Programmed Unit in Chemistry

Mass and Volume Relationships

OBJECTIVES FOR THIS UNIT

The purpose of this unit is to help you learn how to solve problems involving mass and volume relationships in chemical reactions. It is assumed that you can write the chemical formula for a substance and calculate its molecular or formula weight. You should be able to write a balanced chemical equation for a reaction, if the reactants and the products are known. You should know the meaning and significance of Avogadro’s number; that is, of a mole. You should also use units and significant figures accurately. It will be a help also if you can use a slide rule.

INSTRUCTIONS TO THE STUDENT

Programmed instruction is a method to help you learn better and more easily. You proceed in small steps, check yourself at each step, make few errors, and work at your own speed. The form of programmed instruction may make it look like a test, but this is not a test. This is a method of teaching yourself. You will not be graded on the responses you make while learning. However, you will be held responsible for mastery of the content of this unit at a later time.

In addition to a periodic table and this program, you need a sheet of paper, a pen, a slide rule, and an uncluttered desk. Later you will need your notebook. Your instructor will tell you whether to write your responses in the book, or on a separate sheet of paper. The sheet may also be used for scratch work.

Cut out the sample mass to mass problem from the back of the book. Keep it in front of you as you work through this set. (If this book will be used by other students, paperclip the sample problem inside the back cover when you have finished the set.)

Number your responses on the answer sheet as you make them. Place the answer sheet at the first bar, covering the rest of the items.
MASS TO MASS PROBLEMS

INSTRUCTIONS TO THE STUDENT

You know how to write balanced equations which describe chemical reactions. A balanced equation not only describes what the reactants and products are, but is the basis for determining how much of each substance is involved.

In this set you will learn one method of solving mass to mass problems. You will also learn the chemical principles which justify the method. You will learn both the “why” and “how” of mass to mass problems.

A mass to mass problem is one in which you are given the mass of one of the substances in a reaction and you are to calculate the mass of another substance involved in the reaction. The first step in solving any chemical problem is to determine what type of problem it is, since different kinds of problems involve different methods of solution.

1. Read only the word statement of the sample problem. On your answer sheet write “1.” Beside the question number write the word or words which complete the blanks below.

   From the sample problem you see that the known value is _______________ of calcium carbonate and the unknown value of _____________ of calcium oxide.

   Slide your answer sheet down and check your response. If your response is correct, slide the answer sheet to the next bar. If you made an error, draw a line through your incorrect response. Indicate the correction and proceed through the program.

   15 tonnes                         x tones

2. Tonnes are units of mass. Since the known and the unknown quantities are both expressed in units of mass, this is a mass problem. Name three other units of mass.

   Grams, milligrams, and kilograms are sample answers.

3. Identifying the type of problem is Step I. Writing a balanced equation is Step II. Referring to the verbal statement of the sample problem, the balanced equation for this reaction is ___________→ ___________ + ____________.

   \[ \Delta \]
   \[ CaCO_3(s) \rightarrow CaO(s) + CO_2(g) \]

4. A balanced equation shows the same number of atoms of the same elements of on both sides of the equation. A balanced equation obeys the Law of ______________.
Conservation of Mass

5. From the sample problem you also learned that you have 15 tonnes of CaCO$_3$ and x tonnes of CaO. Write this information over the appropriate formulas in the balanced equation. This is Step II.

\[
\begin{align*}
15 \text{ tonnes} & \quad \Delta \quad x \\
\text{CaCO}_3(s) & \rightarrow \text{CaO(s)} + \text{CO}_2(g)
\end{align*}
\]

6. On a molecular scale this equation states that one formula of CaCO$_3$ yields one formula of CaO and one molecule of CO$_2$.

In order to avoid tedious repetition, we will use the terms “molecule” and “molecular weight” to stand also for “formula” and formula weight” when a general principle applies to both ioniically and covalently bonded materials. We will use “formula” and “formula weight” when we are describing a specific ionically bonded material. It is also true that

\[
\begin{align*}
10 \text{ CaCO}_3(s) & \rightarrow \underline{\quad} \text{CaO(s)} + \underline{\quad} \text{CO}_2(g)
\end{align*}
\]

7. And also that

\[
\begin{align*}
10^9 \text{ CaCO}_3(s) & \rightarrow \underline{\quad} \text{CaO(s)} + \underline{\quad} \text{CO}_2(g)
\end{align*}
\]

8. In other reactions, the relationships of molecules and formulas are also true and fixed. In the electrolysis of water,

\[
\begin{align*}
elec \quad 2 \text{ H}_2\text{O}(l) & \rightarrow \quad 2 \text{ H}_2(g) + \text{O}_2(g) \\
\underline{\quad} \text{molecules of water yield} \underline{\quad} \text{molecules of O}_2.
\end{align*}
\]

9. In the Haber process,

\[
\begin{align*}
\text{N}_2(g) + 3 \text{ H}_2(g) & \rightarrow 2 \text{ NH}_3(g) \\
\underline{\quad} \text{molecules of N}_2 \text{ yields} \underline{\quad} \text{molecules of NH}_3.
\end{align*}
\]
10. Also in the Haber process, _______________ molecules of H₂ yield _____________ molecules of NH₃.

11. In our sample problem, the ratio of CaCO₃ to Ca) is ___________ to ____________.  

One One

12. Substances react therefore in the ratio of their coefficients in the balanced equation.  
   On an experimental basis as compared to a molecular basis, we cannot deal with  
   single atoms, or with a few atoms, but with billions of atoms. However, their ratios  
   are fixed.

   In experimenting with gases, Amadeo Avogadro discovered an interesting and useful  
   relationship. Our understanding of this relationship has since been refined and  
   extended. If you are interested in learning how this relationship was discovered and  
   tested, consult a textbook or an encyclopedia. One way of stating this relationship is  

   \[ 6.02 \times 10^{23} \text{ molecules of any substance have a mass equal to the molecular weight of} \]  
   \[ \text{that substance expressed in grams. This is known as the molar mass.} \ 6.02 \times 10^{23} \text{ is} \]  
   \[ \text{called Avogadro’s number.} \]

   Referring to the periodic table, \( 6.02 \times 10^{23} \) molecules of helium have a mass of  
   ________________ .

   4 grams

13. An Avogadro’s number of water molecules have a mass of ________________ .

   18 grams

14. \( 6.02 \times 10^{23} \) indicates a number, a “head count” of particles and is known as  
   _____________ number.

   (name)
Avogadro’s

15. Since saying \(6.02 \times 10^{23}\) particles, or even an Avogadro’s number of particles is awkward, chemists have invented a short word that means the same thing. This word is *mole*. A *mole* is a specific number of particles, \(6.02 \times 10^{23}\) particles or a(n) \(\underline{\text{________}}\) number of particles.

(name)

Avogadro’s

16. For convenience, \(6.02 \times 10^{23}\) molecules of \(\text{CO}_2\) are called a \(\underline{\text{________}}\) of \(\text{CO}_2\).

Mole

17. A mole of \(\text{HCl}\) contains an Avogadro’s number or \(\underline{\text{________}}\) molecules.

(number)

\(6.02 \times 10^{23}\)

18. A mole of \(\text{HCl}\) contains \(\underline{\text{________}}\) \(\text{HCl}\) molecules.

\(6.02 \times 10^{23}\)

19. A mole of \(\text{SO}_3\) contains an Avogadro’s number, that is, \(\underline{\text{________}}\) molecules of \(\text{SO}_3\).

\(6.02 \times 10^{23}\)

20. A mole of any substance contains \(6.02 \times 10^{23}\) molecules of that substance but the mass of a mole will depend upon the mass of the particles that make up that substance. The heavier the mass of the individual molecules, the heavier the mass of that mole. A mole (\(6.02 \times 10^{23}\) or an Avogadro’s number) of \(\text{CO}_2\) molecules has a mass in grams equal to the molecular weight of \(\text{CO}_2\) or \(\underline{\text{________}}\) (3 significant figures).

44.0 grams

21. A mole of \(\text{HCl}\) has a mass of \(\underline{\text{________}}\).
36.5 grams

22. A mole of SO₃ has a mass of ________________.

80.1 grams

23. A mole of monatomic helium contains $6.02 \times 10^{23}$ atoms or molecules of helium, but has a mass of only 4.00 grams since a helium particle is proportionately lighter than a CO₂ molecule.

   A mole of H₂ contains $6.02 \times 10^{23}$ molecules of hydrogen and has a mass of 2.00 grams ($2 \times 1.00$) since a molecule of hydrogen is diatomic. A mole of oxygen has a mass of ______________ grams.

32.0  

32.0  

24. A mole of chlorine has a mass of ________________ grams.

71.0  

25. Avogadro’s principle has been proven true for substances which are not strictly molecular. For example, a mole of zinc atoms ($6.02 \times 10^{23}$ atoms of zinc) has a mass of 65 grams, the atomic weight of zinc. A mole of iron has a mass of ______________ grams.

55.8 grams  

26. $6.02 \times 10^{23}$ aluminum atoms have a mass of ______________ grams.

