Chapter 5
Chemical Quantities and Reactions

5.1
The Mole

A collection term states a specific number of items.

- 1 dozen donuts = 12 donuts
- 1 ream of paper = 500 sheets
- 1 case = 24 cans

A mole is a collection that contains

- the same number of particles as there are carbon atoms in 12.0 g of carbon.
- \(6.02 \times 10^{23}\) atoms of an element (Avogadro’s number).

<table>
<thead>
<tr>
<th>1 mole element</th>
<th>Number of Atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mole C</td>
<td>(6.02 \times 10^{23}) C atoms</td>
</tr>
<tr>
<td>1 mole Na</td>
<td>(6.02 \times 10^{23}) Na atoms</td>
</tr>
<tr>
<td>1 mole Au</td>
<td>(6.02 \times 10^{23}) Au atoms</td>
</tr>
</tbody>
</table>

A mole of a compound

- of a covalent compound has Avogadro’s number of molecules.
  
  \[1 \text{ mole CO}_2 = 6.02 \times 10^{23} \text{ CO}_2 \text{ molecules}\]
  \[1 \text{ mole H}_2\text{O} = 6.02 \times 10^{23} \text{ H}_2\text{O} \text{ molecules}\]

- of an ionic compound contains Avogadro’s number of formula units.
  
  \[1 \text{ mole NaCl} = 6.02 \times 10^{23} \text{ NaCl formula units}\]
  \[1 \text{ mole K}_2\text{SO}_4 = 6.02 \times 10^{23} \text{ K}_2\text{SO}_4 \text{ formula units}\]

Samples of 1 Mole Quantities

- 1 mole of C atoms = \(6.02 \times 10^{23}\) C atoms
- 1 mole of Al atoms = \(6.02 \times 10^{23}\) Al atoms
- 1 mole of S atoms = \(6.02 \times 10^{23}\) S atoms
- 1 mole of H\(2\)O molecules = \(6.02 \times 10^{23}\) H\(2\)O molecules
- 1 mole of CCl\(4\) molecules = \(6.02 \times 10^{23}\) CCl\(4\) molecules

Avogadro’s Number

Avogadro’s number, \(6.02 \times 10^{23}\), can be written as an equality and two conversion factors.

Equality:
\[1 \text{ mole} = 6.02 \times 10^{23} \text{ particles}\]

Conversion Factors:
\[6.02 \times 10^{23} \text{ particles} \quad \text{and} \quad 1 \text{ mole} = 6.02 \times 10^{23} \text{ particles}\]
Using Avogadro’s Number

Avogadro’s number is used to:
- convert moles to particles
- convert particles to moles

Converting Moles to Particles

Avogadro’s number is used to convert moles of a substance to particles.

How many Cu atoms are in 0.50 mole of Cu?

\[ 0.50 \text{ mole Cu} \times \frac{6.02 \times 10^{23} \text{ Cu atoms}}{1 \text{ mole Cu}} = 3.0 \times 10^{23} \text{ Cu atoms} \]

Converting Particles to Moles

Avogadro’s number is used to convert particles of a substance to moles.

How many moles of CO₂ are in 2.50 \times 10^{24} \text{ molecules CO}_2? \[ 2.50 \times 10^{24} \text{ molecules CO}_2 \times \frac{1 \text{ mole CO}_2}{6.02 \times 10^{23} \text{ molecules CO}_2} = 4.15 \text{ moles of CO}_2 \]

Learning Check

1. The number of atoms in 2.0 mole of Al atoms is
   A. 2.0 Al atoms.
   B. 3.0 \times 10^{23} \text{ Al atoms}.
   C. 1.2 \times 10^{24} \text{ Al atoms}.

2. The number of moles of S in 1.8 \times 10^{24} \text{ atoms of S} is
   A. 1.0 \text{ mole of S atoms}.
   B. 3.0 \text{ moles of S atoms}.
   C. 1.1 \times 10^{44} \text{ moles of S atoms}.

Solution

C. 1.2 \times 10^{24} \text{ Al atoms}
   
   \[ 2.0 \text{ mole-Al} \times \frac{6.02 \times 10^{23} \text{ Al atoms}}{1 \text{ mole-Al}} = \text{ } \]

B. 3.0 \text{ moles of S atoms}
   
   \[ 1.8 \times 10^{24} \text{ S atoms} \times \frac{1 \text{ mole S}}{6.02 \times 10^{23} \text{ S atoms}} = \text{ } \]

Subscripts and Moles

The subscripts in a formula show:
- the relationship of atoms in the formula.
- the moles of each element in 1 mole of compound.

Glucose

\[ \text{C}_6\text{H}_{12}\text{O}_6 \]

In 1 molecule: 6 atoms C 12 atoms H 6 atoms O
In 1 mole: 6 moles C 12 moles H 6 moles O
Subscripts State Atoms and Moles

Factors from Subscripts

The subscripts are used to write conversion factors for moles of each element in 1 mole of a compound. For aspirin, C9H8O4, the possible conversion factors are:

- 9 moles C
- 8 moles H
- 4 moles O

Learning Check

A. How many moles of O are in 0.150 mole of aspirin, C9H8O4?

B. How many atoms of O are in 0.150 mole of aspirin, C9H8O4?

Solution

A. Moles of O in 0.150 mole of aspirin, C9H8O4

\[
0.150 \text{ mole } C_9H_8O_4 \times \frac{4 \text{ mole } O}{1 \text{ mole } C_9H_8O_4} = 0.600 \text{ mole of O}
\]

B. Atoms of O in 0.150 mole of aspirin, C9H8O4

\[
0.150 \text{ mole } C_9H_8O_4 \times \frac{4 \text{ mole } O}{1 \text{ mole } C_9H_8O_4} \times \frac{6.02 \times 10^{23} \text{ O atoms}}{1 \text{ mole } O} = 3.61 \times 10^{23} \text{ atoms of O}
\]

Chapter 5
Chemical Quantities and Reactions

5.2
Molar Mass

The molar mass
- is the mass of 1 mole of an element or compound.
- is the atomic or molecular mass expressed in grams.
Molar Mass from Periodic Table

Molar mass is the atomic mass expressed in grams.

