8 Acids and Bases

Study Station ▸▸

A What Is an Acid?

Learning Outcomes

- Define *acid* in terms of the ions it produces in aqueous solutions.
- Describe the characteristic properties of acids in their reactions with metals, bases and carbonates to form salts.

1. An **acid** is a substance that produces hydrogen ions (H^+) when dissolved in water.
2. The names and chemical formulae of some common acids are shown below.

Name of Acid	Chemical Formula
hydrochloric acid	HCl
nitric acid	HNO_3
sulfuric acid	H_2SO_4
ethanoic acid	CH_3COOH

3. All acids produce hydrogen ions (H^+) in aqueous solutions.

   Examples:

   (a) $HCl(aq) \longrightarrow H^+(aq) + Cl^-(aq)$

   (b) $HNO_3(aq) \longrightarrow H^+(aq) + NO_3^-(aq)$

   (c) $H_2SO_4(aq) \longrightarrow 2H^+(aq) + SO_4^{2-}(aq)$

   (d) $CH_3COOH(aq) \rightleftharpoons H^+(aq) + CH_3COO^-(aq)$

Common Error

✗ Hydrogen chloride gas, $HCl(g)$, produces hydrogen ions.

✓ Hydrochloric acid in aqueous state, $HCl(aq)$, produces hydrogen ions.

Explanation

Substances like HCl, HNO_3, H_2SO_4 and CH_3COOH behave as acids by producing hydrogen ions when they are dissolved in water. Thus, in the absence of water, HCl gas remains in its molecular form.

4. Some properties of acids are listed below.
   - They have a sour taste.
   - They conduct electricity due to the mobile ions produced when they dissolve in water.
   - They turn blue litmus paper red.

5. Acids react with some metals to form **salts** and hydrogen gas. Salts are ionic compounds.

acid + metal ⟶ salt + hydrogen

Examples:

(a) hydrochloric acid + magnesium ⟶ magnesium chloride + hydrogen

$2HCl(aq) + Mg(s) \longrightarrow MgCl_2(aq) + H_2(g)$

(b) sulfuric acid + sodium ⟶ sodium sulfate + hydrogen

$H_2SO_4(aq) + 2Na(s) \longrightarrow Na_2SO_4(aq) + H_2(g)$

6. The hydrogen gas produced during the reaction of an acid with a metal can be identified by testing it with a burning splint. The burning splint will be extinguished with a "pop" sound.

Common Misconception

✗ Acids react with all metals.

✓ Acids only react with some metals. They do not react with unreactive metals such as copper and silver.

7. Acids react with bases to form salts and water. Metal oxides and metal hydroxides are examples of bases.

acid + base ⟶ salt + water

Examples:

(a) nitric acid + magnesium oxide ⟶ magnesium nitrate + water

$2HNO_3(aq) + MgO(s) \longrightarrow Mg(NO_3)_2(aq) + H_2O(l)$

(b) hydrochloric acid + potassium hydroxide ⟶ potassium chloride + water

$HCl(aq) + KOH(aq) \longrightarrow KCl(aq) + H_2O(l)$

8. The reaction between an acid and a base is known as a **neutralisation** reaction.

9. Acids react with carbonates to form salts, water and carbon dioxide gas.

acid + carbonate ⟶ salt + water + carbon dioxide

Examples:

(a) hydrochloric acid + sodium carbonate ⟶ sodium chloride + water + carbon dioxide

$2HCl(aq) + Na_2CO_3(s) \longrightarrow 2NaCl(aq) + H_2O(l) + CO_2(g)$

(b) nitric acid + calcium carbonate ⟶ calcium nitrate + water + carbon dioxide

$2HNO_3(aq) + CaCO_3(s) \longrightarrow Ca(NO_3)_2(aq) + H_2O(l) + CO_2(g)$

10. The carbon dioxide gas produced during the reaction of an acid with a carbonate can be identified by bubbling it through limewater. Carbon dioxide forms a white precipitate with limewater.

11. The salt formed in the reactions of acids is:

- a chloride if hydrochloric acid is the reactant;
- a nitrate if nitric acid is the reactant;
- a sulfate if sulfuric acid is the reactant.

Worked Example 8.1

Write a balanced chemical equation, including state symbols, for each of the following.

(a) Reaction between dilute nitric acid and zinc, which is a reactive metal

(b) Reaction between sulfuric acid and aqueous sodium carbonate

Strategy

First, determine the products in each reaction. The products in **(a)** are zinc nitrate and hydrogen gas. The products in **(b)** are sodium sulfate, water and carbon dioxide gas.