27.0  

27. Ionic substances also conform to Avogadro’s principle, although strictly speaking we cannot call them molecular. $6.02 \times 1023$ units of NaCl have a mass equal to the formula weight of NaCl, ______________ grams.

58.5  

28. A mole of MgO has a mass of ________________ grams.
29. A mole of ZnS contains ______ formula units of ZnS and has a mass of ______.

6.02 x 10^23  97.5 grams

30. To summarize, a mole is

6.02 x 10^23 molecules of a molecular substance, or
6.02 x 10^23 atoms of a substance that is monatomic, or
6.02 x 10^23 formula units of a substance that is ionic.

6.02 x 10^23 particles, that is, an Avogadro’s number of particles, or an mole of any substances, has a mass equal to the molecular weight or formula weight of that substance expressed in grams.

Applying this principle to our sample problem, a mole of CaCO\(_3\) will have a mass equal to the formula weight of CaCO\(_3\) or ________________.

100 grams

31. Write 100 g under the formula for CaCO\(_3\) in your balanced equation for the sample problem. This is Step IV. A mole of CaCO has a mass of ________________.

56.1 g

32. Write 56.1 g under the formula for CaCO in the balanced equation for the sample problem. This is part of Step IV. You need not calculate the molecular weight for all the substances in the reaction. Calculate the molecular (formula) weight only for the substances whose masses are given or are to be calculated.

\[
15 \text{ tonnes} \times \frac{\text{CaCO}_3(s) \rightarrow \text{CaCO}(s) + \text{CO}_2(g)}{100 \text{ g} \quad 56.1 \text{ g}}
\]

The preceding equation indicates that the following relationships exit:

1 formula of CaCO\(_3\) produces 1 formula of CaO (and 1 molecules of CO\(_2\), but our problem is concerned only with the mass of CaO, so we will ignore the CO\(_2\) from now on).

6.02 x 10^23 molecules of CaCO\(_3\) \rightarrow 6.02 x 10^23 molecules of CaO
1 mole of CaCO$_3$ → 1 mole of CaO

100 grams of CaCO$_3$ → 56.1 grams of CaO

Substances react, therefore, in proportion to:

(1) The ratio of their molecules (formulas), and

(2) The ratio of their molecular (formula) weights.

If 100 grams of CaCO$_3$ → 56.1 grams of CaO,
10 grams of CaCO$_3$ → ________________ grams of CaO.

5.61

33. 1 gram of CaCO$_3$ → ________________ gram of CaO.

0.561

33. The relative masses of CaCO$_3$ and CaO are always in proportion to their formula weights. The ratio of CaCO$_3$ to CaO is ____________ to ____________.

100 g
100 to 56.1   or   56.1

35. Thus, in our sample problem,

\[
\frac{1 \text{ CaCO}_3}{1 \text{ CaO}} \text{ or } \frac{100 \text{ g}}{56.1 \text{ g}} \text{ and } x
\]

When written as an identity, the equation becomes

\[
\frac{100 \text{ g}}{56.1 \text{ g}} = \frac{15 \text{ tonnes}}{x}
\]

Writing the identity as Step V. Solving the identity is Step VI.

100 x = 15 tonnes x 56.1

x = ________________________________
8.4 tonnes (Units and the correct number of significant figures are required.)

36. Now go back to the beginning of this program and work through it again, making sure you understand the reason and justification for each step. When you return to this point, proceed with the next item.

37. Example 2: How many grams of chlorine can be produced by the electrolysis of 500 grams of molten sodium chloride?

Step I: Identify the type of problem. Since you are given 500 grams of sodium chloride and are to find how many grams of chlorine are produced, this is a __________ to _______________ problem.

Mass to mass (It does not matter whether the units of mass are tones, grams, milligrams, and so n, as long as the units are identical within a given problem.)

38. Step II: Write a balanced equation for the reaction.

D.C. __________________ → ___________ + ___________

(molten) elec

D.C.

2 NaC1(l) → 2 Na(l) + C1_2(g)
elec

39. Step III: Over its formula write the mass of the material whose mass is known, and write x over the formula of the substance whose mass is to be calculated.

500 g x

D.C.

2 NaC1(l) → 2 Na(l) + C1_2(g)
elec

40. Step IV: Calculate the molecular (formula) weights of the substances whose mass is known or whose mass is to be calculated. The formula weight of NaC1 is ___________. The molecular weight of C1_2 is ________________.

NaC1 = 58.5 C1_2 = 71.0 (2 x 35.5 because chlorine is diatomic)

41. Write these molecular weights, expressed in grams, under their formulas in their balanced equation.
500 g  D.C.  
2 NaCl(l) → 2 Na(l) + Cl₂(g) 
58.5 g  elec  71.0 g 

42. Since 2 formulas of NaCl produce one molecule of Cl₂, the ratio of the molecular weights is 

\[
\frac{2 \text{ NaCl}}{\text{Cl}_2} = \frac{2 \times 58.5 \text{ g}}{1 \times 71.0 \text{ g}}
\]

Step V: Write an identity. 

\[
\frac{\text{mass of known}}{\text{mass of unknown}} = \frac{\text{no. of molecules x mol. Wt. of known}}{\text{no of molecules x mol. Wt. of unknown}}
\]

\[
\frac{500 \text{ g}}{x} = \frac{2 \times 58.5 \text{ g}}{1 \times 71.0 \text{ g}}
\]

43. Solve the identity. \(x = \)________________________

303 grams

44. Example 3: What mass of oxygen can be produced by heating 120 grams of potassium chlorate in the presence of manganese dioxide? 
Step I: Identify the type of problem.

Mass to mass

45. Step II: Write a balanced equation.

\[
2 \text{KClO}_3(s) \xrightarrow{\Delta} 2 \text{KCl(s)} + 3 \text{O}_2(g)
\]

46. Step III: Write the know mass over the formula of that substance. Write x over the formula of the substance whose mass is to be determined.
120 g \Delta \xrightarrow{x} \begin{array}{l}
2 \text{KC}1\text{O}_3(\text{s}) \\
\text{MnO}_2
\end{array} \\
\rightarrow
\begin{array}{l}
2 \text{KC}1(\text{s}) + 3 \text{O}_2(\text{g})
\end{array}

47. Step IV: Calculate the molecular (formula) weights of the substances whose mass is known or is to be calculated. Write these values under the proper formulas in the balanced equation.

\[
\begin{array}{l}
120 \text{g} \\
2 \text{KC}1\text{O}_3(\text{s}) \\
\text{MnO}_2
\end{array}
\Delta \xrightarrow{x} \\
\rightarrow \\
\begin{array}{l}
2 \text{KC}1(\text{s}) + 3 \text{O}_2(\text{g})
\end{array}
\]

123 \text{g} 32.0 \text{g}

48. Step V: Write an identity.

\[
\frac{\text{mass of known}}{\text{mass of unknown}} = \frac{\text{no. of molecules of known } x \text{ mol. Wt. of known}}{\text{no. of molecules of unknown } x \text{ mol. Wt. of unknown}}
\]

\[
\begin{array}{l}
120 \text{g} = 2 \times 123 \text{g} \\
x \times 3 \times 32.0 \text{g}
\end{array}
\]

49. Step VI: Solve for the unknown.

\[
120 \text{g} \times 3 \times 32.0 = x(2 \times 123)
\]

\[
X = 46.8 \text{g}
\]

50. Now see if you can solve a problem without having to refer to the sample problem.

After you have worked through the complete problem, slide your answer sheet down to check your answer and method.

Example 4: How many grams of hydrogen can be generated from the reaction of 3.0 grams of zinc with an excess of sulfuric acid?
Step I: mass to mass problem
Step II: Zn(s) + H₂SO₄(aq) → H₂(g) + ZnSO₄(aq)
Step III: 3.0 g Zn(s) + H₂SO₄(aq) → x H₂(g) + ZnSO₄(aq)
Step IV: 65.4 g
Step V: \[ \frac{3.0 \text{ g}}{x} = \frac{1 \times 65.4 \text{ g}}{1 \times 2.0 \text{ g}} \]
Step VI: \[ x = 0.092 \text{ g} \] (This answer is justified only to 2 significant figures.)

51. Example 5: In the previous reaction, how much sulfuric acid is required to react with 3.0 grams of zinc?

Step I: mass to mass problem
Step II: Zn(s) + H₂SO₄(aq) → H₂(g) + ZnSO₄(aq)
Step III: 3.0 g Zn(s) + H₂SO₄(aq) → x H₂(g) + ZnSO₄(aq)
Step IV: 65.4 g 98.1 g
The substance in a reaction will react in proportion to their molecular weights no matter where they occur in the equation. It does not matter whether one substance is a reactant and the other is a product, or whether both are reactants or both are products. Their quantities will be in proportion to their molecular weight and to the number of moles of each.

Now write an identity.

