text{H}_2\text{O}}}{1 \cancel{\text{ mol H}_2\text{O}}} =$$

**235 g  $\text{H}_2\text{O}$**

Before reaction has started

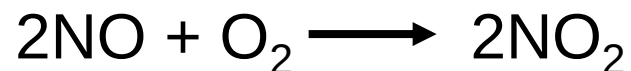


After reaction is complete



# Limiting Reagent

Reactant **used up first** in the reaction



**NO** is the **limiting** reagent

**O<sub>2</sub>** is the **excess** reagent



In one process, 124 g of Al are reacted with 601 g of Fe<sub>2</sub>O<sub>3</sub>



Calculate the mass of Al<sub>2</sub>O<sub>3</sub> formed.

g Al  $\longrightarrow$  mol Al  $\longrightarrow$  mol Fe<sub>2</sub>O<sub>3</sub> needed  $\longrightarrow$  g Fe<sub>2</sub>O<sub>3</sub> needed

OR

g Fe<sub>2</sub>O<sub>3</sub>  $\longrightarrow$  mol Fe<sub>2</sub>O<sub>3</sub>  $\longrightarrow$  mol Al needed  $\longrightarrow$  g Al needed

$$124 \text{ g Al} \times \frac{1 \text{ mol Al}}{27.0 \text{ g Al}} \times \frac{1 \text{ mol Fe}_2\text{O}_3}{2 \text{ mol Al}} \times \frac{160. \text{ g Fe}_2\text{O}_3}{1 \text{ mol Fe}_2\text{O}_3} = 367 \text{ g Fe}_2\text{O}_3$$

Start with 124 g Al  $\longrightarrow$  need 367 g Fe<sub>2</sub>O<sub>3</sub>

Have more Fe<sub>2</sub>O<sub>3</sub> (601 g) **so Al is the limiting reagent**

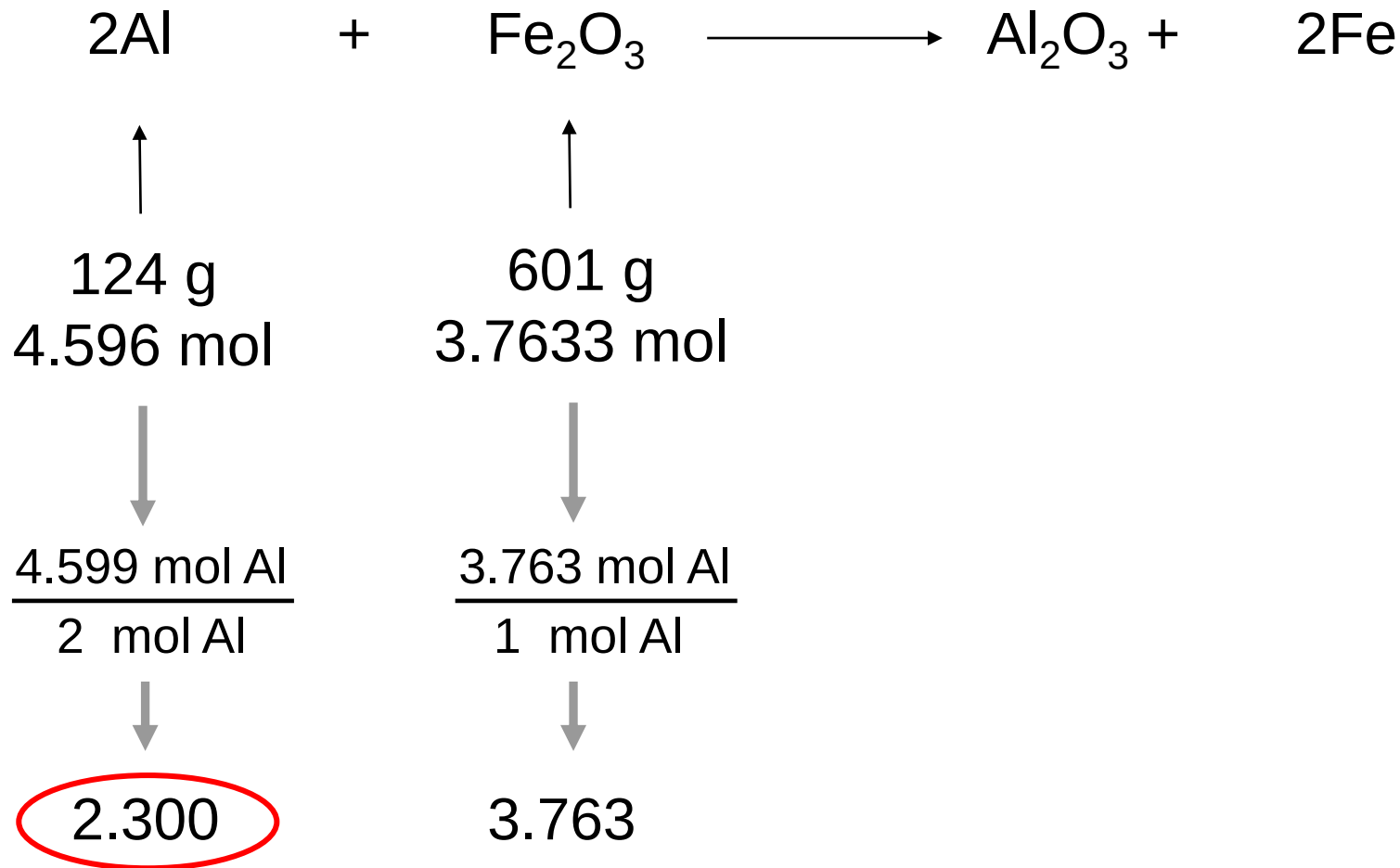
Use limiting reagent (Al) to calculate amount of product that can be formed.



