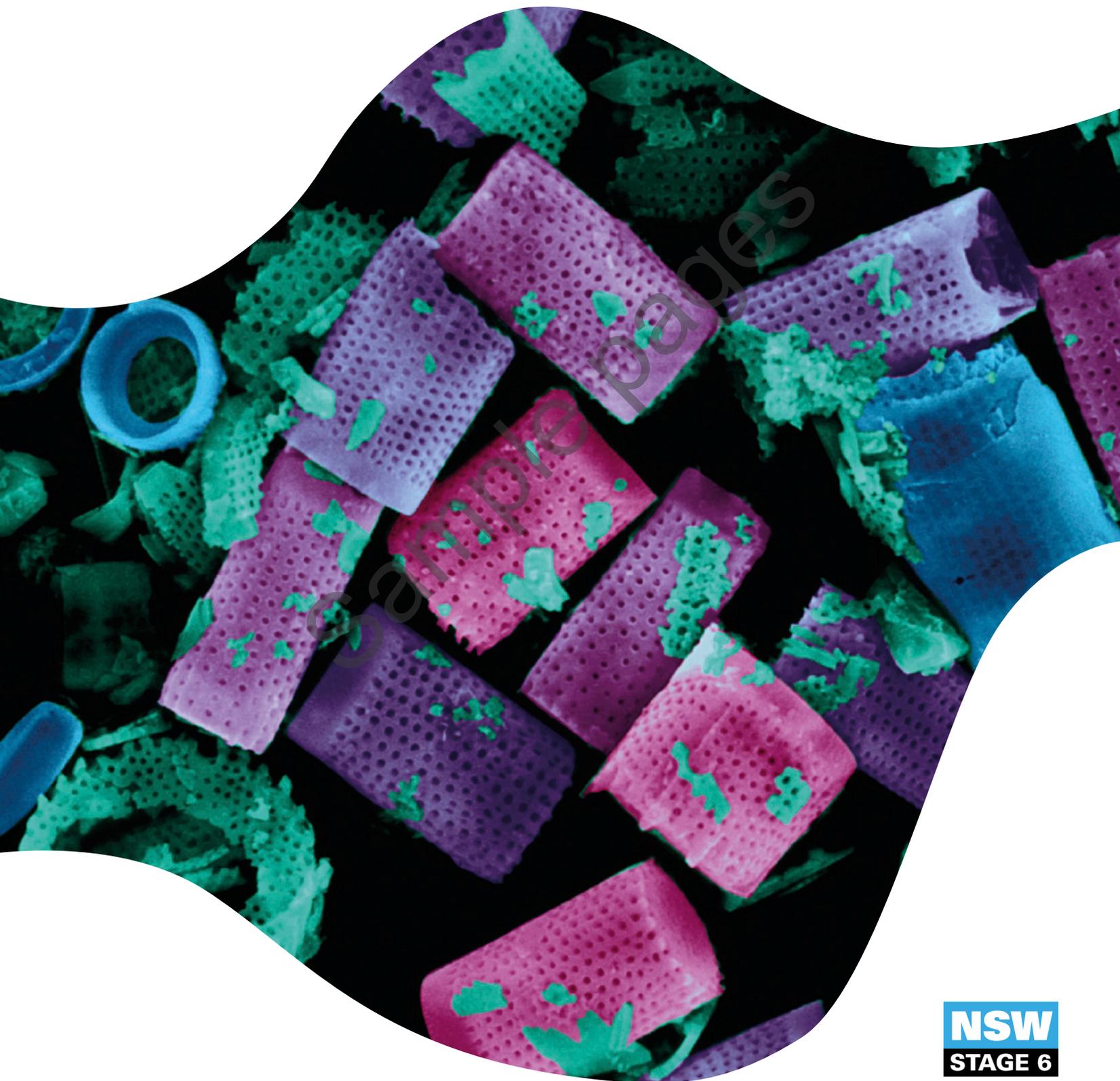


PEARSON  
**CHEMISTRY**

NEW SOUTH WALES

STUDENT BOOK



**NSW**  
STAGE 6

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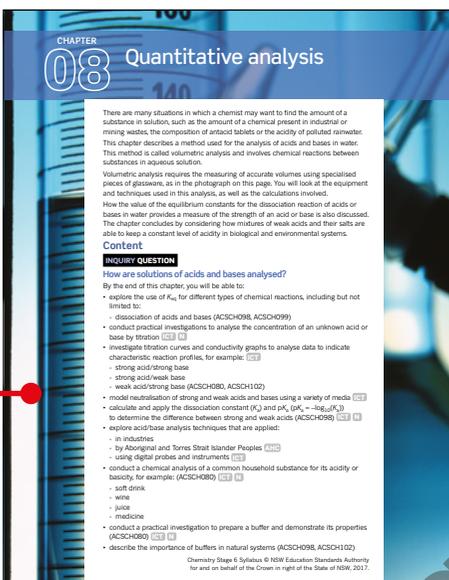
# How to use this book

## Pearson Chemistry 12 New South Wales

Pearson Chemistry 12 New South Wales has been written to fully align with the new Stage 6 syllabus for New South Wales Chemistry. The book covers Modules 5 to 8 in an easy-to-use resource. Explore how to use this book below.