Next, construct each chemical equation by writing the chemical formulae and state symbols of all the reactants and products and then balancing the equation.

Solution

(a) $2HNO_3(aq) + Zn(s) \longrightarrow Zn(NO_3)_2(aq) + H_2(g)$

(b) $H_2SO_4(aq) + Na_2CO_3(aq) \longrightarrow Na_2SO_4(aq) + H_2O(l) + CO_2(g)$

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B What Is a Base?

Learning Outcomes

- Define *alkali* in terms of the ions it produces in aqueous solutions.
- Describe the characteristic properties of bases in their reactions with acids and ammonium salts.
- Describe the reaction between hydrogen ions and hydroxide ions to produce water as neutralisation.

1. A **base** is a metal oxide or a metal hydroxide.
2. Most bases are insoluble in water. For example, magnesium oxide, magnesium hydroxide, copper(II) oxide and copper(II) hydroxide do not dissolve in water.
3. An **alkali** is a soluble base that produces hydroxide ions (OH^-) when dissolved in water.
4. The names and chemical formulae of some common alkalis are shown below.

Name of Alkali	Chemical Formula
sodium hydroxide	$NaOH$
potassium hydroxide	KOH
calcium hydroxide	$Ca(OH)_2$
aqueous ammonia	NH_3

5. All alkalis produce hydroxide ions (OH^-) ions in aqueous solutions.

   Examples:

   (a) $KOH(aq) \longrightarrow K^+(aq) + OH^-(aq)$

   (b) $NaOH(aq) \longrightarrow Na^+(aq) + OH^-(aq)$

   (c) $Ca(OH)_2(aq) \longrightarrow Ca^{2+}(aq) + 2OH^-(aq)$

6. Ammonia does not contain a metal like other alkalis. It ionises partially to produce hydroxide ions when dissolved in water.

   $NH_3(g) + H_2O(l) \rightleftharpoons OH^-(aq) + NH_4^+(aq)$

7. Some properties of alkalis are listed below.
   - They have a bitter taste.
   - They feel soapy.
   - They conduct electricity due to the mobile ions produced when they dissolve in water.
   - They turn red litmus paper blue.

8. Alkalis react with acids to form salts and water.

   alkali + acid $\longrightarrow$ salt + water

   Example:

   sodium hydroxide + nitric acid $\longrightarrow$ sodium nitrate + water

   $NaOH(aq) + HNO_3(aq) \longrightarrow NaNO_3(aq) + H_2O(l)$

9. The reaction between an acid and an alkali is known as a neutralisation reaction. The hydrogen ions from the acid react with the hydroxide ions from the alkali to form water.

10. The ionic equation for a neutralisation reaction is:

    $H^+(aq) + OH^-(aq) \longrightarrow H_2O(l)$

11. Alkalis react with ammonium salts on heating to form salts, water and ammonia gas.

    alkali + ammonium salt $\longrightarrow$ salt + water + ammonia

    Examples:

    (a) sodium hydroxide + ammonium chloride $\longrightarrow$ sodium chloride + water + ammonia

    $NaOH(aq) + NH_4Cl(aq) \longrightarrow NaCl(aq) + H_2O(l) + NH_3(g)$

    (b) potassium hydroxide + ammonium sulfate $\longrightarrow$ potassium sulfate + water + ammonia

    $2KOH(aq) + (NH_4)_2SO_4(aq) \longrightarrow K_2SO_4(aq) + 2H_2O(l) + 2NH_3(g)$

12. The ammonia gas produced during the reaction of an alkali with an ammonium salt can be identified using damp red litmus paper. Ammonia gas turns damp red litmus paper blue.

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Checkpoint 8.1

1. Table 8.1 shows the observations when some reagents were added to dilute nitric acid.

Table 8.1

Reagent Added to Dilute Nitric Acid	Observation(s)
A	The colourless solution turned blue. Bubbles were observed. The gas produced formed a white precipitate with limewater.
B	Bubbles were observed. A "pop" sound was heard when the gas produced was tested with a burning wooden splint.
C	The colourless solution turned blue.

Match reagents **A**, **B** and **C** to the **correct** substances listed below.

silver, calcium carbonate, calcium hydroxide
copper, copper(II) carbonate, copper(II) oxide
zinc, sodium hydroxide

Tip

Reactions involving acids have been tested in examinations, e.g. GCE 'O' Level Science Chemistry Oct/Nov 2014, Paper 3, Q5 and Oct/Nov 2015, Paper 3, Q6.