Step V: \[ \frac{3.0 \text{ g}}{x} = \frac{1 \times 65.4 \text{ g}}{1 \times 98.1 \text{ g}} \]
Step VI: \[ x = 4.5 \text{ g} \]

52. Example 6: In the Haber process, what mass of hydrogen is required to react with 10 tonnes of nitrogen?
Step I:  mass to mass problem

Step II: \[ N_2(g) + 3 H_2(g) \rightarrow 2 \text{NH}_3(g) \]

Step III: \[ 10 \text{ tonnes} \quad x \quad \begin{align*} \frac{N_2(g)}{N_2(g)} & + 3 \frac{H_2(g)}{H_2(g)} \rightarrow 2 \frac{\text{NH}_3(g)}{\text{NH}_3(g)} \\ 28.0 \text{ g} & + 2.0 \text{ g} \rightarrow 2 \text{ NH}_3(g) \end{align*} \]

Step IV: \[ 28.0 \text{ g} \quad x \quad 2.0 \text{ g} \]

Step V: \[ \frac{10 \text{ tonnes}}{x} = \frac{1 \times 28.0 \text{ g}}{3 \times 2.0 \text{ g}} \]

Step VI: \[ x = 2.1 \text{ tonnes} \]

53. Example 7: What mass of ammonia can be produced from 10 tonnes of nitrogen in the Haber process?
VOLUME TO VOLUME OF GASES

INSTRUCTIONS TO THE STUDENT

The purpose of this set is to learn how to solve problems involving the volume relationships of gases. You will learn the principles upon which the method is based.

The same assumptions are made about the skills, information, and proficiency as in the set on mass to mass problems.

In addition, you should know the meaning and significance of STP (standard temperature and pressure), and the K (Kelvin) temperature scale.

The same method is used. You need paper, a pen, a periodic table, a slide rule, and your notebook. Detach the sample problem on Volume to Volume of Gases from the back of the book. (If other students will be using this book, be sure to paperclip the sample problem inside the back cover when you finish this set.)

1. In this set you will learn how to solve problems dealing with the volume relationships of gases in chemical reactions. The volumes of liquids and solids are not related in the same manner.

   This set is concerned only with the volume of ________________.

Gases

2. You will also learn the chemical principles upon which this method is based. You will learn the “why” and “how” of problems involving the volume to volume relationships of gases.

   The first step in solving a chemical problem is to determine the type of problem. You are given the volume of one gas and are to determine the volume of another gas involved in the same chemical reaction.

   Refer to the sample problem for this set. Read only the question part.

   The known value is ________________ of hydrogen and the unknown value is ________________ of chlorine.
12 litres \( x \) litres

3. Hydrogen and chlorine are both gases, so the problem involves \( \frac{\text{volume}}{\text{volume}} \) to \( \text{gaseous} \) relationships of substances in the \( \text{gaseous} \) state.

Volume \( \frac{\text{volume}}{\text{gaseous}} \)

4. Three other units of volume are \( \text{milliliters} \), \( \text{deciliters} \), and \( \text{cubic centimeters} \).

Milliliters, deciliters, cubic centimeters

5. Step II is writing a balanced equation. Referring to the sample problem, the balanced equation for the reaction is

\[ \text{H}_2(g) + \text{Cl}_2(g) \rightarrow 2 \text{HCl}(g) \]

6. A balanced equation shows the same number of atoms of the same elements on both sides of the equation. This is necessary because of the Law of \( \text{Conservation of Mass} \).

Conservation of Mass

7. From the sample problem you also learn that you have 12 litres of hydrogen and \( x \) litres of chlorine. Write this information \( \text{over} \) the appropriate formulas in the balanced equation. This is Step III.

\[ \text{H}_2(g) \quad + \quad \text{Cl}_2(g) \quad \rightarrow \quad 2 \text{HCl}(g) \]

8. To review: STP, standard temperature and pressure, is a temperature of \( 0^\circ \)C and a pressure of \( \text{a pressure of} \) \( \text{mm} \).

9. 760 mm of pressure is the average atmospheric pressure at sea level and is called one \( \text{a pressure of} \) \( \text{mm} \).
Atmosphere or atm

10. $0 \degree C$ is the same as ________________ K.

273 K

11. You used Avogadro’s principle in solving mass to mass problems. In terms of mass relationships this principle states:

6.02 x $10^{23}$ molecules of any substance have a mass equal to the molecular weight of that substance expressed in grams.

Avlgadro first discovered his principle studying volume to volume relationships of gases. Under these circumstances Avogadro’s principles states:

Equal volumes of gases under similar conditions of temperature and pressure contain equal numbers of molecules.

This may seem surprising but experimental evidence supports the truth of this statement. This means that one litre of oxygen at STP contains the same number of molecules as_____________ litre of chlorine at STP.

One

12. One billion molecules of chlorine at STP will occupy the same volume as _________________ molecules of nitrogen at STP.

One billion

13. 12 x $10^9$ molecules of hydrogen at $10 \degree C$ and 1 atmosphere of pressure occupy the same volume as 12 x $10^9$ molecules of neon at _____________ $0 \degree C$ and ____________ of pressure.

10 1 atmosphere

14. 12 x $10^9$ molecules of $H_2$ do not, however, contain the same number of atoms as 12 x $10^9$ molecules of neon. Hydrogen is a diatomic gas, so 12 x $10^9$ molecules of $H_2$ contain ________________ atoms of hydrogen.
24 \times 10^9 \text{ atoms}

15. Neon is monatomic so $12 \times 10^9$ molecules of neon contain _________ atoms of neon.

12 \times 10^9 \text{ atoms}

16. $12 \times 10^9$ molecules of neon at STP occupy the __________ volume as $12 \times 10^9$ molecules of argon at STP.

Same

17. $12 \times 10^9$ molecules of neon at STP __________ occupy the same volume at 
-100 °C and 3 atm of pressure. (do/do not)

Do not

18. $12 \times 10^9$ molecules of neon at any conditions of temperature and pressure occupy the same volume as $12 \times 10^9$ molecules of any other gas under __________ conditions of temperature and pressure.

The same

19. Avogadro’s principle states that __________ volumes of gases under ________ conditions of temperature and pressure contain __________ numbers of molecules.

Equal the same equal

20. Theoretically and experimentally it has been shown that a mole of any gas at STP contains $6.02 \times 10^{23}$ molecules of that gas. You recognize $6.02 \times 10^{23}$ as _________ number.

Avogadro’s

21. Two grams of H2 contain ____________ molecules. (number)
22. An Avogadro’s number of molecules of neon has a mass of __________ and has a mass of __________ grams.

23. A mole of hydrogen chloride molecules contains __________ molecules and has a mass of __________ grams.

24. Now return to the sample problem.

\[
12 \text{ litres } \times \frac{\text{H}_2(\text{g}) + \text{C}_1(\text{g})}{\text{H}_2(\text{g}) + \text{C}_1(\text{g})} \rightarrow 2 \text{ HC}_1(\text{g})
\]

This equation states that 1 molecule of \text{H}_2 combines with one molecule of \text{C}_1 to give 2 molecules of \text{HC}_1.

On a larger scale any number of \text{H}_2 molecules combine with a similar number of \text{C}_1 molecules to form ____________ as many \text{HC}_1 molecules.

Twice (2 times)

25. \text{H}_2, \text{C}_1, \text{and HC}_1 are all gases and they obey Avogadro’s principle. Under similar conditions of temperature and pressure, the volume occupied by a given number of \text{H}_2 molecules is the same as the volume occupied by a similar number of \text{C}_1 molecules. The ratio of \text{H}_2 to \text{C}_1 by volume is __________ to __________.

1 to 1

26. Since the number of \text{HC}_1 molecules produced is twice the number of \text{H}_2 or \text{C}_1 molecules, the volume of \text{HC}_1 is _____________ the volume of \text{H}_2 or \text{C}_1.
Twice (2 times)

27.  12 litres $\times$ H$_2$(g) + Cl$_2$(g) $\rightarrow$ 2 HC1(g)

In summary:

\[
\frac{\text{volume } H_2}{\text{molecules of } H_2} = \frac{\text{volume } Cl_2}{\text{molecules of } Cl_2}
\]

\[
\frac{x}{12 \text{ litres}} = \frac{1}{1}
\]

This is Step IV. Solve the identity for Step V.

---

X = 12 litres

28. Using the same chemical reaction, how many litres of HC1 can be produced by the reaction of 12 litres of hydrogen with chlorine?

Step I: Type of problem.

Volume to volume of gases

29. Step II: Write and balance the equation.

\[
H_2(g) + Cl_2(g) \rightarrow 2 \text{ HC1(g)}
\]

30. Step III: Write the information about the known and unknown quantities over the balanced equation.

\[
12 \text{ litres } \times H_2(g) + Cl_2(g) \rightarrow 2 \text{ HC1(g)}
\]

31. It does not matter whether the known and unknown gases are both reactants, both products, or one a reactant and the other a product. They are related in proportion to the number of molecules of each.