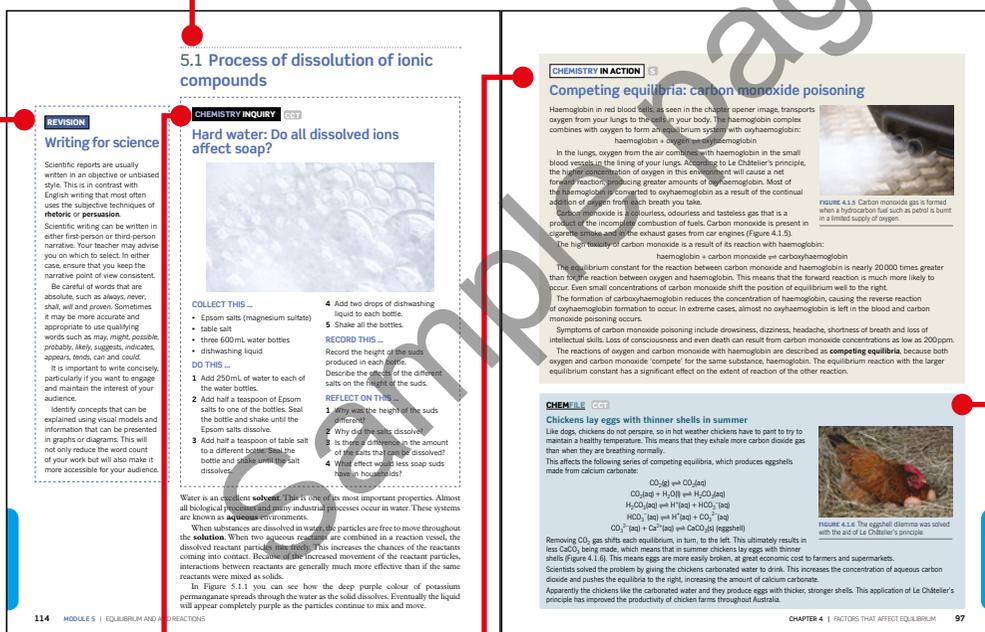
### Chapter opener

The chapter opening page links the syllabus to the chapter content. Key content addressed in the chapter is clearly listed.



### Section

Each chapter is clearly divided into manageable sections of work. Best-practice literacy and instructional design are combined with high-quality, relevant photos and illustrations to help students better understand the ideas or concepts being developed.



### Revision box

Revision boxes are used to remind students of vital concepts previously covered that are required for current learning.

### Chemistry Inquiry

Chemistry Inquiry features are inquiry-based activities that assist students to discover concepts before learning about them. They encourage students to think about what happens in the world and how science can provide explanations.

### Chemistry in Action

Chemistry in Action boxes place chemistry in an applied situation or a relevant context. They refer to the nature and practice of chemistry, its applications and associated issues, and the historical development of its concepts and ideas.

### ChemFile

ChemFiles include a range of interesting and real-world examples to engage students.

## Worked examples

Worked examples are set out in steps that show thinking and working. This format greatly enhances student understanding by clearly linking underlying logic to the relevant calculations. Each Worked example is followed by a Try yourself activity. This mirror problem allows students to immediately test their understanding.

## Highlight box

Highlight boxes focus students' attention on important information such as key definitions, formulae and summary points.

## Additional content

Additional content includes material that goes beyond the core content of the syllabus. They are intended for students who wish to expand their depth of understanding in a particular area.

## Section summary

Each section has a summary to help students consolidate the key points and concepts.

### LEWIS ACIDS AND BASES

Not all acids are substances that can be easily defined by the donation of a proton. In the same year that the Brønsted-Lowry theory was published, Gilbert N. Lewis (of Lewis dot diagrams fame) defined an acid as being a substance that can accept a lone electron pair from another molecule. By contrast, Lewis bases are substances that donate a lone pair of electrons. Brønsted-Lowry bases are also Lewis bases because they donate a pair of electrons in order to accept a proton.

