6 Chemical Formulae and Equations

Study Station ▸▸

A What Are Chemical Formulae?

Learning Outcome

- State the chemical symbols of elements and chemical formulae of compounds.

1. The **chemical formula** of a substance shows the elements that make up the substance and the number of atoms of each constituent element.
2. A chemical formula includes the **chemical symbol(s)** of the element(s), which can be found in the periodic table.
3. Examples of chemical symbols are K, Mg, Fe and Cu.
4. A chemical formula also includes **subscript(s)** which indicate the number(s) of atoms of the element(s).
5. The chemical formulae of elements depend on whether the elements exist as the following:
   (a) Monatomic elements, which are made up of one atom (e.g. Ne and Ar)
   (b) Diatomic molecules, which are made up of two atoms (e.g. H_2, O_2, N_2, Cl_2, and Br_2)
   (c) Polyatomic molecules, which are made up of three or more atoms (e.g. O_3)
6. The chemical formulae of some compounds are shown below.

Compound	Chemical Formula	Particles That Make up the Chemical Formula
potassium iodide	KI	1 potassium ion, 1 iodine ion
magnesium chloride	$MgCl_2$	1 magnesium ion, 2 chlorine ions
aluminium oxide	Al_2O_3	2 aluminium ions, 3 oxide ions
hydrogen bromide	HBr	1 hydrogen atom, 1 bromine atom
methane	CH_4	1 carbon atom, 4 hydrogen atoms
sulfur trioxide	SO_3	1 sulfur atom, 3 oxygen atoms

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B How Are Chemical Formulae Constructed?

Learning Outcomes

- Deduce the chemical formulae of simple compounds from the relative numbers of atoms present and vice versa.
- Deduce the chemical formulae of ionic compounds from the charges of ions and vice versa.

Chemical Formulae of Ionic Compounds

1. To write the chemical formula of an ionic compound, we need to know the **valency** of the elements and ions that make up the compound.
2. The valency of an element can be derived from the number of electrons gained, lost or shared by the element. Examples:
   (a) Magnesium (Mg) has two valence electrons. A magnesium atom loses its two valence electrons to form a Mg^{2+} ion. Thus, magnesium has a valency of 2.
   (b) Chlorine (Cl) has seven valence electrons. A chlorine atom gains one electron to form a Cl^- ion. Thus, chlorine has a valency of 1.
   (c) Hydrogen (H) has one valence electron. A hydrogen atom can lose its valence electron to form H^+ ion. It can also share the electron with another atom to achieve a stable electronic configuration. Thus, hydrogen has a valency of 1.
3. The valency of an element can be derived from the group number of the periodic table.
   Examples:

Element(s)	Group Number	Valency
lithium, sodium, potassium	1	1
magnesium, calcium, barium	2	2
boron, aluminium	13	3
carbon, silicon	14	4
nitrogen, phosphorus	15	3
oxygen, sulfur	16	2
fluorine, chlorine, bromine, iodine	17	1

4. The valency of an ion can be derived from the charge of the ion.
5. Some transition elements (elements in Groups 3 to 11 of the periodic table) form ions with different charge.
   Examples:

Ion	Chemical Formula	Valency
copper(I)	Cu^+	1
copper(II)	Cu^{2+}	2
iron(II)	Fe^{2+}	2
iron(III)	Fe^{3+}	3

6. Polyatomic ions have more than one atom covalently bonded together. Examples:

Polyatomic Ion	Chemical Formula	Valency
ammonium	NH_4^+	1
hydroxide	OH^-	1
nitrate	NO_3^-	1
carbonate	CO_3^{2-}	2
sulfate	SO_4^{2-}	2
phosphate	PO_4^{3-}	3

7. The charge of the cation and anion in an ionic compound must be balanced.

   For example:

   (a) Magnesium has a valency of 2, while chlorine has a valency of 1. One Mg^{2+} ion needs two Cl^- ions to balance its charge. Thus, the chemical formula of magnesium fluoride is $MgCl_2$.