Step IV: Write an identity.

\[
\frac{\text{volume of known}}{\text{volume of unknown}} = \frac{\text{molecules of known}}{\text{molecules of unknown}}
\]
12 litres = \frac{1}{2}

32. Step V: Solve the identity.

X = 24 litres of HCl

33. See if you can solve the following problem without reference to the sample problem. Work out your solution; then check the steps below.

Example III: How many litres of oxygen are required for complete combustion of 18 litres of hydrogen?

Step I: This is a volume to volume gas problem.

Step II: \[2 \text{H}_2(g) + \text{O}_2(g) \rightarrow \text{2H}_2\text{O}(g)\]

Step III: \[18 \text{ litres} \times \frac{x}{2 \text{H}_2(g) + \text{O}_2(g) \rightarrow \text{2H}_2\text{O}(g)}\]

Step IV: \[\frac{18 \text{ litres}}{x} = \frac{2}{1}\]

Step V: \[2x = 18 \text{ litres}\]

\[x = 9 \text{ litres}\]

34. Example IV: What volume of oxygen can be obtained by heating 15 grams of potassium chlorate using manganese dioxide as a catalyst?

Step I: Type of problem.

This is not a volume to volume of gas problem. 15 grams is a mass. KC1O3 is a solid. This problem cannot be solved by this method. You will learn how to solve it later.

35. Example V: How many litres of nitrogen are required to produce 20 litres of ammonia in the Haber process?
Step I: volume of N$_2$ to volume of NH$_3$

Step II: N$_2$(g) + 3 H$_2$(g) → 2 NH$_3$(g)

Step III: \[
\frac{x}{20 \text{ litres}} = \frac{2 \text{ litres}}{N_2(g) + 3 H_2(g) \rightarrow 2 NH_3(g)}
\]

Step IV: \[
x = \frac{1}{2} \times 20 \text{ litres}
\]

Step V: x = 60 litres
x = 30 litres of H$_2$

37. Example VII: What volume of air is required for the conversion of 11 litres of carbon monoxide to carbon dioxide?

Step I: volume to volume of gases

Step II: 2 CO(g) + O$_2$(g) → 2 CO$_2$(g)

Step III: \[
\frac{11 \text{ litres}}{2 \text{ CO(g)}} = \frac{x}{O_2(g) + 2 \text{ CO}_2(g)}
\]

Step IV: \[
\frac{11 \text{ litres}}{x} = \frac{2}{1}
\]

Step V: \[
2x = 11 \text{ litres}
\]

x = 5.5 litres of O$_2$, but air is only 20% O$_2$, so
x = 5 x 5.5 litres or 27.5 litres of air are required.

38. Copy the sample problem into your notebook. Beneath the sample problem, write the statement of Avogadro’s principle as it applies to gases.
MASS TO VOLUME OF ANY GAS AT STP

INSTRUCTIONS TO THE STUDENT

The purpose of this set is to help you learn to solve problems involving relationships of mass and volume for gases at constant temperature and pressure. The title is shortened to mass to volume problems. You will also learn to solve problems involving the molar mass (one mole) and molar volume of gases at STP.

The same background is required for this set as for the set of problems on volume to volume of gases.

The method and materials are also the same.

1. You have learned how to solve mass to mass problems on the basis of the statement of Avogadro’s principle:

   \[ 6.02 \times 10^{23} \text{ molecules of any substance have a mass equal to the molecular weight of that substance expressed in grams (the molar mass, or one mole).} \]

You have learned to solve problems about volume to volume ratios of gases on the basis of this same principle stated as:

Equal volumes of gases under similar conditions of temperature and pressure contain equal numbers of molecules.

These statements lead to another observation. It has been determined experimentally that \(6.02 \times 10^{23}\) molecules of any gas at STP occupy a volume of 22.4 litres. This is an experimental fact and must be memorized.

A mole of any gas at STP occupies \__________\ litres.

22.4

2. 32.0 grams of oxygen at STP contain \__________\ molecules and occupy \__________\ litres.

   \[ 6.02 \times 10^{23} \text{ (or an Avogadro’s number) 22.4} \]

3. A mole of chlorine gas at STP has a mass of \__________\ (3 significant figures) and occupies \__________\.
71.0 grams  22.4 litres

4. 22.4 litres of hydrogen chloride at STP have a mass of _____________ grams.

5. Since a mole of any gas at STP occupies a volume of 22.4 litres, 22.4 litres of a gas at
   STP is known as the molar volume. A mole of any gas at STP occupies a molar
   volume or _______________.

22.4 litres

6. A mole of SO$_2$ at STP contains __________ molecules, has a mass of __________,
   and occupies ________________.

6.02 x $10^{23}$  64.1 grams  22.4 litres

7. A mole of NH$_3$ at STP has a mass of _____________ grams and occupies _________
   litres.

17.0  22.4

8. A mole of helium at -100°C and 1000 mm of pressure _______________ occupy
   (does/does not) 22.4 litres. Why?

Does not  These conditions are not STP.

9. A mole of NaCl, 58.5 g, at STP ________________ occupy 22.4 litres. Why?
   (does/does not)

Does not  NaCl is not a gas at STP.

10. 44 grams of CO$_2$ at STP occupy ________________ litres.
22.4 litres

11. Note that for the volume of a gas to occupy 22.4 litres at STP, the mass of the gas must be in grams. 64 pounds of SO\textsubscript{2} at STP _______ occupy 22.4 litres. (do/do not)

Do not

12. Note also that molar volume is always in litres. A mole of any gas at STP occupies ______________.

22.4 litres

13. Step I is to decide whether the problem given fits the requirements of this relationship.

   It is a gas? At STP?

   Do you know its mass and/or volume, and/or chemical formula, and/or molecular weight?

   Example I: We will determine the volume of 8.0 grams of oxygen at STP. Is the substance in question a gas?

Yes

14. At STP?

Yes

15. What is its mass?

8.0 grams

16. What is its volume?

To be determined.

17. What is the formula of the gas?
O₂

18. What is its molar mass?

32.0 g

19. At STP, a molar mass of any gas occupies a molar volume, or 22.4 litres. Therefore, 32.0 grams of O₂ at STP will occupy 22.4 litres. We have only 8.0 grams of O₂, so the 8.0 grams will occupy proportionately less.

\[
\frac{\text{molar mass}}{\text{Molar volume}} = \frac{32.0 \text{ g}}{22.4 \text{ litres}} = \frac{8.0 \text{ g}}{x}
\]

Solve for x.

\[X = 5.6 \text{ litres}\]

20. Example II: Determine the mass of 8.0 litres of nitrogen at STP. Is it a gas?

Yes

21. At STP?

Yes

22. What is the mass of the gas?

To be determined (x).

23. What is the volume of the gas?

8.0 litres

24. What is its formula?

N₂

25. What is its molecular weight?
28.0

26. \[
\frac{\text{molar mass}}{\text{molar volume}} = \frac{28.0 \text{ g}}{22.4 \text{ litres}} = \frac{x}{8.0 \text{ litres}}
\]

Solve for \(x\).

\[x = 10 \text{ grams}\]

27. The problems on volume to volume of gases were concerned with the ratio of the volume of one gas to the volume of a different gas in a particular chemical reaction. All the problems of this set involve only one gas at a time. The molar mass/molar volume relationship is true only at STP.

Problems involving the relationships of mass and volume of one particular gas can be solved by simple proportion, if the conditions of temperature and pressure remain constant but not necessarily at STP. An example of simple proportion is stated in the familiar problem: “If 10 apples cost $0.50, how much do 6 apples cost?

\[
\frac{10 \text{ apples}}{.50} = \frac{6 \text{ apples}}{x}
\]

\[X = $0.30\]

The ratio of the mass (mass\(_1\)) of a given quantity of a gas to the volume (vol\(_1\)) occupied by that mass is equal to the ratio of the mass (mass\(_2\)) of another quantity of the same gas to its volume (vol\(_2\)), if the temperature and pressure remain constant. Note that the conditions need not be at STP, but must be constant.

\[
\frac{\text{mass}_1}{\text{vol}_1} = \frac{\text{mass}_2}{\text{vol}_2}
\]

Example III: only 250 ml (0.25 litre) of a gas are available (vol\(_1\)). The mass of the gas is 0.41 g (mass\(_1\)). What would be the mass (mass\(_2\)) of 1 litre (vol\(_2\)) of this gas at the same temperature and pressure?

Substituting in \[\frac{\text{mass}_1}{\text{vol}_1} = \frac{\text{mass}_2}{\text{vol}_2}\]

\[
\frac{0.41 \text{ g}}{0.25 \text{ litre}} = \frac{x}{1 \text{ litre}}
\]

Solve for \(x\).
X = 1.6 g (Only 2 significant figures are justified.)

28. Now solve some additional problems. Use the simple proportion, \( \frac{\text{mass}_1}{\text{vol}_1} = \frac{\text{mass}_2}{\text{vol}_2} \), when you are given any three items as in the previous problem.

You were given two different volumes and one mass. It is obvious also that you can solve for any unknown volume, if you know two masses and one volume.