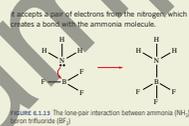


Figure 17.1.13 The lone pair interaction between ammonia (NH<sub>3</sub>) and boron trifluoride (BF<sub>3</sub>)

- When a substance is **soluble**, more than 0.1 mol of the substance will dissolve in 1 L of water.
- When a substance is **insoluble**, less than 0.01 mol of the substance will dissolve in 1 L of water.
- When a substance is **slightly soluble**, 0.01–0.1 mol of the substance will dissolve in 1 L of water.

**Solubility rules**  
Sometimes when two ionic solutions are mixed the ions interact to form a new substance with a lower solubility. This substance may be an insoluble solid, called a **precipitate**. To determine whether two ionic solutions will form a precipitate, you can either conduct an experiment or use the solubility rules. Worked example 5.1.1 on page 120 shows you how to use the solubility rules to determine if two ionic solutions will form a precipitate.

### SKILLBUILDER

#### Mixing solutions to form a precipitate

This chapter explains how to use solubility rules to determine whether a precipitate is formed, you may want to confirm your working experimentally. When mixing two solutions to form a precipitate, you need to remember the following points.

- Place the beaker you will be pouring the solutions into on a flat surface.
- Stand when pouring the solution.
- Slowly trickle the second solution down the inside of the beaker to form the best precipitate. If you add the solution quickly or do not trickle it down the inside of the beaker, the precipitate will trap bubbles and will not be as clear.
- Bring your eyes down to the beaker to observe the precipitate; never hold the beaker up to eye level.
- Ask your teacher or lab technician how to dispose of the remaining solutions and precipitate properly.

### Worked example: Try yourself 17.1.1

#### CALCULATING THE PERCENTAGE YIELD OF A REACTION

80.0 g of propan-1-ol was oxidised to propanoic acid using an acidified solution of K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub>. The propanoic acid obtained at the end of the reaction had a mass of 55.0 g. Calculate the percentage yield of this oxidation reaction.

#### Percentage yields in multistep syntheses

When a reaction proceeds by a number of steps, the overall percentage yield is reduced at each step. The yield for each step has an effect on the overall yield. A low yield in one of the intermediate reactions can have a significant effect on the amount of final product obtained.

A comparison of the overall percentage yields for different pathways to the same product can be used to determine whether a particular synthetic pathway is the best way to produce an organic compound. Finding the most efficient pathway for the production of a desired chemical is critical, because wasting valuable reactants is poor economic and environmental practice.

### Worked example 17.1.2

#### CALCULATING THE PERCENTAGE YIELD OF A MULTISTEP SYNTHESIS

Calculate the overall percentage yield for the preparation of C from A if it proceeds by a two-step synthesis:

The yield of A → B is 80% and the yield of B → C is 70%.

#### Thinking

Calculate the overall yield of C by multiplying the percentage yields together and expressing as a percentage (multiplying by 100).

#### Working

The overall yield of C is:  
 $\frac{80}{100} \times \frac{70}{100} \times 100$   
= 56%

### Worked example: Try yourself 17.1.2

#### CALCULATING THE PERCENTAGE YIELD OF A MULTISTEP SYNTHESIS

Calculate the overall percentage yield for the preparation of D from A if it proceeds by a three-step synthesis:

A → B followed by B → C followed by C → D  
The yield of A → B is 90%, the yield of B → C is 80%, and the yield of C → D is 60%.

#### Atom economy

An important objective for an industrial chemist who is developing a reaction pathway is to use a sequence of chemical reactions that minimises energy consumption, reduces waste and has a low impact on the environment.

One consideration when planning reaction pathways is to maximise atom economy.

The atom economy for a chemical reaction is a measure of the percentage of the atoms in the reactants that end up in the desired product.

As you can see in Figure 17.1.13, if the atom economy of a reaction is high, then there are few, if any, waste products.

The solubility rules tell you which substances are soluble, and to what extent.

### 3.3 Review

#### SUMMARY

- An equilibrium constant for a particular temperature can be calculated from the concentrations of the reactants and products at equilibrium and the expression for the equilibrium constant.
- The concentration of a reactant or product can be calculated if the concentrations of the other reactants and products and the equilibrium constant are known.

- Stoichiometry can be used to calculate equilibrium concentrations of reactants and products, and hence the value of the equilibrium constant, using a reaction (ICE) table.