   (b) The iron(II) ion has a valency of 2, while the phosphate ion has a valency of 3. The total charge of three Fe^{2+} ions is balanced by the total charge of two PO_4^{3-} ions. Thus, the chemical formula of iron(II) phosphate is $Fe_3(PO_4)_2$.

Common Error

✗ The chemical formula of calcium hydroxide is $CaOH_2$.

✓ The chemical formula of calcium hydroxide is $Ca(OH)_2$.

Explanation

Brackets are required to indicate the number of polyatomic ions in an ionic compound correctly. For example, the chemical formula $Ca(OH)_2$ shows clearly that calcium hydroxide is made up of Ca^{2+} and OH^- ions in the ratio of 1 : 2.

Chemical Formulae of Covalent Compounds

1. We can write the chemical formula of a covalent compound based on the number of atoms of the elements which share electrons with each other to achieve the stable electronic configuration of a noble gas.
2. Example:
   - Nitrogen has five valence electrons. Thus, a nitrogen atom shares three valence electrons with another atom to form three covalent bonds and achieve a stable electronic configuration.
   - Hydrogen has one valence electron. Thus, a hydrogen atom shares its valence electron with another atom to form one covalent bond and achieve a stable electronic configuration.
   - Since one nitrogen atom forms three covalent bonds with three hydrogen atoms, the chemical formula of the covalent compound formed is NH_3.
3. For the chemical formulae of covalent compounds that include hydrogen,
   - the chemical symbol of hydrogen is written after the chemical symbols of elements in Groups 14 and 15 of the periodic table. Examples are CH_4 and NH_3.
   - the chemical symbol of hydrogen is written before the chemical symbols of elements in Groups 16 and 17 of the periodic table. Examples are H_2O and HCl.

4. We can also write the chemical formula of a covalent compound based on its chemical name.
5. A covalent compound may have a prefix in its name if it contains one or more atoms of the same element.

Prefix	Number Represented
mono-	1
di-	2
tri-	3
tetra-	4

6. The chemical formulae of some covalent compounds with prefixes in their names are shown below.

Name	Chemical Formula
carbon monoxide	CO
carbon dioxide	CO_2
sulfur dioxide	SO_2
sulfur trioxide	SO_3
carbon tetrachloride	CCl_4

Worked Example 6.1

Oxygen can react with metals and non-metals to form a type of compounds called oxides. Write the chemical formulae of the following oxides.

(a) Barium oxide

(b) Carbon dioxide

Strategy

(a) Barium is a metal while oxygen is a non-metal. Both elements form ions which combine to form an ionic compound. Barium and oxygen have a valency of 2. One Ba^{2+} ion needs one O^{2-} ion to balance its charge.

(b) The word "dioxide" in the chemical name suggests that two oxygen atoms are present in the covalent compound.

Solution

(a) BaO

(b) CO_2

Worked Example 6.2

The chemical formula of a sulfate of vanadium is $V_2(SO_4)_5$.

What is the charge of the vanadium ion?

A −5

B −2

C +2

D +5

Solution

D

Explanation

Since there are five sulfate ions in the chemical formula $V_2(SO_4)_5$, the total charge of the sulfate ions is −10. To balance the negative charge of −10, the total charge of the two vanadium ions must be +10. Thus, the charge of each vanadium ion is +5.

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C What Are Chemical Equations and How Do We Balance Them?

Learning Outcomes

- Interpret chemical equations with state symbols.
- Construct chemical and ionic equations, including state symbols.

Chemical Equations

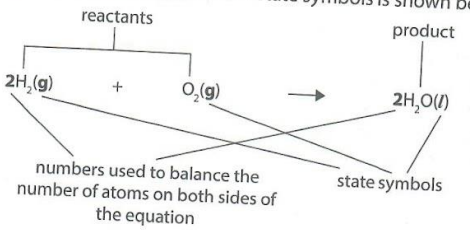
1. A **chemical equation** provides information about a chemical reaction:
   (a) Identities of the reactant(s) and product(s)
   (b) Physical states of the reactant(s) and product(s)
   (c) Relative amounts of the reactant(s) and product(s)
2. In a chemical equation, the chemical formula(e) of the reactant(s) is/are written on the left-hand side, while the chemical formula(e) of product(s) is/are written on the right-hand side. An arrow separates the chemical formulae of the reactant(s) and the product(s).
3. **State symbols** are used to show the physical states of the substances in a chemical equation.