1 mole of Ag = 107.9 g
1 mole of C = 12.01 g
1 mole of S = 32.07 g

Learning Check

Give the molar mass for each (to the tenths decimal place).

A. 1 mole of K atoms = 39.1 g
B. 1 mole of Sn atoms = 118.7 g

Solution

Give the molar mass for each (to the tenths decimal place).

A. 1 mole of K atoms = 39.1 g
B. 1 mole of Sn atoms = 118.7 g

Guide to Calculation Molar Mass of a Compound

1. Obtain the molar mass of each element.
2. Multiply each molar mass by the number of moles (subscript) in the formula.
3. Calculate the molar mass by adding the masses of the elements.

Molar Mass of K₃PO₄

Calculate the molar mass of K₃PO₄.

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of Moles</th>
<th>Atomic Mass</th>
<th>Total Mass in K₃PO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>3</td>
<td>39.1 g/mole</td>
<td>117.3 g</td>
</tr>
<tr>
<td>P</td>
<td>1</td>
<td>31.0 g/mole</td>
<td>31.0 g</td>
</tr>
<tr>
<td>O</td>
<td>4</td>
<td>16.0 g/mole</td>
<td>64.0 g</td>
</tr>
<tr>
<td>K₃PO₄</td>
<td></td>
<td></td>
<td>212.3 g</td>
</tr>
</tbody>
</table>
Some 1-mole Quantities

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2O</td>
<td>32.1 g</td>
</tr>
<tr>
<td>NaCl</td>
<td>55.9 g</td>
</tr>
<tr>
<td>KCl</td>
<td>58.5 g</td>
</tr>
<tr>
<td>Al(OH)3</td>
<td>294.2 g</td>
</tr>
<tr>
<td>CuCl2·2H2O</td>
<td>342.2 g</td>
</tr>
</tbody>
</table>

Learning Check

What is the molar mass of each of the following?

A. K2O
B. Al(OH)3

Solution

A. K2O  
2 moles of K (39.1 g/mole) + 1 mole of O (16.0 g/mole)  
78.2 g + 16.0 g = 94.2 g

B. Al(OH)3  
1 mole of Al (27.0 g/mole) + 3 moles of O (16.0 g/mole)  
27.0 g + 48.0 g + 3.03 g = 78.0 g

Learning Check

Prozac, C17H18F3NO, is an antidepressant that inhibits the uptake of serotonin by the brain. What is the molar mass of Prozac?

3) 309 g/mole

Solution

Prozac, C17H18F3NO, is an antidepressant that inhibits the uptake of serotonin by the brain. What is the molar mass of Prozac?

3) 309 g/mole

17 C (12.0) + 18 H (1.01) + 3 F (19.0) + 1 N (14.0) + 1 O (16.0) =

204 g C + 18.2 g H + 57.0 g F + 14.0 g N + 16.0 g O = 309 g/mole

Molar Mass Factors

Molar mass conversion factors
- are fractions (ratios) written from the molar mass.
- relate grams and moles of an element or compound.
- for methane, CH4, used in gas stoves and gas heaters is

1 mole of CH4 = 16.0 g (molar mass equality)

Conversion factors:

\[
\frac{16.0 \text{ g CH}_4}{1 \text{ mole CH}_4} \quad \text{and} \quad \frac{1 \text{ mole CH}_4}{16.0 \text{ g CH}_4}
\]
Acetic acid, $\text{C}_2\text{H}_4\text{O}_2$, gives the sour taste to vinegar. Write two molar mass conversion factors for acetic acid.

Calculate molar mass for acetic acid $\text{C}_2\text{H}_4\text{O}_2$:
$$
24.0 \text{ g C} + 4.04 \text{ g H} + 32.0 \text{ g O} = 60.0 \text{ g/mole C}_2\text{H}_4\text{O}_2
$$

1 mole of acetic acid = $60.0 \text{ g acetic acid}$

Molar mass factors:
$$
\frac{1 \text{ mole acetic acid}}{60.0 \text{ g acetic acid}} \text{ and } \frac{60.0 \text{ g acetic acid}}{1 \text{ mole acetic acid}}
$$

Aluminum is often used to build lightweight bicycle frames. How many grams of Al are in 3.00 mole of Al?

Molar mass equality: 1 mole of Al = 27.0 g of Al

Setup with molar mass as a factor:
$$
3.00 \text{ mole Al} \times \frac{27.0 \text{ g Al}}{1 \text{ mole Al}} = 81.0 \text{ g of Al}
$$

Calculate the molar mass of $\text{C}_6\text{H}_{10}\text{S}$.

$$(6 \times 12.0) + (10 \times 1.01) + (1 \times 32.1) = 114.2 \text{ g/mole}$$

Set up the calculation using a mole factor.
$$
225 \text{ g C}_6\text{H}_{10}\text{S} \times \frac{1 \text{ mole C}_6\text{H}_{10}\text{S}}{114.2 \text{ g C}_6\text{H}_{10}\text{S}} \text{ molar mass factor (inverted)}
$$

= 1.97 moles of $\text{C}_6\text{H}_{10}\text{S}$
Learning Check

How many \( \text{H}_2\text{O} \) molecules are in 24.0 g of \( \text{H}_2\text{O} \)?

1) \( 4.52 \times 10^{23} \text{ H}_2\text{O} \) molecules

2) \( 1.44 \times 10^{25} \text{ H}_2\text{O} \) molecules

3) \( 8.03 \times 10^{23} \text{ H}_2\text{O} \) molecules

Solution

How many \( \text{H}_2\text{O} \) molecules are in 24.0 g of \( \text{H}_2\text{O} \)?

3) \( 8.02 \times 10^{23} \)

\[
24.0 \text{ g H}_2\text{O} \times \frac{1 \text{ mole H}_2\text{O}}{18.0 \text{ g H}_2\text{O}} \times 6.02 \times 10^{23} \text{ H}_2\text{O} \text{ molecules} = 8.03 \times 10^{23} \text{ H}_2\text{O} \text{ molecules}
\]

Learning Check

If the odor of \( \text{C}_6\text{H}_{10}\text{S} \) can be detected from \( 2 \times 10^{-13} \) g in 1 liter of air, how many molecules of \( \text{C}_6\text{H}_{10}\text{S} \) are present?