#### KEY QUESTIONS

- Calculate the equilibrium constant for the reaction represented by the equation  $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$  if an equilibrium mixture in a 2.0 L container was found to consist of 0.80 mol of  $N_2$  and 0.40 mol of  $NH_3$ . Phosgene is a poisonous gas that was used during World War I. It can be formed by the reaction of carbon monoxide with chlorine gas in an equilibrium reaction:  
 $CO(g) + Cl_2(g) \rightleftharpoons COCl_2(g)$   
In an experiment, this reaction was allowed to proceed at 24°C until equilibrium was reached. The equilibrium concentrations of each species was determined and recorded as follows:  
 $[CO] = 2.4 \times 10^{-2} \text{ mol L}^{-1}$ ,  $[Cl_2] = 0.108 \text{ mol L}^{-1}$  and  $[COCl_2] = 0.28 \text{ mol L}^{-1}$ . Calculate the equilibrium constant for the reaction at this temperature.
- The following reaction was allowed to reach equilibrium at a temperature of 230°C:  
 $2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$   
The value of the equilibrium constant was determined to be  $6.44 \times 10^3$ . If the equilibrium concentration of  $[NO] = 15.5 \text{ mol L}^{-1}$  and  $[NO_2] = 0.0642 \text{ mol L}^{-1}$ , determine the concentration of  $O_2$  in the equilibrium mixture.
- 4.0 mol of  $NO_2$  and 5.0 mol of  $CO_2$  were mixed in a 2.0 L vessel. They reacted according to the equation:  
 $PCl_5(g) + Cl_2(g) \rightleftharpoons PCl_3(g)$   
When equilibrium was reached, it was found that 0.30 mol of  $PCl_5$  had been formed. Calculate the value of the equilibrium constant.
- 5.89 mol of  $N_2$  and 8.23 mol of  $H_2$  were mixed in a 5.00 L vessel. They reacted according to the equation:  
 $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$   
When equilibrium was reached, it was found that 0.48 mol of  $NH_3$  had been formed. Calculate the value of the equilibrium constant.
- The equilibrium constant for the following reaction is 48.8 at 455°C:  
 $2HI(g) \rightleftharpoons H_2(g) + I_2(g)$   
a. An equilibrium mixture in a 2.0 L vessel at 455°C contains 0.20 mol of  $H_2$  and 0.11 mol of  $I_2$ . Calculate the concentration of HI in this mixture.  
b. Another mixture was prepared by placing 4.00 mol of HI in a 2.0 L vessel at 330°C. At equilibrium, 0.44 mol of  $H_2$  and 0.44 mol of  $I_2$  were present. Calculate the value of the equilibrium constant at this temperature.  
c. A third mixture consisted of 1.0 mol of HI, 0.24 mol of  $H_2$  and 0.32 mol of  $I_2$  in a 2.0 L container at 330°C. Decide whether the mixture is at equilibrium and, if not, predict the direction the reaction will shift to reach equilibrium.

## SkillBuilder

A SkillBuilder outlines a method or technique. They are instructive and self-contained. They step students through the skill to support science application.

## Section review questions

Each section finishes with key questions to test students' understanding of and ability to recall the key concepts of the section.

# How to use this book

## Chapter review

Each chapter finishes with a list of key terms covered in the chapter and a set of questions to test students' ability to apply the knowledge gained from the chapter.

## Module review

Each module finishes with a set of questions, including multiple choice and short answer. These assist students in drawing together their knowledge and understanding, and applying it to these types of questions.

**Chapter review**

**KEY TERMS**

collision theory  
competing equilibria

Le Chatelier's principle  
position of equilibrium

**REVIEW QUESTIONS**

1 a State Le Chatelier's principle.  
b Write an equilibrium equation in terms of reactants A and B in equilibrium with products C and D, and use Le Chatelier's principle to explain what occurs when the products are gradually removed.  
2 Predict the effect of the following changes on the position of equilibrium in the system:  
 $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$   
a adding  $SO_2$  to the equilibrium system  
b removing  $O_2$  from the equilibrium system  
c removing  $SO_3$  from the equilibrium system  
3 The following equilibrium system is present in a sealed container of fixed volume:  
 $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$   
What change in the concentration of hydrogen gas can cause the following changes to the system at constant temperature?  
a The concentration of the product increases.  
b There is a net reverse reaction.  
4 Calcium is essential for maintaining bone strength. Elderly people, especially women, can become very susceptible to bone breakages. It is thought that as people age they absorb  $Ca^{2+}$  from food inefficiently, reducing the concentration of these ions in body fluids. An equilibrium exists between calcium phosphate in bone and calcium ions in body fluids:  
 $Ca_3(PO_4)_2(s) \rightleftharpoons 3Ca^{2+}(aq) + 2PO_4^{3-}(aq)$   
Use your understanding of equilibrium to explain why inefficient absorption of  $Ca^{2+}$  ions could cause weakness in bones.  
5 How will the concentration of hydrogen gas in each of the following equilibrium mixtures change when the mixtures are heated without changing the volume?  
a  $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$   $\Delta H = -91 \text{ kJ mol}^{-1}$   
b  $CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g)$   $\Delta H = +208 \text{ kJ mol}^{-1}$   
6 When solutions of  $Fe(NO_3)_3$  and  $KSCN$  are mixed, a red solution is formed as a result of the formation of  $FeSCN^{2+}$  (aq):  
 $Fe^{3+}(aq) + SCN^{-}(aq) \rightleftharpoons FeSCN^{2+}(aq)$   
Which one or more of the following would reduce the intensity of the red colour of the solution?