Physical State	State Symbol
solid	s
liquid	*l*
gas	g
aqueous solution	aq

4. Some examples of compounds and their state symbols are $CaCO_3(s)$, $H_2O(l)$, $NH_3(g)$ and NaCl(aq).

5. In a **balanced** chemical equation, the number of atoms of each element involved in the chemical reaction is the same on both sides of the equation.

6. An example of a balanced chemical equation with state symbols is shown below.



Tip

The chemical formulae of the reactant(s) and product(s) in a chemical equation should be written correctly so that the equation can be balanced.

7. The steps for writing a balanced chemical equation are shown in the following examples.

(a) Nitrogen gas and oxygen gas react to form nitrogen dioxide gas.

Step 1: Write the chemical formulae of the reactants on the left-hand side of the chemical equation and the chemical formulae of the product on the right-hand side. Include the state symbols after the chemical formulae.	Nitrogen and oxygen are the reactants, while nitrogen dioxide is the product. $N_2(g) + O_2(g) \longrightarrow NO_2(g)$
Step 2: Count the number of atoms of each element on both sides of the chemical equation.	$N_2(g) + O_2(g) \longrightarrow NO_2(g)$ Left-hand side: 2 N atoms, 2 O atoms Right-hand side: 1 N atom, 2 O atoms
Step 3: Balance the number of atoms of each element by adding a number before the chemical formula of one or more substances until there is an equal number of atoms of the element on both sides of the chemical equation.	The number of N atoms on each side of the chemical equation can be balanced by adding "2" before the chemical formula NO_2. $N_2(g) + O_2(g) \longrightarrow 2NO_2(g)$ There are now two more O atoms on the right-hand side than the left-hand side. The number of O atoms can be balanced by adding "2" before the chemical formula O_2. $N_2(g) + 2O_2(g) \longrightarrow 2NO_2(g)$

(b) Aqueous sodium hydroxide and aqueous copper(II) chloride react to form aqueous sodium chloride and solid copper(II) hydroxide.

Step 1: Write the chemical formulae of the reactants on the left-hand side of the chemical equation and the chemical formulae of the products on the right-hand side. Include the state symbols after the chemical formulae.	$NaOH(aq) + CuCl_2(aq) \longrightarrow NaCl(aq) + Cu(OH)_2(s)$
Step 2: Count the number of each type of ion on both sides of the chemical equation.	$NaOH(aq) + CuCl_2(aq) \longrightarrow NaCl(aq) + Cu(OH)_2(s)$ Left-hand side: 1 Na^+ ion, 1 OH^- ion, 1 Cu^{2+} ion, 2 Cl^- ions Right-hand side: 1 Na^+ ion, 2 OH^- ions, 1 Cu^{2+} ion, 1 Cl^- ion
Step 3: Balance the number of each type of ion by adding a number before the chemical formula of one or more substances until there is an equal number of the type of ion on both sides of the chemical equation.	The number of Cl^- ions can be balanced by adding "2" before the chemical formula NaCl. $NaOH(aq) + CuCl_2(aq) \longrightarrow 2NaCl(aq) + Cu(OH)_2(s)$ There is now one more Na^+ ion and one more OH^- ion on the right-hand side than the left-hand side. The number of these ions can be balanced by adding "2" before the chemical formula NaOH. $2NaOH(aq) + CuCl_2(aq) \longrightarrow 2NaCl(aq) + Cu(OH)_2(s)$

Common Misconception

✗ A chemical equation can be balanced by changing the chemical formulae of the reactants and/or products.

✓ A chemical equation can be balanced by adding a number before one or more chemical formulae in the equation so that the number of atoms on both sides of the equation is the same.

Explanation

The chemical formulae of the reactants and products are fixed. Thus, they cannot be changed to balance a chemical equation.