Solution

If the odor of \( \text{C}_6\text{H}_{10}\text{S} \) can be detected from \( 2 \times 10^{-13} \) g in 1 liter of air, how many molecules of \( \text{C}_6\text{H}_{10}\text{S} \) are present?

\[
2 \times 10^{-13} \text{ g} \times \frac{1 \text{ mole}}{114.2 \text{ g}} \times \frac{6.02 \times 10^{23} \text{ molecules}}{1 \text{ mole}} = 1 \times 10^9 \text{ molecules of C}_6\text{H}_{10}\text{S are present}
\]

Chapter 5
Chemical Quantities and Reactions

5.3 Chemical Changes
Physical Change

In a physical change,
• the state, shape, or size of the material changes.
• the identity and composition of the substance do not change.

Chemical Change

In a chemical change,
• reacting substances form new substances with different compositions and properties.
• a chemical reaction takes place.

Some Examples of Chemical and Physical Changes

<table>
<thead>
<tr>
<th>Chemical Changes</th>
<th>Physical Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burning a candle</td>
<td>Melting ice</td>
</tr>
<tr>
<td>Bleaching a stain</td>
<td>Boiling water</td>
</tr>
<tr>
<td>Burning a log</td>
<td>Sewing a log in half</td>
</tr>
<tr>
<td>Rusting silver</td>
<td>Teaing paper</td>
</tr>
<tr>
<td>Fermenting grapes</td>
<td>Breaking a glass</td>
</tr>
<tr>
<td>Souring of milk</td>
<td>Pouring milk</td>
</tr>
</tbody>
</table>

Learning Check

Classify each of the following as a 1) physical change or 2) chemical change.
A. _____ Burning a candle.
B. _____ Ice melting on the street.
C. _____ Toasting a marshmallow.
D. _____ Cutting a pizza.
E. _____ Polishing a silver bowl.

Solution

Classify each of the following as a 1) physical change or 2) chemical change.
A. 2) Burning a candle.
B. 1) Ice melting on the street.
C. 2) Toasting a marshmallow.
D. 1) Cutting a pizza.
E. 2) Polishing a silver bowl.

Chemical Reaction

In a chemical reaction
• a chemical change produces one or more new substances.
• there is a change in the composition of one or more substances.
Chemical Reaction

In a chemical reaction
• old bonds are broken and new bonds are formed.
• atoms in the reactants are rearranged to form one or more different substances.

Chapter 5
Chemical Quantities and Reactions

5.4 Chemical Equations

A chemical equation gives
• the formulas of the reactants on the left of the arrow.
• the formulas of the products on the right of the arrow.

Reactants: C(s) + O₂(g) → CO₂(g)

Symbols Used in Equations

Symbols in chemical equations show
• the states of the reactants.
• the states of the products.
• the reaction conditions.

Chemical Equations are Balanced

In a balanced chemical reaction
• no atoms are lost or gained.
• the number of reacting atoms is equal to the number of product atoms.
A Balanced Chemical Equation

In a balanced chemical equation,
- the number of each type of atom on the reactant side is equal to the number of each type of atom on the product side.
- numbers called coefficients are used in front of one or more formulas to balance the number of atoms.

\[
\begin{align*}
2 \text{Al} + 3 \text{S} & \rightarrow \text{Al}_2\text{S}_3 & \text{Not Balanced} \\
2 \text{Al} + 3 \text{S} & \rightarrow 2 \text{Al} + 3 \text{S} & \text{Balanced using coefficients}
\end{align*}
\]

A Study Tip: Using Coefficients

When balancing a chemical equation,
- use one or more coefficients to balance atoms.
- never change the subscripts of any formula.

\[
\begin{align*}
\text{N}_2 + \text{O}_2 & \rightarrow \text{NO} & \text{Not Balanced} \\
\text{N}_2 + \text{O}_2 & \rightarrow \text{N}_2\text{O}_2 & \text{Incorrect formula} \\
\text{N}_2 + \text{O}_2 & \rightarrow 2 \text{NO} & \text{Correctly balanced using coefficients}
\end{align*}
\]

Learning Check

State the number of atoms of each element on the reactant side and the product side for each of the following balanced equations.

A. \( \text{P}_4(\text{s}) + 6\text{Br}_2(\text{l}) \rightarrow 4\text{PBr}_3(\text{g}) \)

B. \( 2\text{Al}(\text{s}) + \text{Fe}_2\text{O}_3(\text{s}) \rightarrow 2\text{Fe}(\text{s}) + \text{Al}_2\text{O}_3(\text{s}) \)

Solution

A. \( \text{P}_4(\text{s}) + 6\text{Br}_2(\text{l}) \rightarrow 4\text{PBr}_3(\text{g}) \)

- 4 P atoms = 4 P atoms
- 12 Br atoms = 12 Br atoms

B. \( 2\text{Al}(\text{s}) + \text{Fe}_2\text{O}_3(\text{s}) \rightarrow 2\text{Fe}(\text{s}) + \text{Al}_2\text{O}_3(\text{s}) \)

- 2 Al atoms = 2 Al atoms
- 2 Fe atoms = 2 Fe atoms
- 3 O atoms = 3 O atoms

Learning Check

Determine if each equation is balanced or not.

A. \( \text{Na}(\text{s}) + \text{N}_2(\text{g}) \rightarrow \text{Na}_3\text{N}(\text{s}) \)

B. \( \text{C}_2\text{H}_4(\text{g}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{C}_2\text{H}_6\text{O}(\text{l}) \)

Solution

A. \( \text{Na}(\text{s}) + \text{N}_2(\text{g}) \rightarrow \text{Na}_3\text{N}(\text{s}) \)

No. 2 N atoms on reactant side; only 1 N atom on the product side. 1 Na atom on reactant side; 3 Na atoms on the product side.

B. \( \text{C}_2\text{H}_4(\text{g}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{C}_2\text{H}_6\text{O}(\text{l}) \)

Yes. 2 C atoms = 2 C atoms
6 H atoms = 6 H atoms
1 O atom = 1 O atom
Guide to Balancing a Chemical Equation

Steps in Balancing an Equation

To balance the following equation,
\[ \text{Fe}_3\text{O}_4(s) + \text{H}_2(g) \rightarrow \text{Fe}(s) + \text{H}_2\text{O}(l) \]
- work on one element at a time.
- use only coefficients in front of formulas.
- do not change any subscripts.