$$124 \text{ g Al} \times \frac{1 \text{ mol Al}}{26.98 \text{ g Al}} \times \frac{1 \text{ mol Al}_2\text{O}_3}{2 \text{ mol Al}} \times \frac{102.0 \text{ g Al}_2\text{O}_3}{1 \text{ mol Al}_2\text{O}_3} = 234.4 \text{ g Al}_2\text{O}_3$$

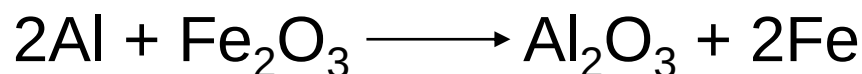
At this point, all the Al is consumed and Fe<sub>2</sub>O<sub>3</sub> remains in excess.

## Another method



**Al** is the **least** thus it is the **limiting reagent**

Use limiting reagent (Al) to calculate amount of product that can be formed.



$$124 \cancel{\text{g Al}} \times \frac{1 \cancel{\text{mol Al}}}{26.98 \cancel{\text{g Al}}} \times \frac{1 \cancel{\text{mol Al}_2\text{O}_3}}{2 \cancel{\text{mol Al}}} \times \frac{102.0 \text{ g Al}_2\text{O}_3}{1 \cancel{\text{mol Al}_2\text{O}_3}} = 234.4 \text{ g Al}_2\text{O}_3$$

At this point, all the **Al** is consumed and **Fe<sub>2</sub>O<sub>3</sub>** remains in **excess**.