Worked Example 6.3

Solid sulfur reacts with oxygen gas to form sulfur trioxide gas.

Which of the following **correctly** represents the chemical equation, including state symbols, for the reaction?

A $S(s) + 3O(g) \longrightarrow SO_3(g)$

B $S(s) + 3O_2(g) \longrightarrow SO_3(g)$

C $2S(s) + 3O_2(g) \longrightarrow 2SO_3(g)$

D $2S(s) + 6O(g) \longrightarrow 2SO_3(g)$

Solution

C

Explanation

Oxygen gas exists as a diatomic molecule. Thus, its chemical formula with state symbols is written as $O_2(g)$. Only option **C** shows a balanced chemical equation such that there are two S atoms and six O atoms on each side of the equation.

Worked Example 6.4

Aqueous silver nitrate was added to aqueous magnesium chloride. A suspension of solid silver chloride in aqueous magnesium nitrate was formed.

Write a balanced chemical equation, with state symbols, for the above reaction.

Strategy

Write the chemical formulae and state symbols of the reactants and products. Then, balance the chemical equation.

The reactants and products involved are ionic compounds. To obtain the chemical formula of each compound, find out the numbers of cations and anions required to balance the charge of the ions. For example, one Ag^+ ion needs one NO_3^- ion to balance its charge. Thus, the chemical formula of silver nitrate is $AgNO_3$.

Solution

$2AgNO_3(aq) + MgCl_2(aq) \longrightarrow 2AgCl(s) + Mg(NO_3)_2(aq)$

Ionic Equations

1. An **ionic equation** is a simplified version of a chemical equation. It shows the ions involved in a reaction and contains at least one substance that is not in the aqueous state.
2. The steps for writing an ionic equation are shown in the example below.

   Sodium hydroxide and copper(II) chloride react to form sodium chloride and copper(II) hydroxide.

Step 1: Write a balanced chemical equation with state symbols.	$2NaOH(aq) + CuCl_2(aq) \longrightarrow 2NaCl(aq) + Cu(OH)_2(s)$
Step 2: Write the chemical formulae of the compounds that are in aqueous state in the form of ions.	$2Na^+(aq) + 2OH^-(aq) + Cu^{2+}(aq) + 2Cl^-(aq) \longrightarrow 2Na^+(aq) + 2Cl^-(aq) + Cu(OH)_2(s)$
Step 3: Cancel out the chemical formulae of the ions that are present on both sides of the chemical equation. These ions are called **spectator ions**.	~~$2Na^+(aq)$~~ $+ 2OH^-(aq) + Cu^{2+}(aq) +$ ~~$2Cl^-(aq)$~~ $\longrightarrow$ ~~$2Na^+(aq)$~~ ~~$+ 2Cl^-(aq)$~~ $+ Cu(OH)_2(s)$
Step 4: The ionic equation for the reaction is obtained.	$Cu^{2+}(aq) + 2OH^-(aq) \longrightarrow Cu(OH)_2(s)$

Worked Example 6.5

When aqueous barium chloride reacts with aqueous potassium sulfate, solid barium sulfate and aqueous potassium chloride are formed.

Which of the following **correctly** shows the ionic equation for the reaction?

A $Ba^{2+}(aq) + SO_4^{2-}(aq) \longrightarrow Ba^{2+}(s) + SO_4^{2-}(s)$

B $Ba^{2+}(aq) + SO_4^{2-}(aq) \longrightarrow BaSO_4(s)$

C $BaCl_2(aq) + K_2SO_4(aq) \longrightarrow BaSO_4(s) + 2KCl(aq)$

D $2Cl^-(aq) + 2K^+(aq) \longrightarrow 2KCl(aq)$

Solution

B

Explanation

The ionic equation is derived from the balanced chemical equation
$BaCl_2(aq) + K_2SO_4(aq) \longrightarrow BaSO_4(s) + 2KCl(aq)$.