Fe:
\[ \text{Fe}_3\text{O}_4(s) + \text{H}_2(g) \rightarrow 3\text{Fe}(s) + \text{H}_2\text{O}(l) \]

O:
\[ \text{Fe}_3\text{O}_4(s) + \text{H}_2(g) \rightarrow 3\text{Fe}(s) + 4\text{H}_2\text{O}(l) \]

H:
\[ \text{Fe}_3\text{O}_4(s) + 4\text{H}_2(g) \rightarrow 3\text{Fe}(s) + 4\text{H}_2\text{O}(l) \]

Balancing Chemical Equations

1. Write the equation with the correct formulas.
   \[ \text{NH}_3(g) + \text{O}_2(g) \rightarrow \text{NO}(g) + \text{H}_2\text{O}(g) \]
2. Determine if the equation is balanced.
   No, H atoms are not balanced.
   \[ 2\text{NH}_3(g) + \text{O}_2(g) \rightarrow 2\text{NO}(g) + 3\text{H}_2\text{O}(g) \]
   Double the coefficients to give even number of O atoms.
   \[ 4\text{NH}_3(g) + 7\text{O}_2(g) \rightarrow 4\text{NO}(g) + 6\text{H}_2\text{O}(g) \]

Balancing Chemical Equations

4. Check that atoms of each element are equal in reactants and products.
   \[ 4\text{NH}_3(g) + 5\text{O}_2(g) \rightarrow 4\text{NO}(g) + 6\text{H}_2\text{O}(g) \]
   \[ \begin{align*}
       4 \text{ N} & \quad (4 \times 1 \text{ N}) \\
       12 \text{ H} & \quad (4 \times 3 \text{ H}) \\
       10 \text{ O} & \quad (5 \times 2 \text{ O})
   \end{align*} \]

Equation for a Chemical Reaction

Checking a Balanced Equation

\[ \text{C}_2\text{H}_4(g) + 2\text{O}_2(g) \rightarrow 2\text{CO}_2(g) + 2\text{H}_2\text{O}(g) \]

Reactants | Products
---|---
1 C atom | 1 C atom
4 H atoms | 4 H atoms
4 O atoms | 4 O atoms
Check the balance of atoms in the following:
Fe$_3$O$_4$(s) + 4H$_2$(g) $\rightarrow$ 3Fe(s) + 4H$_2$O(l)

A. Number of H atoms in products.
   1) 2  2) 4  3) 8
B. Number of O atoms in reactants.
   1) 2  2) 4  3) 8
C. Number of Fe atoms in reactants.
   1) 1  2) 3  3) 4

Learning Check

Balance each equation and list the coefficients in the balanced equation going from reactants to products:
A. __Mg(s) + __N$_2$(g) → __Mg$_3$N$_2$(s)
   1) 1, 3, 2  2) 3, 1, 2  3) 3, 1, 1
B. __Al(s) + __Cl$_2$(g) → __AlCl$_3$(s)
   1) 3, 3, 2  2) 1, 3, 1  3) 2, 3, 2

Solution

Fe$_3$O$_4$(s) + 4H$_2$(g) $\rightarrow$ 3Fe(s) + 4H$_2$O(l)
A. Number of H atoms in products.
   3) 8 (4H$_2$O)
B. Number of O atoms in reactants.
   2) 4 (Fe$_3$O$_4$)
C. Number of Fe atoms in reactants.
   2) 3 (Fe$_3$O$_4$)

Learning Check

Balance each equation and list the coefficients in the balanced equation going from reactants to products:
A. __Mg(s) + __N$_2$(g) → __Mg$_3$N$_2$(s)
   3) 3, 1, 1
B. __Al(s) + __Cl$_2$(g) → __AlCl$_3$(s)
   3) 2, 3, 2

Solution

A. 3) 3, 1, 1
   3Mg(s) + 1N$_2$(g) → 1Mg$_3$N$_2$(s)
B. 3) 2, 3, 2
   2Al(s) + 3Cl$_2$(g) → 2AlCl$_3$(s)

Equations with Polyatomic Ions

Na$_3$PO$_4$(aq) + MgCl$_2$(aq) → Mg$_3$(PO$_4$)$_2$(s) + NaCl(aq)

Balance PO$_4^{3-}$ as a unit

2Na$_3$PO$_4$(aq) + MgCl$_2$(aq) → Mg$_3$(PO$_4$)$_2$(s) + NaCl(aq)

2 PO$_4^{3-}$ = 2 PO$_4^{3-}$

Check Na$^+$ balance

6 Na$^+$ = 6 Na$^+$

Balance Mg and Cl

2Na$_3$PO$_4$(aq) + 3MgCl$_2$(aq) → Mg$_3$(PO$_4$)$_2$(s) + 6NaCl(aq)

3 Mg$^{2+}$ = 3 Mg$^{2+}$

6 Cl$^-$ = 6 Cl$^-$

Balancing with Polyatomic Ions
Balance and list the coefficients from reactants to products.

A. \( \text{Fe}_2\text{O}_3(s) + \text{C}(s) \rightarrow \text{Fe}(s) + \text{CO}_2(g) \)
   1) 2, 3, 2, 3  2) 2, 3, 4, 3  3) 1, 1, 2, 3

B. \( \text{Al}(s) + \text{FeO}(s) \rightarrow \text{Fe}(s) + \text{Al}_2\text{O}_3(s) \)
   1) 2, 3, 3, 1  2) 2, 1, 1, 1  3) 3, 3, 3, 1

C. \( \text{Al}(s) + \text{H}_2\text{SO}_4(aq) \rightarrow \text{Al}_2\text{(SO}_4\text{)}_3(aq) + \text{H}_2(g) \)
   1) 3, 2, 1, 2  2) 2, 3, 1, 3  3) 2, 3, 2, 3

Solution

A. 2) 2, 3, 4, 3
   \( 2\text{Fe}_2\text{O}_3(s) + 3\text{C}(s) \rightarrow 4\text{Fe}(s) + 3\text{CO}_2(g) \)

B. 1) 2, 3, 3, 1
   \( 2\text{Al}(s) + 3\text{FeO}(s) \rightarrow 3\text{Fe}(s) + \text{Al}_2\text{O}_3(s) \)

C. 2) 2, 3, 1, 3
   \( 2\text{Al}(s) + 3\text{H}_2\text{SO}_4(aq) \rightarrow \text{Al}_2\text{(SO}_4\text{)}_3(aq) + 3\text{H}_2(g) \)

Chapter 5
Chemical Quantities and Reactions

5.5
Types of Reactions

Chemical reactions can be classified as
- combination reactions.
- decomposition reactions.
- single replacement reactions.
- double replacement reactions.