Example IV: 2.0 litres of hydrogen chloride has a mass of 3.2 grams. What volume is occupied by 10.0 grams of this gas at the same temperature and pressure?

\[
\begin{align*}
\text{vol}_1 & = 2.0 \text{ litres} \\
\text{mass}_1 & = 3.2 \text{ grams} \\
\text{vol}_2 & = x \\
\text{mass}_2 & = 10.0 \text{ grams}
\end{align*}
\]

Vol\(_1\) = 2.0 litres; mass\(_1\) = 3.2 grams; vol\(_2\) = x; mass\(_2\) = 10.0 grams

29. Simple proportion states \( \frac{\text{mass}_1}{\text{vol}_1} = \frac{\text{mass}_2}{\text{vol}_2} \).

\[
\frac{3.2 \text{ g}}{2.0 \text{ litres}} = \frac{10.0 \text{ g}}{x}
\]

30. Substituting the data of this problem, \( \frac{\text{mass}_1}{\text{vol}_1} = \frac{\text{mass}_2}{\text{vol}_2} \).

31. Solve for x.

\[
x = 6.2 \text{ litres} \quad \text{(to 2 significant figures)}
\]

Review Example I: How many litres (volume) will 8.0 g (mass) of oxygen occupy at STP?

You are given only one mass (8.0 g) and are to find an unknown volume. However, since you know the gas is oxygen, you can calculate its molar mass as 32.0 g. Since it is STP, the molar volume is 22.4 litres.

\[
\frac{\text{mass}}{\text{Volume}} = \frac{\text{molar mass}}{\text{molar volume}} = \frac{32.0 \text{ g}}{22.4 \text{ litres}} = \frac{8.0 \text{ g}}{x}
\]

\[
x = 5.6 \text{ litres}
\]
You were given a mass of a gas at STP and were asked to find its volume. By similar proportion, you can determine the mass of a gas, if you are given its volume. You must also know the name or formula of the gas so that you can calculate the molecular weight. The condition must be STP.

32. Example V: What is the mass of 25.0 litres of chlorine at STP?

\[
\text{mass} = \quad ; \quad \text{volume} = \quad
\]

\[
\text{X} \quad 25.0 \text{litres}
\]

33. Since the gas is chlorine at STP, molar mass = \quad ; molar volume = \quad .

\[
\begin{array}{c|c}
\text{71.0 grams} & 22.4 \text{litres} \\
\end{array}
\]

34. \[ \frac{\text{molar mass}}{\text{molar volume}} = \frac{\text{mass}}{\text{volume}} \]

Substitute: \[ \frac{17.8 \text{ g}}{22.4 \text{ litres}} = \frac{x}{25.0 \text{ litres}} \]

Solve for x.

\[
X = 79.2 \text{ grams}
\]

Now solve these problems using the appropriate method: simple proportion or \[ \frac{\text{molar mass}}{\text{molar volume}} \].

35. Example VI: Determine the mass of 100 litres of hydrogen at STP. Is hydrogen gas at STP?

Yes

36. The known is \quad ; the unknown is \quad .

\[
\begin{array}{c|c}
\text{100 litres} & \text{the mass} \\
\end{array}
\]

37. The formula is \quad and the molar mass is \quad .
H₂ 2.0 g

38. The appropriate relationship is ____________________.

\[
\frac{\text{molar mass}}{\text{molar volume}} = \frac{2.0\ \text{g}}{22.4\ \text{litres}} = \frac{x}{100\ \text{litres}}
\]

39. Solve for x.

\[X = 8.9\ \text{grams}\]

40. Example VII: If 2.0 litres of hydrogen sulfide has a mass of 3.0 grams, what is the mass of 16.8 litres at the same temperature and pressure?

\[
\begin{align*}
\text{mass}_1 &= \frac{3.0\ \text{g}}{2.0\ \text{litres}} \\
\text{vol}_1 &= \frac{22.4\ \text{litres}}{100\ \text{litres}} \\
\text{mass}_2 &= \frac{x}{16.8\ \text{litres}} \\
\text{vol}_2 &= 100\ \text{litres}
\end{align*}
\]

Mass₁ = 3.0 grams; vol₁ = 2.0 litres; mass₂ = x; vol₂ = 16.8 litres

41. Set up the appropriate ratios and solve.

\[
\frac{3.0\ \text{g}}{2.0\ \text{litres}} = \frac{x}{16.8\ \text{litres}}
\]

\[X = 25\ \text{grams} \ (2\ \text{significant figures})\]

42. Example VIII: 100 grams of hydrogen occupy what volume at STP?

\[
\begin{align*}
\text{mass} &= \frac{100\ \text{g}}{16.8\ \text{litres}} \\
\text{volume} &= \frac{x}{16.8\ \text{litres}}
\end{align*}
\]

43. Since the gas is hydrogen, a molar mass occupies a molar volume at STP, or, ________ grams occupy ________ litres.

\[2.0 \quad 22.4\]

44. Select the appropriate relationship, substitute, and solve for x.
\[
\frac{\text{molar mass}}{\text{Molar volume}} = \frac{2.0 \text{ g}}{22.4 \text{ litres}} = \frac{100 \text{ g}}{x}
\]

\[X = 1,100 \text{ litres} \quad \text{(2 significant figures)}\]

45. The molecular weight of a gaseous substance can also be calculated from this relationship.

Example IX: What is the molecular weight of a gas if 10 litres have a mass of 14.3 grams at STP? If you know the mass of 22.4 litres of a gas at STP, you know its molecular weight:

\[
\frac{\text{molar mass}}{\text{Molar volume}} = \frac{\text{mass}}{\text{volume}}
\]

Substitute: \[\frac{\text{molar mass}}{22.4 \text{ litres}} = \frac{14.3 \text{ g}}{10 \text{ litres}}\]

Solve for molar mass.

The molecular weight of this gas is 32.

46. Example X: 85 litres of a certain gas at STP have a mass of 15.3 grams. What is its molecular weight?

\[
\frac{\text{molar mass}}{22.4 \text{ litres}} = \frac{15.3 \text{ grams}}{8.5 \text{ litres}}
\]

Solve for molar mass.

Molar mass = 4.0 g; the molecular weight is 4.0.

47. The gas is called ____________________ .
48. Show your mastery of this method by solving the following problems.
Example XI: What is the mass of 12 litres of methane (CH₄) at STP?

\[
\frac{\text{molar mass}}{\text{Molar volume}} = \frac{\text{mass}}{\text{volume}}
\]

Substitute: \(\frac{16.0 \text{ grams}}{22.4 \text{ litres}} = \frac{x}{12 \text{ litres}}\)

Solve for \(x\).

\[8.6 \text{ grams}\]

49. Example XII: What is the density of benzene (C₆H₆) vapor at STP? (Density is often expressed in grams per litre.)

\[
\frac{\text{molar mass}}{\text{Molar volume}} = \frac{\text{mass}}{\text{volume}}
\]

Molar mass of benzene (C₆H₆) = 78.0

\[
\frac{78.0 \text{ grams}}{22.4 \text{ litres}} = \frac{x}{1 \text{ litre}}
\]

\[X = 3.5 \text{ grams}\]

Density = 3.5 g/litre

50. Example XIII: What is the mass of 100 litres of CO₂ at STP?

\[
\frac{\text{molar mass}}{\text{Molar volume}} = \frac{\text{mass}}{\text{volume}}
\]

\[
\frac{44.0 \text{ grams}}{22.4 \text{ litres}} = \frac{x}{100 \text{ litres}}
\]

\[X = 196 \text{ grams}\]

51. Example XIV: A chemist produces a new gaseous substance. 26 litres of this gas at STP have a mass of 80 grams. What is the molecular weight of this substance?
\[
\text{molar mass} = \frac{\text{mass}}{\text{volume}}
\]

Molar volume \hspace{1cm} \text{volume}

\[
\text{molar mass} = \frac{\text{80 grams}}{26 \text{ litres}}
\]

Molar mass = 69 grams; molecular weight = 69

52. Read the program over again and in your notebook write the important principles, conditions, and examples for solving problems involving mass, volume, and molecular relationships of gases.

---

**MASS OF A SUBSTANCE TO VOLUME OF A GAS**

**INSTRUCTIONS TO THE STUDENT**

The purpose of this set is to help you learn how to solve problems involving the mass of one substance in a reaction and the volume of another gaseous substance.

It is assumed that you have already learned how to solve problems involving mass to mass, volume to volume, and mass to volume of a single gas. You must know the meaning of STP, molar mass and molar volume.

1. You have already learned how to solve problems involving the mass of one component of a reaction and the mass of another component of the reaction. You are also able to solve problems concerning the mass to volume relationship of a particular gas at STP. By doing these two operations consecutively you should be able to solve the following problem.