The chemical formulae of the compounds in the aqueous state are written in the form of ions.
$Ba^{2+}(aq) + 2Cl^-(aq) + 2K^+(aq) + SO_4^{2-}(aq) \longrightarrow BaSO_4(s) + 2K^+(aq) + 2Cl^-(aq)$

The spectator ions, $K^+(aq)$ and $Cl^-(aq)$, are then removed from both sides of the equation.
$Ba^{2+}(aq) + \cancel{2Cl^-(aq)} + \cancel{2K^+(aq)} + SO_4^{2-}(aq) \longrightarrow BaSO_4(s) + \cancel{2K^+(aq)} + \cancel{2Cl^-(aq)}$

Thus, the ionic equation is $Ba^{2+}(aq) + SO_4^{2-}(aq) \longrightarrow BaSO_4(s)$.

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Checkpoint 6.1

1. Liquid hydrazine (N_2H_4) decomposes into nitrogen gas and hydrogen gas when it is heated strongly.
   (a) Write a balanced chemical equation, with state symbols, for the decomposition of hydrazine.
   (b) Explain why an ionic equation **cannot** be written for the decomposition of hydrazine.
2. When ammonium chloride reacts with sodium hydroxide, the products ammonia gas, sodium chloride and water are formed.
   (a) Write an ionic equation, with state symbols, for the reaction.
   (b) Sodium chloride and water are also formed when sodium hydroxide reacts with hydrochloric acid. Write an ionic equation, including state symbols, for the reaction.

Test Station ▸▸

1. Which of the following chemical formulae is **not** correct?

   A $CaCO_3$

   B CH_4

   C CS

   D $ZnCO_3$

2. The chemical formula of sodium nitrite is $NaNO_2$.

   What is the chemical formula of iron(III) nitrite?

   A $FeNO_2$

   B $Fe(NO_2)_2$

   C $Fe(NO_2)_3$

   D Fe_3NO_2

3. In order to extract iron from iron ore (Fe_2O_3), solid carbon is heated with oxygen gas to form carbon monoxide gas. The carbon monoxide gas formed is used to react with iron ore to form molten iron and carbon dioxide gas.

   Which of the following **correctly** shows the chemical equations that represents the reactions described above?

	Reaction 1	Reaction 2
A	$C + O_2 \longrightarrow CO_2$	$3CO + Fe_2O_3 \longrightarrow 2Fe + 3CO_2$
B	$C + O_2 \longrightarrow CO_2$	$3CO_2 + Fe_2O_3 \longrightarrow 2Fe + 3CO_3$
C	$2C + O_2 \longrightarrow 2CO$	$3C + Fe_2O_3 \longrightarrow 2Fe + 3CO$
D	$2C + O_2 \longrightarrow 2CO$	$3CO + Fe_2O_3 \longrightarrow 2Fe + 3CO_2$

4. Manganese is a transition element that is able to form ions with different charge. Table 6.1 shows the names and chemical formulae of some manganese ions.

Table 6.1

Name of Ion	Chemical Formula of Ion
manganese(II)	
	Mn^{4+}
manganese(V)	
manganese(VI)	
	Mn^{7+}

(a) Complete Table 6.1 by writing the names and chemical formulae of the ions. [2]

(b) Solid manganese(IV) oxide reacts with dilute hydrochloric acid, HCl, to form a solution containing manganese(IV) chloride and water.

Based on the information in Table 6.1, write a balanced chemical equation, with state symbols, to represent the reaction. [2]

(c) On heating, manganese(V) carbonate decomposes and forms carbon dioxide, manganese(IV) oxide and compound **Y**.

(i) Write a balanced chemical equation to represent the reaction. [2]

(ii) Hence, identify compound **Y**. [1]

5. Nitrogen monoxide, nitrogen dioxide and dinitrogen oxide are examples of oxides of nitrogen.

(a) Write the chemical formulae of nitrogen monoxide, nitrogen dioxide and dinitrogen oxide. [3]

(b) Dinitrogen oxide is converted into nitrogen monoxide and an element when it is heated. Write a balanced chemical equation for the reaction and identify the product that is an element. [2]

(c) Carbon monoxide reacts with nitrogen monoxide and nitrogen dioxide separately to form the same products, carbon dioxide and nitrogen. Write balanced chemical equations to represent the reactions. [2]