**04**

A adding a small volume of  $KSCN$  solution, which increases the concentration of  $SCN^{-}$  (aq).  
B adding a small volume of  $AgNO_3$  solution, which reacts to form insoluble  $AgSCN$ .  
C adding a small volume of  $Fe(NO_3)_3$  solution, which increases the concentration of  $Fe^{3+}$  (aq).  
D adding a small volume of water.  
7 The reaction represented by the following equation is exothermic:  
 $C_2(g) + CO(g) \rightleftharpoons COC_2(g)$   
At equilibrium at constant temperature, the volume is halved by increasing the pressure. Which one of the following statements is correct?  
A The new equilibrium concentration of  $CO$  will be less than the initial concentration.  
B The value of  $K_{eq}$  will increase.  
C The amount of  $COC_2$  will increase.  
D A net reverse reaction will occur.  
8 Dinitrogen tetroxide ( $N_2O_4$ ) and nitrogen dioxide ( $NO_2$ ) coexist according to the equilibrium reaction:  
 $N_2O_4(g) \rightleftharpoons 2NO_2(g)$   
a The graph below shows the change of the concentration of the two gases with time as they reach equilibrium at constant temperature.

Which gas does curve A represent? Which gas does curve B represent? Explain your answer.

CHAPTER 4 | FACTORS THAT AFFECT EQUILIBRIA 109

**MODULE 5 • REVIEW**

**REVIEW QUESTIONS**

**Equilibrium and acid reactions**

**Multiple choice**

1 Which one of the following statements is correct in relation to an endothermic reaction?  
A The value of the activation energy is  $< 0$  and the value of  $\Delta H$  is  $< 0$ .  
B The value of the activation energy is  $< 0$  and the value of  $\Delta H$  is  $> 0$ .  
C The value of the activation energy is  $> 0$  and the value of  $\Delta H$  is  $> 0$ .  
D The value of the activation energy is  $> 0$  and the value of  $\Delta H$  is  $< 0$ .

The following information refers to Questions 2 and 3. The energy profile diagram shown below is for the following reaction:

$CO_2(g) + NO(g) \rightleftharpoons CO(g) + NO_2(g)$

2 What is  $\Delta H$  of the forward reaction, in  $\text{kJ mol}^{-1}$ ?  
A -170  
B +130  
C -130  
D +170

3 What is the activation energy of the reverse reaction, in  $\text{kJ mol}^{-1}$ ?  
A 40  
B 130  
C 230  
D 360

4 Consider the following reaction equations:  
A  $A(g) + B(g) \rightleftharpoons 2C(g)$   $\Delta H = +180 \text{ kJ mol}^{-1}$   
B  $D(g) + 3E(g) \rightleftharpoons 2F(g)$   $\Delta H = -90 \text{ kJ mol}^{-1}$   
C  $2G(g) \rightleftharpoons H(g) + I(g)$   $\Delta H = -180 \text{ kJ mol}^{-1}$

From a comparison of the enthalpy changes,  $\Delta H$ , which of the following is definitely true?  
A Activation energy of equation 1 > activation energy of equation 2.  
B Activation energy of equation 1 > activation energy of equation 3.  
C Activation energy of equation 1 = activation energy of equation 3.  
D No information about activation energy can be deduced.

5 Select the correct statement about an open system.  
A Neither energy nor matter are exchanged with the surroundings.  
B Energy can be exchanged with the surroundings but not matter.  
C Matter can be exchanged with the surroundings but not energy.  
D Energy and matter can both be exchanged with the surroundings.