In the laboratory preparation of oxygen, how many litres of oxygen at STP can be produced by the heat decomposition of 2.0 grams of potassium chlorate with manganese dioxide as a catalyst? First calculate the mass of oxygen which will be produced and check your answer below.
\[ 2.0 \text{ g} \quad \Delta \quad x \]
\[ 2 \text{ KCIO}_3(s) \rightarrow 2 \text{ KCl}(s) + 3 \text{ O}_2(g) \]
\[ 123 \text{ g} \quad \text{MnO}_2 \quad 32 \text{ g} \]

\[ \frac{2.0 \text{ g}}{x} = \frac{2 \times 123}{3 \times 32} \]

\[ x = 0.78 \text{ g O}_2 \]

2. At STP, 0.78 g of O\(_2\) occupies what volume? Solve and check.

\[ \frac{\text{molar mass}}{\text{At STP, molar volume}} = \frac{32.0 \text{ g}}{22.4 \text{ litres}} = \frac{0.78 \text{ g}}{x} \]

\[ x = 0.55 \text{ litre of O}_2 \text{ produced from 2.0 g of KCIO}_3 \text{ at STP} \]

3. Instead of performing two separate operations, you can combine them for problems of this sort, since for any gas at STP, the molar mass will occupy the molar volume. A molar mass (one mole) of any gas at STP will occupy 22.4 litres. Therefore, we can substitute directly 22.4 litres for one mole of any gas. For example, in the problem we have just done:

\[ 2.0 \text{ g} \quad x(\text{litres, instead of grams}) \]
\[ 2 \text{ KCIO}_3(s) \rightarrow 2 \text{ KCl}(s) + 3 \text{ O}_2(g) \]
\[ 123 \text{ g} \quad 22.4 \text{ litres (22.4 litres, the molar volume, instead of 32.0 g, the molar mass)} \]

The identity becomes directly

\[ \frac{2.0 \text{ g}}{x} = \frac{2 \times 123}{3 \times 22.4 \text{ litres}} \]

\[ x = 0.55 \text{ litre of O}_2 \text{ at STP} \]

Now return to item 1 and go through the reasoning again. When you return to this point, complete the following item.

4. This process is applicable only for the \textit{volume} of a gas at STP, because only for gases at STP does a molar volume, 22.4 litres, equal \underline{______________}. 


A mole or a molar mass

5. Solve the following problem stepwise, using this direct method. In the laboratory preparation of hydrogen, how many litres of hydrogen at STP will be produced by the reaction of 1.5 grams of zinc with an excess of sulfuric acid?

*Step I:* Type of problem.

Mass of one substance to find volume of another gaseous substance

6. *Step II:* Write and balance the equation.

\[
\text{Zn(s)} + \text{H}_2\text{SO}_4(\text{aq}) \rightarrow \text{H}_2(\text{g}) + \text{ZnSO}_4(\text{aq})
\]

7. *Step III:* Over the formulas indicate the quantity known and the quantity to be determined. You need not recopy the equation at each step.

\[
\begin{align*}
1.5 \text{ g} & \quad x \\
\text{Zn(s)} + \text{H}_2\text{SO}_4(\text{aq}) & \rightarrow \text{H}_2(\text{g}) + \text{ZnSO}_4(\text{aq})
\end{align*}
\]

8. *Step IV:* Under the formula of substance whose mass is involved, write its molecular weight (formula weight, atomic weight). Under the formula of the substance whose volume is involved, write 22.4 litres.

\[
\begin{align*}
1.5 \text{ g} & \quad x \\
65.4 \text{ g} & \quad 22.4 \text{ litres}
\end{align*}
\]


\[
\frac{\text{mass}}{\text{volume}} = \frac{\text{number of moles x molecular (atomic) weight}}{\text{number of moles x 22.4 litres}}
\]

\[
\frac{1.5 \text{ g}}{x} = \frac{1 \times 65.4 \text{ g}}{1 \times 22.4 \text{ litres}}
\]

10. Solve for x to the appropriate number of significant figures.
X = 0.51 litre

11. Without referring to the sample problem, solve this problem. How many grams of limestone (CaCO3) are required to react with an excess of hydrochloric acid in order to produce 20 litres of carbon dioxide at STP?

\[
\begin{align*}
&\text{CaCO}_3(s) + 2 \text{HCl}(aq) \rightarrow \text{CaCl}_2(aq) + \text{H}_2\text{O} + \text{CO}_2(g) \\
&\text{100 g} \quad \text{20 litres} \\
&\hphantom{\text{CaCO}_3(s) + 2 \text{HCl}(aq) \rightarrow \text{CaCl}_2(aq) + \text{H}_2\text{O} + \text{CO}_2(g)} \\
\hphantom{\text{100 g} \quad \text{20 litres}} \\
\frac{x}{20 \text{ litres}} = \frac{100 \text{ g}}{22.4 \text{ litres}} \\
x = 89 \text{ g}
\end{align*}
\]

12. In this problem, what volume of CaCl\textsubscript{2} will be produced?

The volume of CaCl\textsubscript{2}, which is a white crystalline solid (not a gas), cannot be calculated from this information.

13. What volume of gas at STP can be obtained by the complete combustion of 50 grams of pure carbon? Solve, then check.

\[
\begin{align*}
&\text{C(s)} + \text{O}_2(g) \rightarrow \text{CO}_2(g) \\
&\text{12.0 g} \quad \text{22.4 litres} \\
\hphantom{\text{C(s)} + \text{O}_2(g) \rightarrow \text{CO}_2(g)} \\
\hphantom{\text{12.0 g} \quad \text{22.4 litres}} \\
\frac{50 \text{ g}}{x} = \frac{1 \times 12.0 \text{ g}}{1 \times 22.4 \text{ litres}} \\
x = 93 \text{ litres}
\end{align*}
\]

14. 26 grams of ammonium chloride are reacted with calcium hydroxide in the usual laboratory preparation of ammonia. What volume of ammonia at STP can you obtain from this mass of ammonium chloride?
26 g
2 \text{NH}_4\text{Cl(s)} + \text{Ca(OH)}_2(\text{s}) \rightarrow \text{CaCl}_2(\text{aq}) + \frac{x}{2} \text{NH}_3(\text{g}) + 2 \text{H}_2\text{O}
53.5 g
22.4 \text{litres}

\frac{26 \text{ g}}{x} = \frac{2 \times 53.5 \text{ g}}{2 \times 22.4 \text{ litres}}

x = 11 \text{ litres}, \text{ to correct number of significant figures}

15. How much iron(II) sulfide is required to react with hydrochloride acid in order to produce 10 litres of hydrogen sulfide at STP?

\frac{x}{10 \text{ litres}} = \frac{1 \times 87.9 \text{ g}}{1 \times 22.4 \text{ litres}}

x = 39 \text{ g}

THE MOLE METHOD OF SOLVING CHEMICAL PROBLEMS

INSTRUCTIONS TO THE STUDENT

Up until this time you have been solving chemical problems by the proportion method. This set will help you learn a more general method called the \textit{mole method}. It is beyond the intent of these Units to prove to you that these methods are mathematically equivalent. Your science or mathematics teacher can show you, if you are interested.

Use whichever method you find easier, or the method your teacher asks you to use. This set will teach you how to solve problems involving mass to mass and mass to volume of a gas at STP.

It is assumed that you can balance a chemical equation. If not, work through the Unit on \textit{Balancing Chemical Equations}. You should also be able to write a formula, to calculate molecular weight, and to convert grams to moles and moles to grams. If you cannot, work through these sections in \textit{Molecular Weight Calculations}.

Since answers are required to only three significant figures, you are encouraged to use a slide rule. You need paper, pen, and a periodic table. The method is the same as in other sets.

\textbf{First, let us review.}
1. How many moles are in 10.0 grams of barium chloride? The formula for barium chloride is \( \text{BaCl}_2 \).

2. The molecular weight of barium chloride, to 3 significant figures is ____________.

\[
\begin{align*}
1 \text{ Ba} & = 1 \times 137 \text{ u} = 137 \text{ u} \\
2 \text{ Cl} & = 2 \times 35.5 \text{ u} = 71.0 \text{ u} \\
\text{molecular weight} & = 208 \text{ u or 208 g}
\end{align*}
\]

“u” stands for unified atomic mass unit. It is the mass of one atom of a specific carbon isotope and is equal to \(1.66053 \times 10^{-27}\) kg.

3. Now convert 10.0 grams of \( \text{BaCl}_2 \) to moles.

\[
\frac{1 \text{ mole } \text{BaCl}_2}{208 \text{ g } \text{BaCl}_2} \times 10.0 \text{ g } \text{BaCl}_2 = 0.0481 \text{ mole } \text{BaCl}_2
\]

4. How many grams are in 0.100 mole of silver nitrate? Slip the mask down only when you have completed the answer.

Formula is \( \text{AgNO}_3 \)

Molecular weight: 
\[
\begin{align*}
1 \text{ Ag} & \times 108 \text{ u} = 108 \text{ u} \\
1 \text{ N} & \times 14 \text{ u} = 14 \text{ u} \\
3 \text{ O} & \times 16 \text{ u} = 48 \text{ u}
\end{align*}
\]

Molecular weight = 170 u or 170 g

\[
0.100 \text{ mole } \text{AgNO}_3 \times \frac{170 \text{ g}}{1 \text{ mole } \text{AgNO}_3} = 17.0 \text{ g}
\]

5. Now apply these preliminaries to a mass problem by the mole method. How many grams of silver nitrate are required to precipitate 10.0 grams of barium chloride from solutions?