Combination

In a combination reaction,
- two or more elements form one product.
- or simple compounds combine to form one product.

\[
\begin{align*}
\text{2Mg}(s) + \text{O}_2(g) & \rightarrow \text{2MgO}(s) \\
\text{2Na}(s) + \text{Cl}_2(g) & \rightarrow \text{2NaCl}(s) \\
\text{SO}_3(g) + \text{H}_2\text{O}(l) & \rightarrow \text{H}_2\text{SO}_4(aq)
\end{align*}
\]
**Decomposition**

In a *decomposition reaction*,
- one substance splits into two or more simpler substances.

\[
\begin{align*}
\text{Single replacement} & \quad \text{One element replaces another element} \\
& \quad A + BC \rightarrow AC + B
\end{align*}
\]

- \(2\text{HgO}(s)\) \(\rightarrow\) \(2\text{Hg}(l) + \text{O}_2(g)\)
- \(2\text{KClO}_3(s)\) \(\rightarrow\) \(2\text{KCl}(s) + 3\text{O}_2(g)\)

**Learning Check**

Classify the following reactions as 1) combination or 2) decomposition.

- A. \(\text{H}_2(g) + \text{Br}_2(g) \rightarrow 2\text{HBr}(l)\)
- B. \(\text{Al}_2(\text{CO}_3)_3(s) \rightarrow \text{Al}_2\text{O}_3(s) + 3\text{CO}_2(g)\)
- C. \(4\text{Al}(s) + 3\text{C}(s) \rightarrow \text{Al}_4\text{C}_3(s)\)

**Solution**

Classify the following reactions as 1) combination or 2) decomposition.

1. A. \(\text{H}_2(g) + \text{Br}_2(g) \rightarrow 2\text{HBr}(l)\)
2. B. \(\text{Al}_2(\text{CO}_3)_3(s) \rightarrow \text{Al}_2\text{O}_3(s) + 3\text{CO}_2(g)\)
3. C. \(4\text{Al}(s) + 3\text{C}(s) \rightarrow \text{Al}_4\text{C}_3(s)\)

**Single Replacement**

In a *single replacement* reaction,
- one element takes the place of a different element in another reacting compound.

\[
\begin{align*}
\text{Single replacement} & \quad \text{One element replaces another element} \\
& \quad A + BC \rightarrow AC + B
\end{align*}
\]

- \(\text{Zn}(s) + 2\text{HCl}(aq) \rightarrow \text{ZnCl}_2(aq) + \text{H}_2(g)\)
- \(\text{Fe}(s) + \text{CuSO}_4(aq) \rightarrow \text{FeSO}_4(aq) + \text{Cu}(s)\)

**Zn and HCl is a Single Replacement Reaction**
Double Replacement

In a **double replacement**, two elements in the reactants exchange places.

**Double replacement**

![Diagram of double replacement reaction]

- **Example 1:**
  \[ \text{AgNO}_3(\text{aq}) + \text{NaCl}(\text{aq}) \rightarrow \text{AgCl}(s) + \text{NaNO}_3(\text{aq}) \]
  \[ \text{ZnS}(s) + 2\text{HCl}(\text{aq}) \rightarrow \text{ZnCl}_2(\text{aq}) + \text{H}_2\text{S}(g) \]

**Learning Check**

Classify the following reactions as 1) single replacement or 2) double replacement.

- **A.** \(2\text{Al}(s) + 3\text{H}_2\text{SO}_4(\text{aq}) \rightarrow \text{Al}_2(\text{SO}_4)_3(s) + 3\text{H}_2(g)\)
- **B.** \(\text{Na}_2\text{SO}_4(\text{aq}) + 2\text{AgNO}_3(\text{aq}) \rightarrow \text{Ag}_2\text{SO}_4(s) + 2\text{NaNO}_3(\text{aq})\)
- **C.** \(3\text{C}(s) + \text{Fe}_2\text{O}_3(s) \rightarrow 2\text{Fe}(s) + 3\text{CO}(g)\)

**Solution**

Classify the following reactions as 1) single replacement or 2) double replacement.

- **1.** \(2\text{Al}(s) + 3\text{H}_2\text{SO}_4(\text{aq}) \rightarrow \text{Al}_2(\text{SO}_4)_3(s) + 3\text{H}_2(g)\)
- **2.** \(\text{Na}_2\text{SO}_4(\text{aq}) + 2\text{AgNO}_3(\text{aq}) \rightarrow \text{Ag}_2\text{SO}_4(s) + 2\text{NaNO}_3(\text{aq})\)
- **3.** \(3\text{C}(s) + \text{Fe}_2\text{O}_3(s) \rightarrow 2\text{Fe}(s) + 3\text{CO}(g)\)

**Learning Check**

Identify each reaction as 1) combination, 2) decomposition, 3) single replacement, or 4) double replacement.