2. Hydrogen bromide has a melting point of –87 °C and a boiling point of –67 °C.
   (a) Explain, in terms of structure and bonding, why hydrogen bromide has low melting and boiling points.
   (b) Draw a dot-and-cross diagram to show the arrangement of electrons in a molecule of hydrogen bromide. Show only the valence electrons.
   (c) Hydrogen bromide dissolves in water to form an acidic solution. Write the chemical formulae of the ions formed when hydrogen bromide dissolves in water.
   (d) Explain why an aqueous solution of hydrogen bromide conducts electricity but hydrogen bromide gas does not.

Tip

The different physical states of hydrogen chloride have been tested in examinations, e.g. GCE 'O' Level Science Chemistry Oct/Nov 2016, Paper 3, Q10(b)(i).

3. Ammonium carbonate decomposes readily to form ammonia, carbon dioxide and water. Thus, it can be used as a smelling salt to help someone who has fainted regain consciousness.
   (a) Write a balanced chemical equation for the decomposition of ammonium carbonate.
   (b) Name the gas given off when ammonium carbonate reacts with
      (i) dilute nitric acid,
      (ii) aqueous potassium hydroxide.

Tip

Reactions of carbonates have been tested in examinations, e.g. GCE 'O' Level Science Chemistry Oct/Nov 2010, Paper 3, Q2 and Oct/Nov 2021, Paper 3, Q7.

C How Do We Compare Relative Acidity and Alkalinity?

Learning Outcome

- Describe neutrality and relative acidity and alkalinity based on relative concentrations of hydrogen and hydroxide ions, and using Universal Indicator and the pH scale.

1. **Acidity** depends on the concentration of hydrogen ions (H^+) relative to that of hydroxide ions (OH^-) in a solution.
2. If the concentration of hydrogen ions in a solution is higher than the concentration of hydroxide ions, the solution is **acidic**.
3. **Alkalinity** depends on the concentration of hydroxide ions (OH^-) relative to that of hydrogen ions (H^+) in a solution.
4. If the concentration of hydroxide ions in a solution is higher than the concentration of hydrogen ions, the solution is **alkaline**.
5. In a **neutral** solution, the concentrations of hydrogen ions and hydroxide ions are the same.
6. The **pH scale** is used to indicate the acidity and alkalinity of solutions.
   - The lower the pH value, the higher the concentration of hydrogen ions compared to that of hydroxide ions in the solution and the higher the acidity.
   - The higher the pH value, the higher the concentration of hydroxide ions compared to that of hydrogen ions in the solution and the higher the alkalinity.

pH Value	< 7	7	> 7
Nature of Solution	acidic	neutral	alkaline

7. **Universal Indicator** is an indicator that shows a variety of colours at different pH values.
8. The colours of Universal Indicator at pH 1 to 14 are shown below.

pH	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Colour	red	red-orange	orange	beige	yellow	lime-green	green	dark green	turquoise	pale blue	blue	dark blue	violet	purple

decreasing pH values indicate increasing concentration of H^+ ions (increasing acidity)

increasing pH values indicate increasing concentration of OH^- ions (increasing alkalinity)

9. Some other indicators and their colour changes in acidic and alkaline solutions are shown below.

Indicator	Colour in Acidic Solution	pH Range at Which Indicator Changes Colour	Colour in Alkaline Solution
methyl orange	red	3–5	yellow
screened methyl orange	violet	3–5	green
bromothymol blue	yellow	6–8	blue

Worked Example 8.2

Dilute hydrochloric acid reacts with aqueous sodium hydroxide.

(a) Write a chemical equation and an ionic equation, including state symbols, for the reaction.

(b) Based on your answer in **(a)**, explain why the reaction is a neutralisation reaction.

Strategy

(a) First, determine the products in the reaction. Next, construct the chemical equation by writing the chemical formulae and state symbols of all the reactants and products and then balancing the equation.

To obtain the ionic equation, write down only the chemical formulae of the constituent ions of the substances in the aqueous state and keep the chemical formula of any substance in the solid, liquid or gaseous state in the chemical equation. Next, remove the spectator ions from the equation.

(b) Focus on the ionic equation since it shows the ions that take part in the reaction.

Solution

(a) Chemical equation: $HCl(aq) + NaOH(aq) \longrightarrow NaCl(aq) + H_2O(l)$

Ionic equation: $H^+(aq) + OH^-(aq) \longrightarrow H_2O(l)$

(b) The ionic equation shows that hydrogen ions from dilute hydrochloric acid and hydroxide ions from aqueous sodium hydroxide combine to form water which is neutral. Thus, this is known as a neutralisation reaction.

Worked Example 8.3

Universal Indicator was added into some household chemicals. The colour of the indicator was observed.