The known quantity in this reaction is __________ of __________.

(units) (formula)
10.0 grams \( \text{BaCl}_2 \)

6. The unknown quantity is \( \text{__________} \) of \( \text{__________} \).

\[ \text{X grams} \quad \text{AgNO}_3 \]

7. Write a balanced equation for the reaction. You may omit (s), (g), and (aq) in order to save time.

\[ 2 \text{AgNO}_3 + \text{BaCl}_2 \rightarrow \text{Ba(NO}_3)_2 + 2 \text{AgCl} \]

If you are in error, review Balancing Chemical Equations. Recall that this equation can be read, “2 molecules of AgNO3 combine with 1 molecule of BaCl2 to form 1 molecule of Ba(NO3)2 and 2 molecules of AgCl.” Since individual molecules are so small, it can also be read, “2 moles (1 mole = an Avogadro’s number of molecules) of AgNO3 combine with 1 mole of BaCl2 to form a mole of Ba(NO3)2 and 2 moles of AgCl.”

It cannot be interpreted as “2 grams AgNO3 with 1 gram of BaCl2 yield 1 gram of Ba(NO3)2 and 2 grams of AgCl.” Moles of different substances have different masses, because the masses of the elements which make up the substances are different.

8. You have now determined that the known quantity is 10.0 of BaCl2 and the unknown quantity is \( x \) g of AgNO3. From the balance equation, the mole ratio of:

\[ \frac{\text{AgNO}_3}{\text{BaCl}_2} = \frac{2}{1} \]

Now calculate the molecular weight of both the known and unknown substances.

\[
\text{BaCl}_2 = 208 \text{ g; AgNO}_3 = 170 \text{ g} \quad \text{(See items 2 and 4.)}
\]

You will not need to use the molecular weight of the AgNO3 until later in the problem.

9. Calculate the number of moles of BaCl2 in 10.0 grams of the substance.
0.0481 mole BaCl\(_2\) (See item 3.)

10. AgNO\(_3\) combines with BaCl\(_2\) in a ratio of 2:1. (See balanced equation, item 7.) Therefore,

\[
\frac{x \text{ mole AgNO}_3}{0.0481 \text{ mole BaCl}_2} = \frac{2}{1}
\]

Solve for x moles AgNO\(_3\).

0.0962 mole AgNO\(_3\)

11. Convert 0.0962 mole AgNO\(_3\) to grams. (See item 4.)

\[
\frac{170 \text{ g AgNO}_3}{0.0962 \text{ mole AgNO}_3} \times \frac{1 \text{ mole AgNO}_3}{1} = 16.4 \text{ g AgNO}_3
\]

This is the answer to the original problem it item 5.

12. At this point, go back to item 5, work your way through the problem again, and see if you can identify the general process at each step.

- **Step I.** Identify the known and unknown substances with their formulas (item 5 and 6).
- **Step II.** Write a balanced equation for the reaction (item 7).
- **Step III.** Determine the mole ratios of known and unknown (item 8).
- **Step IV.** Calculate the molecular weights of both the known and unknown substances (item 8).
- **Step V.** Convert grams of known substances of moles (item 9).
- **Step VI.** From the mole ratios of unknown to known (from the balanced equation), calculate the moles of unknown (item 10).
- **Step VII.** Convert moles of unknown to grams of unknown (item 11).

Copy these steps in your notebook. Then go on to the next item, which is a similar problem.
13. We will use the same reaction, but not the same known and unknown substances, in order to simplify your calculations.

In the reaction of silver nitrate and barium chloride, barium nitrate and silver chloride are produced. If 20.0 grams of barium nitrate are formed, how many grams of silver chloride are also produced?

**Step I:** The known substance is ________ of ________. The unknown substance is ________ of ________.

<table>
<thead>
<tr>
<th>Amount</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0 g</td>
<td>Ba(NO₃)₂</td>
</tr>
<tr>
<td>x g</td>
<td>AgCl</td>
</tr>
</tbody>
</table>

14. **Step II:** Write the balanced equation for the reaction.

\[ 2 \text{AgNO}_3 + \text{BaCl}_2 \rightarrow \text{Ba(NO}_3)_2 + 2 \text{AgCl} \]

15. **Step III:** What is the mole ratio of Ba(NO₃)₂ to AgCl?

\[ \frac{1}{2} \]

16. **Step IV:** The molecular weight of Ba(NO₃)₂ is ____________. The molecular weight of AgCl is ____________.

<table>
<thead>
<tr>
<th>Molecular Weight</th>
<th>Substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>261 g</td>
<td>Ba(NO₃)₂</td>
</tr>
<tr>
<td>143 g</td>
<td>AgCl</td>
</tr>
</tbody>
</table>

17. **Step V:** How many moles of Ba(NO₃)₂ are formed in the reaction?

\[ \frac{1 \text{ mole Ba(NO}_3)_2}{20.0 \text{ g Ba(NO}_3)_2} \times \frac{261 \text{ g Ba(NO}_3)_2}{1 \text{ mole Ba(NO}_3)_2} = 0.0766 \text{ mole Ba(NO}_3)_2 \]

18. **Step VI:** How many moles of AgCl are formed in the reaction?
\[
\frac{2 \text{ moles AgCl}}{1 \text{ mole Ba(NO}_3)_2} = \frac{x \text{ mole AgCl}}{0.0766 \text{ mole Ba(N}_3)_2}
\]

\[x = 0.153 \text{ mole AgCl}\]

19. **Step VII**: How many grams of AgCl are formed in the reaction?

\[
\frac{143 \text{ g AgCl}}{0.153 \text{ mole AgCl}} \times \frac{1 \text{ mole AgCl}}{1 \text{ mole AgCl}} = 21.9 \text{ g AgCl}
\]

20. In order to prove to yourself that you can use the mole method of solving mass to mass problems, work out the solution to this one.

The thermite reaction is a very spectacular one in which molten iron is released to produce fast welds in breaks which are difficult to reach. How many grams of iron can be produced by reacting 500 g of aluminum with iron(III) oxide? You may refer to the steps outlined in item 12 or to your notes. Remember that the logic of the process is based upon the fact that *substances react by mole ratios, not by gram ratios.*

**Step I**: The known substance is ____________ grams of ______________. The unknown substance is ____________ grams of ______________.

21. **Step II**: Write the balanced equation for the reaction.

\[2 \text{ Al} + \text{ Fe}_2\text{O}_3 \rightarrow 2 \text{ Fe} + \text{ Al}_2\text{O}_3\]

22. **Step III**: What is the mole ratio of Al to Fe?

\[
\frac{2}{2} \text{ or } \frac{1}{1}
\]

23. **Step IV**: The molecular weight of Al is ______________. The molecular weight of Fe is ______________.
27.0 g  55.8 g

24. Step V: How many moles of Al are used in the reaction?

\[
\frac{1 \text{ mole Al}}{500 \text{ g Al}} \times \frac{27.0 \text{ g Al}}{1 \text{ mole Al}} = 18.5 \text{ moles Al}
\]

25. Step VI: How many moles of Fe are formed in the reaction?

\[
\frac{1 \text{ mole Fe}}{1 \text{ mole Al}} \times \frac{x \text{ moles Fe}}{18.5 \text{ moles Al}}
\]

\[x = 18.5 \text{ moles Fe}\]

26. Step VII: How many grams of Fe are formed in the reaction?

\[
\frac{55.8 \text{ g Fe}}{18.5 \text{ moles Fe}} \times \frac{1 \text{ mole Fe}}{1 \text{ mole Fe}} = 1030 \text{ g Fe (to 3 significant figures)}
\]

All mass to mass problems can be solved by this method. Refer to your text for additional examples.

27. The next items consider mass to volume of a gas at STP problems by the mole method. The only way in which these problems differ from the mass to mass problems you have just done is that, in this case, one of the substances is a gas and the conditions are STP. If the conditions are not STP, a separate gas law problem must also be done.

You make use of the experimental fact that a mole of any gas at STP occupies a volume of 22.4 litres. Begin by practicing a few conversions from moles of a gas at STP to its volume. Based on Avogadro’s principle, 22.4 litres is the volume of any gas at STP.

What is the volume occupied by 0.20 mole of carbon monoxide at STP, calculated to 3 significant figures?

\[
0.20 \text{ mole CO} \times \frac{22.4 \text{ litres CO}}{1 \text{ mole CO}} = 4.48 \text{ litres CO}
\]

28. 85.0 litres of SO₂ at STP equal how many moles?
85.0 litres \( \text{SO}_2 \) x \( \frac{22.4 \text{ litres } \text{SO}_2}{1 \text{ mole } \text{SO}_2} \) = 3.79 moles \( \text{SO}_2 \)

The principle is obvious and you may invent other examples for yourself, if you need more practice.