- **A.** \(3\text{Ba}(s) + \text{N}_2(g) \rightarrow \text{Ba}_3\text{N}_2(s)\)
- **B.** \(2\text{Ag}(s) + \text{H}_2\text{S}(\text{aq}) \rightarrow \text{Ag}_2\text{S}(s) + \text{H}_2(g)\)
- **C.** \(\text{SiO}_2(s) + 4\text{HF}(\text{aq}) \rightarrow \text{SiF}_4(s) + 2\text{H}_2\text{O}(l)\)
- **D.** \(\text{PbCl}_2(\text{aq}) + \text{K}_2\text{SO}_4(\text{aq}) \rightarrow 2\text{KCl}(\text{aq}) + \text{PbSO}_4(s)\)
- **E.** \(\text{K}_2\text{CO}_3(s) \rightarrow \text{K}_2\text{O}(\text{aq}) + \text{CO}_2(g)\)

**Solution**

- **1.** \(3\text{Ba}(s) + \text{N}_2(g) \rightarrow \text{Ba}_3\text{N}_2(s)\)
- **2.** \(2\text{Ag}(s) + \text{H}_2\text{S}(\text{aq}) \rightarrow \text{Ag}_2\text{S}(s) + \text{H}_2(g)\)
- **3.** \(\text{SiO}_2(s) + 4\text{HF}(\text{aq}) \rightarrow \text{SiF}_4(s) + 2\text{H}_2\text{O}(l)\)
- **4.** \(\text{PbCl}_2(\text{aq}) + \text{K}_2\text{SO}_4(\text{aq}) \rightarrow 2\text{KCl}(\text{aq}) + \text{PbSO}_4(s)\)
- **5.** \(\text{K}_2\text{CO}_3(s) \rightarrow \text{K}_2\text{O}(\text{aq}) + \text{CO}_2(g)\)
Learning Check

Each of the following reactions occur in the formation of smog or acid rain. Identify the type of reaction and balance each.
A. NO(g) + O2(g) → NO2(s)
B. N2(g) + O2(g) → NO(g)
C. SO2(g) + O2(g) → SO3(g)
D. NO2(g) → NO(g) + O(g)

Solution

Each of the following reactions occur in the formation of smog or acid rain. Identify the type of reaction and balance each.

Combination
A. 2NO(g) + O2(g) → 2NO2(s)
B. N2(g) + O2(g) → 2NO(g)
C. 2SO2(g) + O2(g) → 2SO3(g)

Decomposition
D. NO2(g) → NO(g) + O(g)

Chapter 5
Chemical Quantities and Reactions

5.6 Oxidation-Reduction Reactions

Oxidation and Reduction

An oxidation-reduction reaction involves
• a transfer of electrons from one reactant to another.
• oxidation as a loss of electrons (LEO).
• reduction as a gain of electrons (GER).

Electron Loss and Gain

An oxidation-reduction reaction involves
• a transfer of electrons from one reactant to another.
• oxidation as a loss of electrons (LEO).
• reduction as a gain of electrons (GER).

Oxidation and Reduction

Reduced
Na  →  Na⁺ + e⁻
Ca  →  Ca²⁺ + 2e⁻
2Br⁻  →  Br₂ + 2e⁻
Fe²⁺  →  Fe³⁺ + e⁻

Oxidized
Oxidation: lose e⁻
Na⁺ + e⁻
Ca²⁺ + 2e⁻
Br₂ + 2e⁻
Fe³⁺ + e⁻

Reduction: gain e⁻
Zn and Cu\(^{2+}\)

\[ \text{Zn}(s) \rightarrow \text{Zn}^{2+}(aq) + 2e^- \quad \text{oxidation} \]

\[ \text{Cu}^{2+}(aq) + 2e^- \rightarrow \text{Cu}(s) \quad \text{reduction} \]

Electron Transfer from Zn to Cu\(^{2+}\)

**Oxidation:** loss of electrons

**Reduction:** gain of electrons

Learning Check

Identify each of the following as 1) oxidation or 2) reduction.

A. Sn\((s)\) \rightarrow Sn\(^{4+}\)(aq) + 4e\(^-\)

B. Fe\(^{3+}\)(aq) + 1e\(^-\) \rightarrow Fe\(^{2+}\)(aq)

C. Cl\(_2\)(g) + 2e\(^-\) \rightarrow 2Cl\(^-\)(aq)

Solution

Identify each of the following as 1) oxidation or 2) reduction.

1. A. Sn\((s)\) \rightarrow Sn\(^{4+}\)(aq) + 4e\(^-\)

2. B. Fe\(^{3+}\)(aq) + 1e\(^-\) \rightarrow Fe\(^{2+}\)(aq)

2. C. Cl\(_2\)(g) + 2e\(^-\) \rightarrow 2Cl\(^-\)(aq)

Writing Oxidation and Reduction Reactions

Write the separate oxidation and reduction reactions for the following equation.

\[ 2\text{Cs}(s) + \text{F}_2(g) \rightarrow 2\text{CsF}(s) \]

A cesium atom loses an electron to form cesium ion.

\[ \text{Cs}(s) \rightarrow \text{Cs}^+(s) + 1e^- \quad \text{oxidation} \]

Fluorine atoms gain electrons to form fluoride ions.

\[ \text{F}_2(s) + 2e^- \rightarrow 2\text{F}^-(s) \quad \text{reduction} \]

Learning Check

In light-sensitive sunglasses, UV light initiates an oxidation-reduction reaction.

\[ \text{uv light} \quad \text{Ag}^+ + \text{Cl}^- \rightarrow \text{Ag} + \text{Cl} \]

A. Which reactant is oxidized?

B. Which reactant is reduced?
Solution

In light-sensitive sunglasses, UV light initiates an oxidation-reduction reaction.

\[
\text{uv light} \\
\text{Ag}^+ + Cl^- \rightleftharpoons Ag + Cl
\]

A. Which reactant is oxidized? \(Cl^-\) \(\rightarrow\) \(Cl + 1e^-\)

B. Which reactant is reduced? \(Ag^+ + 1e^-\) \(\rightarrow\) \(Ag\)

Learning Check

Identify the substances that are oxidized and reduced in each of the following reactions.

A. \(\text{Mg}(s) + 2\text{H}^+(aq) \rightleftharpoons \text{Mg}^{2+}(aq) + \text{H}_2(g)\)

B. \(2\text{Al}(s) + 3\text{Br}_2(g) \rightleftharpoons 2\text{AlBr}_3(s)\)

Solution

A. Mg is oxidized. \(\text{Mg}(s) \rightarrow \text{Mg}^{2+}(aq) + 2e^-\)

\(\text{H}^+\) is reduced. \(2\text{H}^+ + 2e^- \rightarrow \text{H}_2\)

B. Al is oxidized. \(\text{Al} \rightarrow \text{Al}^{3+} + 3e^-\)

Br is reduced. \(\text{Br} + e^- \rightarrow \text{Br}^-\)

Chapter 5

Chemical Quantities and Reactions

5.7

Mole Relationships in Chemical Equations

Law of Conservation of Mass

The law of conservation of mass indicates that in an ordinary chemical reaction,

- matter cannot be created or destroyed.
- no change in total mass occurs in a reaction.
- mass of products is equal to mass of reactants.