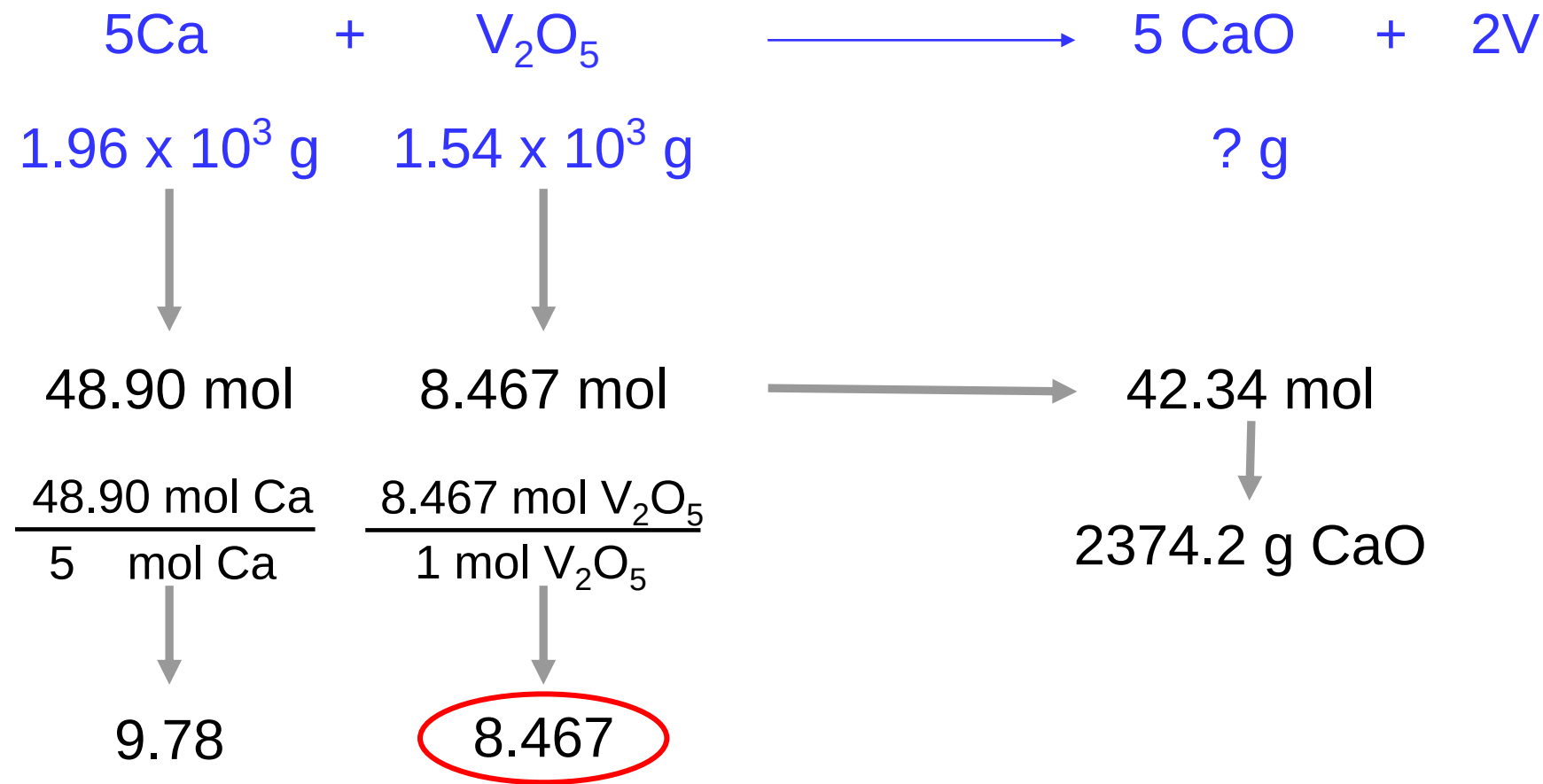
# Reaction Yield

***Theoretical Yield*** is the amount of product that would result if all the limiting reagent reacted.

***Actual Yield*** is the amount of product actually obtained from a reaction.

$$\% \text{ Yield} = \frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\%$$

Calculate % yield if 803 g of CaO is produced?



$$\text{\% Yield} = \frac{803 \text{ g}}{2374.2 \text{ g}} \times 100 = 33.8\%$$

### EXAMPLE 3.16

Titanium is a strong, lightweight, corrosion-resistant metal that is used in rockets, aircraft, jet engines, and bicycle frames. It is prepared by the reaction of titanium(IV) chloride with molten magnesium between 950°C and 1150°C:



In a certain industrial operation  $3.54 \times 10^7$  g of  $\text{TiCl}_4$  are reacted with  $1.13 \times 10^7$  g of Mg. (a) Calculate the theoretical yield of Ti in grams. (b) Calculate the percent yield if  $7.91 \times 10^6$  g of Ti are actually obtained.

**Solution** Carry out two separate calculations to see which of the two reactants is the limiting reagent. First, starting with  $3.54 \times 10^7$  g of  $\text{TiCl}_4$ , calculate the number of moles of Ti that could be produced if all the  $\text{TiCl}_4$  reacted. The conversions are

$$\begin{aligned} \text{grams of TiCl}_4 &\longrightarrow \text{moles of TiCl}_4 \longrightarrow \text{moles of Ti} \\ \text{moles of Ti} &= 3.54 \times 10^7 \text{ g TiCl}_4 \times \frac{1 \text{ mol TiCl}_4}{189.7 \text{ g TiCl}_4} \times \frac{1 \text{ mol Ti}}{1 \text{ mol TiCl}_4} \\ &= 1.87 \times 10^5 \text{ mol Ti} \end{aligned}$$

Next, we calculate the number of moles of Ti formed from  $1.13 \times 10^7$  g of Mg. The conversion steps are

$$\begin{aligned} \text{grams of Mg} &\longrightarrow \text{moles of Mg} \longrightarrow \text{moles of Ti} \\ \text{moles of Ti} &= 1.13 \times 10^7 \text{ g Mg} \times \frac{1 \text{ mol Mg}}{24.31 \text{ g Mg}} \times \frac{1 \text{ mol Ti}}{2 \text{ mol Mg}} \\ &= 2.32 \times 10^5 \text{ mol Ti} \end{aligned}$$

Therefore,  $\text{TiCl}_4$  is the limiting reagent because it produces a smaller amount of Ti. The mass of Ti formed is

$$1.87 \times 10^5 \text{ mol Ti} \times \frac{47.88 \text{ g Ti}}{1 \text{ mol Ti}} = 8.95 \times 10^6 \text{ g Ti} \quad (\text{Continued})$$

**Solution** The percent yield is given by

$$\begin{aligned}\% \text{yield} &= \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\% \\ &= \frac{7.91 \times 10^6 \text{ g}}{8.95 \times 10^6 \text{ g}} \times 100\% \\ &= 88.4\%\end{aligned}$$