29. Now work out this mass to volume of a gas at STP problem with the same steps used in the previous mass to mass problems up to Step VII.

   How many litres of carbon dioxide are produced when 40.0 g of carbon are burned in pure oxygen?

   **Step I:** The known substance is \( \text{_____________ of } \text{______________} \). The unknown substance is \( \text{_____________ of } \text{______________} \).

     \[
     \begin{align*}
     40.0 \text{ g} & \quad \text{C} & \quad x \text{ litres} & \quad \text{CO}_2
     \end{align*}
     \]

   **Step II:** Write the balanced equation for the reaction.

       \[
       \text{C(s) + O}_2(g) \rightarrow \text{CO}_2(g)
       \]

   **Step III:** What is the mole ratio of C to CO\(_2\)?

       \[
       \frac{1}{1}
       \]

   **Step IV:** The molecular weight of C is \( \text{______________} \). (In mass to volume problems, you need to calculate only the molecular weight of the substance involving mass.)

       12.0 g (the same as the atomic weight)

   **Step V:** How many moles of C are used in the reaction?

       \[
       \begin{align*}
       40.0 \text{ g } \text{C} & \quad x \quad \frac{1 \text{ mole C}}{12.0 \text{ g } \text{C}} = 3.33 \text{ mole C}
       \end{align*}
       \]

   **Step VI:** How many moles of CO\(_2\) are formed in the reaction?
\[ \frac{x \text{ moles CO}_2}{3.33 \text{ moles C}} = \frac{1}{1} \]

\[ x = 3.33 \text{ moles CO}_2 \]

35. Now Step VII is different. The question asks for litres of CO\(_2\) not grams of CO\(_2\). Convert moles of CO\(_2\) to litres.

\[ \frac{22.4 \text{ litres CO}_2}{3.33 \text{ moles CO}_2 \times 1 \text{ mole CO}_2} = 74.6 \text{ litres of CO}_2 \text{ at STP} \]

36. In the regional problem in item 29, how many litres of pure O\(_2\) are required? Read over items 29-35. The problem may be easier than you think.

\[ \frac{\text{moles O}_2}{74.6 \text{ litres of O}_2 \text{ at STP}, \text{ because moles CO}_2 = \frac{1}{1}} \text{ Therefore, litres of O}_2 \text{ equal litres of CO}_2. \]

37. Air is about 20% O\(_2\), so how much air would be required?

5 times as much air would be required.
5 x 74.6 litres = 373 litres of air

38. Now work out another mass to volume of a gas at STP problem to be sure that you know how to do them.

A convenient method of producing small quantities of ammonia in the laboratory is by heating ammonium chloride with calcium hydroxide to yield ammonia, water, and calcium chloride. How many litres of NH\(_3\) at STP can be produced by using 50.0 g of NH\(_4\)C\(_1\)?

Do not slip down the mask until you have completed the whole problem.

Step I: known is 50.0 g NH\(_4\)C\(_1\); unknown is x litres NH\(_3\)

Step II: \[ 2 \text{ NH}_4\text{C}_1 + \text{Ca(OH)}_2 \rightarrow 2 \text{ NH}_3 + \text{H}_2\text{O} + \text{CaCl}_2 \]

\[ \frac{\text{NH}_4\text{C}_1}{\text{NH}_3} = \frac{2}{2} \text{ or } \frac{1}{1} \]

Step IV: molecular weight of NH\(_4\)C\(_1\) = 53.5 g
Step V: \[
\frac{1 \text{ mole } \text{NH}_4\text{Cl}}{50.0 \text{ g } \text{NH}_4\text{Cl}} \times \frac{53.5 \text{ g } \text{NH}_4\text{Cl}}{1 \text{ mole } \text{NH}_4\text{Cl}} = 0.934 \text{ mole } \text{NH}_4\text{Cl}
\]

\[
\frac{\text{moles } \text{NH}_3}{\text{moles } \text{NH}_4\text{Cl}} = \frac{1}{1} = 0.934 \text{ mole } \text{NH}_4\text{Cl}
\]
\[
x = 0.934 \text{ mole } \text{NH}_3
\]

Step VI: \[
\frac{22.4 \text{ litres}}{\text{22.4 litres } \text{NH}_3} \times 1 \text{ mole } \text{NH}_3 = 20.9 \text{ litres } \text{NH}_3 \text{ at STP}
\]

39. It is also possible to solve these problems going from volume at STP to mass. In the same reaction as before, how many grams of \text{NH}_4\text{Cl} are required to produce 10.0 litres of \text{NH}_3 at STP?

Step I: known is 10.0 litres \text{NH}_3; unknown is \(x\) g \text{NH}_4\text{Cl}

Step II: as in item 38

Step III: as in item 38

Step IV: molecular weight of \text{NH}_4\text{Cl} = 53.5 g (This is needed because in Step VII you will convert moles to grams.)

Step V: moles of \text{NH}_3:
\[
\frac{1 \text{ mole } \text{NH}_3}{22.4 \text{ litres } \text{NH}_3} \times 10.0 \text{ litres } \text{NH}_3 = 0.446 \text{ mole } \text{NH}_3
\]
\[
\frac{\text{mole } \text{NH}_4\text{Cl}}{\text{mole } \text{NH}_3} = \frac{1}{1} = \frac{x}{0.446 \text{ mole } \text{NH}_3}
\]
\[
x = 0.446 \text{ mole } \text{NH}_4\text{Cl}
\]

Step VII: \[
0.446 \text{ mole } \text{NH}_4\text{Cl} \times \frac{53.5 \text{ g } \text{NH}_4\text{Cl}}{1 \text{ mole } \text{NH}_4\text{Cl}} = 23.9 \text{ g } \text{NH}_4\text{Cl}
\]

If you follow these steps, and show units at every step, you should be able to solve all mass and volume of a gas at STP problems using the mole method.
**SAMPLE PROBLEM**

**MASS TO MASS**

How many tonnes of calcium oxide can be obtained by heating 15 tonnes of calcium carbonate?

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Determine type of problem.</td>
<td>Mass to mass</td>
</tr>
<tr>
<td>II.</td>
<td>Write a balanced equation.</td>
<td>( \text{CaCO}_3(s) \rightarrow \text{CaO}(s) + \text{CO}_2(g) )</td>
</tr>
<tr>
<td>III.</td>
<td>Over their formulas, write the information about the known and unknown quantities.</td>
<td>15 tonnes ( x ) ( \text{CaCO}_3(s) \rightarrow \text{CaO}(s) + \text{CO}_2(g) )</td>
</tr>
<tr>
<td>IV.</td>
<td>Calculate the molecular weight or formula weight of the substances involved to three significant figures. Write these, expressed in grams, under their formulas in the balanced equation.</td>
<td>15 tonnes ( x ) ( \text{CaCO}_3(s) \rightarrow \text{CaO}(s) + \text{CO}_2(g) ) ( 100g ) ( 56.1 \text{ g} )</td>
</tr>
</tbody>
</table>
| V.   | Write an identity. | \[
\frac{\text{mass of known}}{\text{mass of unknown}} = \frac{\text{no. of molecules of known x mol. wt. of known}}{\text{no. of molecules of unknown x mol. wt. of unknown}}
\] |
| VI.  | Solve for unknown with units and correct number of significant figures. | \[
\frac{15 \text{ tonnes}}{x} = \frac{1 \times 100 \text{ g}}{1 \times 56.1 \text{ g}}
\] |

Copy this sample problem into your notebook. Leave several lines of space below it. After you have completed the program through item 53, summarize in the space the physical principles upon which this method is based.
### SAMPLE PROBLEM

**VOLUME TO VOLUME OF GASES**

How many litres of chlorine react with 12 litres of hydrogen to form hydrogen chloride?

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Determine type of problem.</td>
<td>Volume to volume</td>
</tr>
<tr>
<td>II.</td>
<td>Write a balanced equation.</td>
<td>( \text{H}_2(g) + \text{Cl}_2(g) \rightarrow 2 \text{HCl}(g) )</td>
</tr>
<tr>
<td>III.</td>
<td>Over their formulas, write the information about the known and unknown quantities.</td>
<td>12 litres ( x ) H(_2)(g) (+) Cl(_2)(g) (\rightarrow) 2 HCl(g)</td>
</tr>
<tr>
<td>IV.</td>
<td>Do not calculate molecular weights. If the gases are under the same temperature and pressure, they combine in proportion to their number of molecules. Write an identity.</td>
<td></td>
</tr>
<tr>
<td>V.</td>
<td>Solve for unknown with units and correct number of significant figures.</td>
<td>( x = 12 \text{ litres} )</td>
</tr>
</tbody>
</table>

\[
\frac{\text{volume of known}}{\text{volume of unknown}} = \frac{\text{coefficient of known}}{\text{coefficient of unknown}}
\]

\[
\frac{\text{H}_2}{\text{Cl}_2} = \frac{12 \text{ litres}}{x} = 1
\]