Conservation of Mass

\[
\begin{align*}
2 \text{ moles of Ag} & + 1 \text{ mole of S} = 1 \text{ mole of Ag}_2\text{S} \\
2(107.9 \text{ g}) & + 1(32.1 \text{ g}) = 1(247.9 \text{ g}) \\
247.9 \text{ g reactants} & = 247.9 \text{ g product}
\end{align*}
\]
Reading Equations in Moles

Consider the following equation:

\[ 4 \text{Fe}(s) + 3 \text{O}_2(g) \rightarrow 2 \text{Fe}_2\text{O}_3(s) \]

This equation can be read in "moles" by placing the word "moles of" between each coefficient and formula.

4 moles of Fe + 3 moles of O\(_2\) = 2 moles of Fe\(_2\)O\(_3\)

Writing Mole-Mole Factors

A mole-mole factor is a ratio of the moles for any two substances in an equation.

\[ \frac{4 \text{ moles Fe}}{3 \text{ moles O}_2} \rightarrow \frac{2 \text{ moles Fe}_2\text{O}_3}{4 \text{ moles Fe}} \]

Fe and O\(_2\)

Fe and Fe\(_2\)O\(_3\)

O\(_2\) and Fe\(_2\)O\(_3\)

Learning Check

Consider the following equation:

\[ 3\text{H}_2(g) + \text{N}_2(g) \rightarrow 2\text{NH}_3(g) \]

A. A mole-mole factor for H\(_2\) and N\(_2\) is

1) 3 moles N\(_2\)
2) 1 mole N\(_2\)
3) 1 mole N\(_2\)

B. A mole-mole factor for NH\(_3\) and H\(_2\) is

1) 3 moles H\(_2\)
2) 2 moles NH\(_3\)
3) 3 moles N\(_2\)

Solution

\[ 3\text{H}_2(g) + \text{N}_2(g) \rightarrow 2\text{NH}_3(g) \]

A. A mole-mole factor for H\(_2\) and N\(_2\) is

1) 1 mole N\(_2\)

2) 2 moles NH\(_3\)

B. A mole-mole factor for NH\(_3\) and H\(_2\) is

1) 2 moles NH\(_3\)

Calculations with Mole Factors

How many moles of Fe\(_2\)O\(_3\) can form from 6.0 moles of O\(_2\)?

\[ 4\text{Fe}(s) + 3\text{O}_2(g) \rightarrow 2\text{Fe}_2\text{O}_3(s) \]

Relationship: 3 mole O\(_2\) = 2 mole Fe\(_2\)O\(_3\)

Use a mole-mole factor to determine the moles of Fe\(_2\)O\(_3\).

\[ 6.0 \text{ mole O}_2 \times \frac{2 \text{ mole Fe}_2\text{O}_3}{3 \text{ mole O}_2} = 4.0 \text{ moles of Fe}_2\text{O}_3 \]

Guide to Using Mole Factors

1. Write the given and needed moles.
2. Write a plan to convert the given to the needed moles.
3. Use coefficients to write relationships and mole-mole factors.
4. Set up problem using the mole factor that cancels given moles.
Learning Check

How many moles of Fe are needed for the reaction of 12.0 moles of O₂?
4Fe(s) + 3O₂(g) → 2Fe₂O₃(s)

1) 3.00 moles of Fe
2) 9.00 moles of Fe
3) 16.0 moles of Fe

Study Tip: Mole Factors

In a problem, identify the compounds given and needed.

How many moles of Fe are needed for the reaction of 12.0 moles of O₂?
4Fe(s) + 3O₂(g) → 2Fe₂O₃(s)
The possible mole factors for the solution are:

| 4 moles Fe | and | 3 moles O₂ |
| 3 moles O₂ | 4 moles Fe |

Solution

3) 16.0 moles of Fe

12.0 moles O₂ x 4 moles Fe =
16.0 moles of Fe
3 moles O₂

Chapter 5
Chemical Quantities and Reactions

5.8
Mass Calculations for Reactions

Moles to Grams

Suppose we want to determine the mass (g) of NH₃ that can form from 2.50 moles of N₂:
N₂(g) + 3H₂(g) → 2NH₃(g)
The plan needed would be:

<table>
<thead>
<tr>
<th>moles N₂</th>
<th>moles NH₃</th>
<th>grams NH₃</th>
</tr>
</thead>
</table>

The factors needed would be:

| mole factor NH₃/N₂ | and | molar mass NH₃ |
|-------------------| and | 17.0 g NH₃ |

Moles to Grams

The setup for the solution would be:

2.50 mole N₂ x 2 moles NH₃
1 mole N₂ x 1 mole NH₃
given | mole-mole factor | molar mass |

= 85.0 g of NH₃
How many grams of O₂ are needed to produce 0.400 mole of Fe₂O₃ in the following reaction?

\[ 4\text{Fe(s)} + 3\text{O}_2(g) \rightarrow 2\text{Fe}_2\text{O}_3(s) \]

1) 38.4 g of O₂
2) 19.2 g of O₂
3) 1.90 g of O₂

Solution

2) 19.2 g of O₂

\[
0.400 \text{ mole Fe}_2\text{O}_3 \times \frac{3 \text{ mole O}_2}{2 \text{ mole Fe}_2\text{O}_3} \times \frac{32.0 \text{ g O}_2}{1 \text{ mole O}_2} = 19.2 \text{ g of O}_2
\]

The reaction between H₂ and O₂ produces 13.1 g of water. How many grams of O₂ reacted?