Household Chemical	Colour of Universal Indicator
bleach	dark blue
toothpaste	turquoise
vinegar	orange
washing soda	blue

Which household chemical has the highest pH value?

A Bleach **B** Toothpaste **C** Vinegar **D** Washing soda

Solution

A

Explanation

An alkaline solution has a higher pH value than an acidic solution. When Universal Indicator is added to an alkaline solution, the colour observed is usually turquoise, blue or purple. From the table, bleach is more alkaline than toothpaste and washing soda. Thus, it has the highest pH value.

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D How Is the pH of Soil Controlled?

Learning Outcomes

- Describe the importance of controlling the pH of soil.
- Describe how excess acidity can be treated using calcium hydroxide.

1. Soil of appropriate pH provides sufficient amounts of the required nutrients to plants. Different plants thrive on soil of different pH values. In general, plants grow better in soil with pH range of 5 to 7.
2. Soil tends to become more acidic over time due to different environmental conditions, such as acid rain.
3. Bases, such as calcium hydroxide (also known as slaked lime), can be added to soil that is too acidic. The process of adding slaked lime to soil is known as **liming**.
4. During liming, the base reacts with the acids present in the soil to raise the pH of the soil. To ensure that the right amount of the base is added, the pH of the soil should be measured before and during the process.

Worked Example 8.4

A farmer added excess fertilisers on the soil, causing it to become too acidic.

Which of the following could be used to neutralise the soil?

A Calcium oxide

B Dilute ethanoic acid

C Dilute sulfuric acid

D Sodium chloride

Solution

A

Explanation

Calcium oxide is a base. Dilute ethanoic acid and dilute sulfuric acid are acids, while sodium chloride is a salt. Only calcium oxide can be used to neutralise the soil.

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E How Are Oxides Classified?

Learning Outcome

- Classify oxides as acidic, basic, amphoteric or neutral based on their metallic or non-metallic characteristics.

1. Both metals and non-metals react with oxygen in air to form oxides. Most of these oxides have basic or acidic properties, which are affected by the metallic or non-metallic character of the element bonded to oxygen.
2. Most non-metals react with oxygen to form **acidic oxides**. Examples of acidic oxides are sulfur dioxide (SO_2), sulfur trioxide (SO_3) and carbon dioxide (CO_2).
3. When dissolved in water,
   - sulfur dioxide forms sulfurous acid (H_2SO_3);
   - sulfur trioxide forms sulfuric acid (H_2SO_4); and
   - carbon dioxide forms carbonic acid (H_2CO_3).
4. Acidic oxides react with alkalis to form salts and water.

   Examples:

   (a) sulfur dioxide + potassium hydroxide ⟶ potassium sulfite + water

   $SO_2(g) + 2KOH(aq) \longrightarrow K_2SO_3(aq) + H_2O(l)$

   (b) carbon dioxide + sodium hydroxide ⟶ sodium carbonate + water

   $CO_2(g) + 2NaOH(aq) \longrightarrow Na_2CO_3(aq) + H_2O(l)$
5. Most metals react with oxygen to form **basic oxides**. An example of basic oxides is magnesium oxide (MgO).
6. Basic oxides react with acids to form salts and water.

   Example:

   magnesium oxide + nitric acid ⟶ magnesium nitrate + water

   $MgO(s) + 2HNO_3(aq) \longrightarrow Mg(NO_3)_2(aq) + H_2O(l)$
7. Some non-metals react with oxygen to form **neutral oxides**. These oxides are neither acidic nor basic. Examples of neutral oxides are carbon monoxide (CO), nitrogen monoxide (NO) and water (H_2O).
8. Some metals react with oxygen to form **amphoteric oxides**. Examples of amphoteric oxides are aluminium oxide (Al_2O_3) and zinc oxide (ZnO).
9. Amphoteric oxides have both acidic and basic properties. Hence, they can react with both bases and acids.

   Examples:

   (a) $Al_2O_3(s) + 2KOH(aq) \longrightarrow 2KAlO_2(aq) + H_2O(l)$

   $Al_2O_3(s) + 6HNO_3(aq) \longrightarrow 2Al(NO_3)_3(aq) + 3H_2O(l)$

   (b) $ZnO(s) + 2KOH(aq) \longrightarrow K_2ZnO_2(aq) + H_2O(l)$

   $ZnO(s) + 2HNO_3(aq) \longrightarrow Zn(NO_3)_2(aq) + H_2O(l)$

Worked Example 8.5

Classify the following oxides according to whether they are acidic, basic or amphoteric.

aluminium oxide	carbon dioxide	copper(II) oxide
phosphorus(V) oxide	potassium oxide	zinc oxide

Strategy

Most non-metals react with oxygen to form acidic oxides, while most metals react with oxygen to form basic oxides. Some metals, such as zinc and aluminium, react with oxygen to form amphoteric oxides.