6 Which of the following is an example of an irreversible reaction?  
A Boiling an egg  
B Freezing a sample of water  
C Mixing of ethanol and water  
D The air trapped in a sealed soft drink container

7 Which of the following systems is not at equilibrium?  
A A sealed bottle of soft drink  
B A burning candle  
C A saturated solution of salt with solid salt on the bottom of the beaker  
D A gaseous reaction in a sealed container stored at constant temperature

8 Water vapour reacts with chlorine according to the following equation:  
 $2H_2O(g) + 2Cl_2(g) \rightleftharpoons 4HCl(g) + O_2(g)$   
At a particular temperature, the value of the equilibrium constant,  $K_{eq}$ , for this reaction is  $4.0 \times 10^{-2}$ . At the same temperature, what is the value of the equilibrium constant for the following reaction?  
 $2HCl(g) + \frac{1}{2}O_2(g) \rightleftharpoons H_2O(g) + Cl_2(g)$   
A  $2 \times 10^{-4}$   
B  $2 \times 10^{-2}$   
C  $2.5 \times 10^3$   
D 50

REVIEW QUESTIONS 135

## Icons

The NSW Stage 6 syllabus 'Learning across the curriculum' and 'General capabilities' content are addressed throughout the series and are identified using the following icons.



'Go to' icons are used to make important links to relevant content within the same Student Book.



This icon indicates when it is the best time to engage with a worksheet (WS), a practical activity (PA), a depth study (DS) or module review (MR) questions in *Pearson Chemistry 12 New South Wales Skills and Assessment* book.



This icon indicates the best time to engage with a practical activity on *Pearson Chemistry 12 New South Wales Reader+*.



## Glossary

Key terms are shown in **bold** in sections and listed at the end of each chapter. A comprehensive glossary at the end of the book includes and defines all the key terms.

## Answers

Numerical answers and key short response answers are included at the back of the book. Comprehensive answers and fully worked solutions for all section review questions, Worked example: Try yourself features, chapter review questions and module review questions are provided on *Pearson Chemistry 12 New South Wales Reader+*.

# Pearson Chemistry 12

## New South Wales



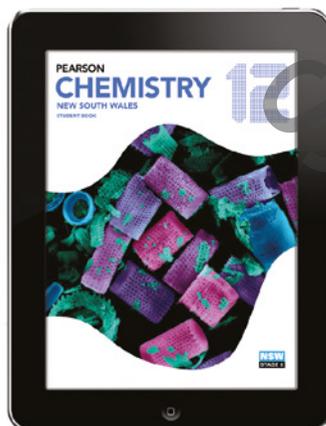
### Student Book

*Pearson Chemistry 12 New South Wales* has been written to fully align with the new Stage 6 syllabus for New South Wales. The Student Book includes the very latest developments in, and applications of, chemistry and incorporates best-practice literacy and instructional design to ensure the content and concepts are fully accessible to all students.



### Skills and Assessment Book

*Pearson Chemistry 12 New South Wales Skills and Assessment* book gives students the edge in preparing for all forms of assessment. Key features include a toolkit, key knowledge summaries, worksheets, practical activities, suggested depth studies and module review questions. It provides guidance, assessment practice and opportunities for developing key skills.



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### Teacher Support

Online teacher support for the series includes syllabus grids, a scope and sequence plan, and three practice exams per year level. Fully worked solutions to all Student Book questions are provided, as well as teacher notes for the chapter inquiry tasks. Skills and Assessment book resources include solutions to all worksheets, practical activities, depth studies and module review questions; teacher notes, safety notes, risk assessments and lab technician's checklists and recipes for all practical activities; and assessment rubrics and exemplar answers for the depth studies.



Access your digital resources at [pearsonplaces.com.au](http://pearsonplaces.com.au)  
Browse and buy at [pearson.com.au](http://pearson.com.au)

# Acid/base reactions

In this module you will analyse how and why the definitions of both an acid and a base have changed over time, and how the current definitions characterise the many chemical reactions of acids. Acids react in particular ways with a variety of substances. These reactions follow a pattern that you will identify and explore in detail.

Acids and bases, and their reactions, are used extensively in everyday life and in biological systems. The chemistry of acids and bases is important in industrial, biological and environmental contexts. Therefore it is essential that the degree of acidity in these situations is monitored. By investigating the qualitative and quantitative properties of acids and bases, you will learn to appreciate the importance of factors such as pH and indicators.

## Outcomes

By the end of this module, you will be able to:

- develop and evaluate questions and hypotheses for scientific investigation (CH12-1)
- design and evaluate investigations in order to obtain primary and secondary data and information (CH12-2)
- conduct investigations to collect valid and reliable primary and secondary data and information (CH12-3)
- analyse and evaluate primary and secondary data and information (CH12-5)
- describe, explain and quantitatively analyse acids and bases using contemporary models (CH12-13)

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Acids and bases have important and diverse roles. They are common in homes and are used extensively in industry and agriculture. Acids and bases are also the reactants and products in many chemical reactions that take place in environmental and biological systems.