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

\[
\frac{13.1 \text{ g H}_2\text{O}}{18.0 \text{ g H}_2\text{O}} \times \frac{1 \text{ mole H}_2\text{O}}{2 \text{ mole H}_2\text{O}} = 11.6 \text{ g of O}_2
\]

Acetylene gas, C₂H₂, burns in the oxyacetylene torch for welding. How many grams of C₂H₂ are burned if the reaction produces 75.0 g of CO₂?

\[ 2\text{C}_2\text{H}_2(g) + 5\text{O}_2(g) \rightarrow 4\text{CO}_2(g) + 2\text{H}_2\text{O}(g) \]

3) 22.2 g of C₂H₂

\[
75.0 \text{ g CO}_2 \times \frac{1 \text{ mole CO}_2}{44.0 \text{ g CO}_2} \times \frac{1 \text{ mole C}_2\text{H}_2}{4 \text{ moles CO}_2} \times \frac{2 \text{ moles C}_2\text{H}_2}{1 \text{ mole CO}_2} = 22.2 \text{ g of C}_2\text{H}_2
\]
Calculating the Mass of Product

When 18.6 g of ethane gas, C₂H₆, burns in oxygen, how many grams of CO₂ are produced?

\[ 2\text{C}_2\text{H}_6(g) + 7\text{O}_2(g) \rightarrow 4\text{CO}_2(g) + 6\text{H}_2\text{O}(g) \]

18.6 g

The plan and factors would be

g C₂H₆  mole C₂H₆  mole CO₂  g of CO₂

molar  mole-mole  molar  molar

mass C₂H₆ factor  mass CO₂

\[ \frac{30.1 \text{ g C}_2\text{H}_6}{\text{ mole-C}_2\text{H}_6} \times \frac{2 \text{ mole-CO}_2}{4 \text{ mole-C}_2\text{H}_6} \times \frac{44.0 \text{ g CO}_2}{1 \text{ mole-CO}_2} = 54.4 \text{ g CO}_2 \]

Study Tip: Check Units

Be sure to check that all units cancel to give the needed unit. Note each cancelled unit in the following setup:

\[ \frac{\text{g C}_2\text{H}_6}{\text{g C}_2\text{H}_6} \times \frac{\text{mole C}_2\text{H}_6}{\text{g C}_2\text{H}_6} \times \frac{\text{mole CO}_2}{\text{mole C}_2\text{H}_6} \times \frac{\text{g CO}_2}{\text{mole CO}_2} \]

Learning Check

How many grams of H₂O are produced when 35.8 g of C₃H₈ react by the following equation?

\[ \text{C}_3\text{H}_8(g) + 5\text{O}_2(g) \rightarrow 3\text{CO}_2(g) + 4\text{H}_2\text{O}(g) \]

1) 14.6 g of H₂O
2) 58.6 g of H₂O
3) 117 g of H₂O

Solution

2) 58.6 g of H₂O

\[ \frac{35.8 \text{ g C}_3\text{H}_8}{\text{g C}_3\text{H}_8} \times \frac{1 \text{ mole C}_3\text{H}_8}{44.0 \text{ g C}_3\text{H}_8} \times \frac{4 \text{ mole-H}_2\text{O}}{1 \text{ mole C}_3\text{H}_8} \times \frac{18.0 \text{ g H}_2\text{O}}{1 \text{ mole-H}_2\text{O}} = 58.6 \text{ g H}_2\text{O} \]
Collision Theory of Reactions

A chemical reaction occurs when
• collisions between molecules have sufficient energy to break the bonds in the reactants.
• bonds between atoms of the reactants (N₂ and O₂) are broken and new bonds (NO) can form.

Activation Energy

• The activation energy is the minimum energy needed for a reaction to take place.
• When a collision provides energy equal to or greater than the activation energy, product can form.

Exothermic Reactions

In an exothermic reaction,
• heat is released.
• the energy of the products is less than the energy of the reactants.
• heat is a product.

C(s) + 2H₂(g) → CH₄(g) + 18 kcal

Endothermic Reactions

In an endothermic reaction
• Heat is absorbed.
• The energy of the products is greater than the energy of the reactants.
• Heat is a reactant (added).

N₂(g) + O₂(g) + 43.3 kcal → 2NO(g)

Learning Check

Identify each reaction as
1) exothermic or 2) endothermic.
A. N₂ + 3H₂ → 2NH₃ + 22 kcal
B. CaCO₃ + 133 kcal → CaO + CO₂
C. 2SO₂ + O₂ → 2SO₃ + heat

Solution

Identify each reaction as
1) exothermic or 2) endothermic.
1. A. N₂ + 3H₂ → 2NH₃ + 22 kcal
2. B. CaCO₃ + 133 kcal → CaO + CO₂
1. C. 2SO₂ + O₂ → 2SO₃ + heat
Rate of Reaction

**Reaction rate**

- is the speed at which reactant is used up.
- is the speed at which product forms.
- increases when temperature rises because reacting molecules move faster, providing more colliding molecules with energy of activation.

Reaction Rate and Catalysts

**A catalyst**

- increases the rate of a reaction.
- lowers the energy of activation.
- is not used up during the reaction.

Summary

<table>
<thead>
<tr>
<th>Factor</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>More reactants</td>
<td>More collisions</td>
</tr>
<tr>
<td>Higher temperature</td>
<td>More collisions with energy of activation</td>
</tr>
<tr>
<td>Adding a catalyst</td>
<td>Lowered energy of activation</td>
</tr>
</tbody>
</table>

Learning Check

State the effect of each on the rate of reaction as:

1) increases  2) decreases  3) no change

A. increasing the temperature.
B. removing some of the reactants.
C. adding a catalyst.
D. placing the reaction flask in ice.
E. increasing the concentration of one of the reactants.

Solution

State the effect of each on the rate of reaction as:

1) increases  2) decreases  3) no change

1. A. increasing the temperature.
2. B. removing some of the reactants.
3. C. adding a catalyst.
4. D. placing the reaction flask in ice.
5. E. increasing the concentration of one of the reactants.

Learning Check

Indicate the effect of each factor listed on the rate of the following reaction as:

1) increases  2) decreases  3) none

\[2\text{CO}(g) + \text{O}_2(g) \longrightarrow 2\text{CO}_2(g)\]

A. raising the temperature
B. adding \(\text{O}_2\)
C. adding a catalyst
D. lowering the temperature
Solution

Indicate the effect of each factor listed on the rate of the following reaction as
1) increases  2) decreases  3) none

\[ 2\text{CO}(g) + \text{O}_2(g) \rightarrow 2\text{CO}_2(g) \]

1. A. raising the temperature
2. B. adding \text{O}_2
3. C. adding a catalyst
4. D. lowering the temperature

Summary of Factors That Increase Reaction Rate

<table>
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