Solution

Acidic oxides: carbon dioxide, phosphorus(V) oxide

Basic oxides: copper(II) oxide, potassium oxide

Amphoteric oxides: aluminium oxide, zinc oxide

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Checkpoint 8.2

1. Sodium burns in excess oxygen to form sodium oxide.
   (a) Write a balanced chemical equation, including state symbols, to show the formation of sodium oxide.
   (b) (i) Sodium oxide dissolves readily in water. If Universal Indicator is added to it, what colour would be observed?
   (ii) What substance can be added to the solution in **(b)(i)** so that the colour of Universal Indicator becomes green?
2. A farmer planted rice on his field. He wanted to use a small plot of his field to grow paprika too. The pH ranges of the soil required for growing the two crops are shown in Table 8.2.

Table 8.2

Crop	rice	paprika
pH Range of Soil Required to Grow the Crop	5.0–6.5	7.0–8.5

   (a) The farmer added calcium hydroxide (slaked lime) to the soil on his field. Explain why adding calcium hydroxide would make the soil suitable for growing paprika.
   (b) The farmer waited for a few days before adding ammonium sulfate fertiliser to the soil.
   (i) Write a chemical equation for the reaction between calcium hydroxide and ammonium sulfate.
   (ii) Based on **(b)(i)**, explain why the farmer should **not** add ammonium sulfate immediately after adding calcium hydroxide to the soil.

Tip

The effect of acidity on the pH of soil has been tested in examinations, e.g. GCE 'O' Level Science Chemistry Oct/Nov 2017, Paper 3, Q5.

Test Station ▸▸

1. What is the ionic equation for the reaction between magnesium and dilute nitric acid?

   A $Mg(s) + H^+(aq) \longrightarrow Mg^+(aq) + H(g)$

   B $Mg(s) + H^+(aq) \longrightarrow Mg^{2+}(aq) + H(g)$

   C $Mg(s) + 2H^+(aq) \longrightarrow Mg^{2+}(aq) + H_2(g)$

   D $Mg(s) + 2H^+(aq) \longrightarrow Mg^{2+}(aq) + 2H(g)$

2. Solution **P** contains 0.01 mol/dm^3 of acid H**X** and has a pH of 2.0. Solution **Q** contains 0.10 mol/dm^3 of acid H**Y** and has a pH of 3.9.

   Which of the following statements about solutions **P** and **Q** is **correct**?

   A Magnesium reacts more vigorously with solution **Q** than with solution **P**.

   B Solution **P** contains a higher concentration of hydrogen ions than solution **Q**.

   C Solutions **P** and **Q** react with ammonium salts to give off ammonia gas when heated.

   D Solutions **P** and **Q** turn Universal Indicator red.

3. Oxide **X** reacts with oxygen gas to form oxide **Y**. Oxides **X** and **Y** are gases which are insoluble in water. Table 8.3 shows their solubilities in different solutions.

   Table 8.3

Solution	Oxide X	Oxide Y
aqueous potassium hydroxide	insoluble	soluble
dilute hydrochloric acid	insoluble	insoluble

Which types of oxides are oxides **X** and **Y**?

	Oxide X	Oxide Y
A	acidic	acidic
B	amphoteric	neutral
C	basic	amphoteric
D	neutral	acidic

4. (a) Different types of fertilisers are shown in Table 8.4. Complete the table. [3]

Table 8.4

Name of Fertiliser	Chemical Formula of Fertiliser	Ions Present
ammonium nitrate		
ammonium sulfate	$(NH_4)_2SO_4$	
	KNO_3	
calcium phosphate		Ca^{2+} and PO_4^{3-}

(b) Ammonium nitrate can be formed by reacting an alkali with an acid.

Name the alkali and the acid. [1]

5. Aluminium hydroxide is often used as an antacid, which can be used to relieve indigestion.

(a) Write a balanced chemical equation for the reaction between hydrochloric acid and aluminium hydroxide. [1]

Q (b) A patient produces an excess of 0.08 mol of hydrochloric acid in his stomach per day.

Given that 100 cm^3 of an antacid contains 2.6 g of aluminium hydroxide, calculate the volume of antacid required per day to neutralise the excess acid in the patient's stomach. [3]

(c) Calcium carbonate can also be used as an antacid.

Write a balanced chemical equation for the reaction between calcium carbonate and hydrochloric acid. [1]