In this chapter you will study a theory that explains the properties of acids and bases and the characteristic reactions of acids and bases. You will learn to represent common reactions of acids and bases using ionic equations.

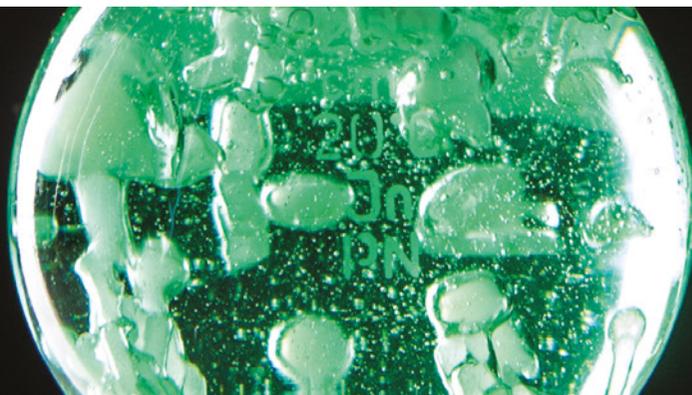
## Content

### INQUIRY QUESTION

#### What is an acid and what is a base?

By the end of this chapter, you will be able to:

- investigate the correct IUPAC nomenclature and properties of common inorganic acids and bases (ACSCH067)
- predict the products of acid reactions and write balanced equations to represent: **ICT**
  - acids and bases
  - acids and carbonates
  - acids and metals (ACSCH067)
- investigate applications of neutralisation reactions in everyday life and industrial processes
- conduct a practical investigation to measure the enthalpy of neutralisation (ACSCH093)
- explore the changes in definitions and models of an acid and a base over time to explain the limitations of each model, including but not limited to:
  - Arrhenius' theory
  - Brønsted–Lowry theory (ACSCH064, ACSCH067) **ICT**
- write ionic equations to represent the dissociation of acids and bases in water, conjugate acid/base pairs in solution and amphiprotic nature of some salts, for example:
  - sodium hydrogen carbonate
  - potassium dihydrogen phosphate



## 6.1 Introducing acids and bases



### CHEMISTRY INQUIRY S CCT

## An environmentally friendly drain cleaner

### COLLECT THIS...

- 60 g ( $\frac{1}{4}$  cup) sodium hydrogen carbonate (bicarbonate of soda) powder
- 250 mL (1 cup) vinegar
- 60 g ( $\frac{1}{4}$  cup) coarse salt
- tablespoon
- boiling water

### DO THIS...

- 1 Using the spoon, sprinkle the sodium hydrogen carbonate into a drain, particularly around the edges of the underlying pipe. Residual water within the pipe should allow the sodium hydrogen carbonate to stick to the pipe.
- 2 Using the spoon, sprinkle the salt into the drain.
- 3 Pour the vinegar into the drain pipe. Be sure to go around the edges.
- 4 Wait 20 minutes.
- 5 Rinse the drain with about 1 cup of fresh boiling water.

### RECORD THIS...

Describe what happened during the reaction of the sodium hydrogen carbonate and vinegar.

Research the ingredients of common drain cleaners.

### REFLECT ON THIS...

- 1 What is the purpose of adding the coarse salt to the reaction?
- 2 Classify the vinegar and sodium hydrogen carbonate as either an acid or base.
- 3 With your understanding of reaction types, what are the expected products of this reaction?
- 4 Compare the ingredients of common drain cleaners. How is this reaction more environmentally friendly?

Acids and bases make up some of the household products in your kitchen and laundry (Figure 6.1.1). In this section you will be introduced to a theory that explains the chemical properties of acids and bases, helping you to explain their usefulness within the home and industry. You will also look at how the acidity of a solution can be measured, so that acid solutions can be defined as a strong or weak acid.



FIGURE 6.1.1 Some common household products that contain acids or bases

## CHEMFILE IU

### Saving the Nobel Prize gold medals

George de Hevesy (1885–1966) worked for the Niels Bohr Institute in Denmark during World War II. The Institute was looking after a number of valuable gold medals that had been awarded to recipients of the Nobel Prize.

When Germany invaded Denmark at the beginning of World War II, de Hevesy was concerned that the Germans would confiscate the gold medals. He dissolved the gold medals in aqua regia, which is a mixture of concentrated hydrochloric and nitric acid. Aqua regia is strong enough to dissolve gold, a metal known for its lack of chemical reactivity.

He hid the bottle containing the gold solution among the hundreds of other bottles on his laboratory shelves. The bottle was never found by the German occupiers and after the war de Hevesy retrieved the precious bottle and precipitated the gold out of solution. The gold was sent to the Nobel Foundation, who had the medals recast into duplicates of the originals and returned to their owners (Figure 6.1.2).

Between 1901 and 2017 the Nobel Prize in Chemistry has been awarded 109 times to 177 individuals, including de Hevesy in 1943 for his work on radioactive tracers. Frederick Sanger is the only double Nobel laureate in Chemistry: in 1958 for his work on the structure of proteins, especially that of insulin, and in 1980 for his fundamental studies on the biochemistry of nucleic acids, with particular regard to recombinant DNA.

Sir Fraser Stoddart, one of the recipients of the 2016 Nobel Prize in Chemistry for his contributions to the design and synthesis of molecular machines, commented that because of the rarity and unknowing nature of receiving the Nobel Prize, the dream of winning such a prize should not be the focus of a budding scientist. Instead, a focus on people, deep connections and an insatiable passion for the subject should inspire scientists.



FIGURE 6.1.2 Recipients of the Nobel Prize are given a sum of money and a gold medal weighing about 175 g.

## ACIDS AND BASES

**Acids** are used in our homes, in agriculture and in industry. They also have important roles in our bodies. Table 6.1.1 gives the names, chemical formulae and uses of some common acids.

**TABLE 6.1.1** Common acids and their everyday uses

Name	Formula	Uses
hydrochloric acid	HCl	present in stomach acid to help break down proteins; used as a cleaning agent for brickwork, and in the manufacture of a wide range of products
sulfuric acid	H <sub>2</sub> SO <sub>4</sub>	one of the most common chemicals manufactured; used in car batteries and in the manufacture of fertilisers, dyes and detergents
nitric acid	HNO <sub>3</sub>	used in the manufacture of fertilisers, dyes and explosives
ethanoic acid (acetic acid)	CH <sub>3</sub> COOH	found in vinegar; used as a preservative and in the manufacture of glues and plastics
carbonic acid	H <sub>2</sub> CO <sub>3</sub>	used to carbonate soft drinks and beer
phosphoric acid	H <sub>3</sub> PO <sub>4</sub>	used as a flavouring and in the manufacture of fertilisers and pharmaceutical products
citric acid	C <sub>6</sub> H <sub>8</sub> O <sub>7</sub>	found in citrus fruits; used as a flavouring and preservative
ascorbic acid (vitamin C)	C <sub>6</sub> H <sub>8</sub> O <sub>6</sub>	found in citrus fruits; used as a health supplement and as an antioxidant in food production

### CHEMFILE WE

#### Handle strong bases with care

Bases feel slippery to the touch because they react with fats in our skin to produce soap. Strong bases should be handled with care. Oven cleaners contain about 4% of the strong base sodium hydroxide. A common name of sodium hydroxide is caustic soda.

Figure 6.1.3 shows the safety instructions on a can of oven cleaner.



**FIGURE 6.1.3** Oven cleaners remove fatty deposits by reacting with them to form soaps. Note the safety instructions.

Many cleaning agents used in the home, such as washing powders and oven cleaners, contain **bases**. Solutions of ammonia are used as floor cleaners, and sodium hydroxide is the major active ingredient in oven cleaners. Bases are effective cleaners because they react with fats and oils to produce water-soluble soaps. A water-soluble base is called an **alkali**.

**i** Alkalis are bases that can dissolve in water. The solution is said to be alkaline, with a pH greater than 7.0. Calcium carbonate will react with acids, but it is not an alkali because it is insoluble in water.

Table 6.1.2 gives the names, chemical formulae and uses of some common bases.

**TABLE 6.1.2** Common bases and their everyday uses

Name	Formula	Uses
Sodium hydroxide (caustic soda)	NaOH	drain and oven cleaners, soap-making, industrial applications
Ammonia	NH <sub>3</sub>	household cleaners, fertilisers, explosives, plastics manufacture
Calcium hydroxide	Ca(OH) <sub>2</sub>	cement and mortar, garden lime, food preparation
Magnesium hydroxide	Mg(OH) <sub>2</sub>	antacids such as milk of magnesia, to treat indigestion
Sodium carbonate	Na <sub>2</sub> CO <sub>3</sub>	manufacture of washing powders, soaps, glass, paper

## CHANGING IDEAS ABOUT THE NATURE OF ACIDS AND BASES

Over the years there have been many attempts to define acids and bases. At first, acids and bases were defined in terms of their observed properties such as their taste, effect on **indicators** and reactions with other substances.

For example, in the 17th century, British scientist Robert Boyle described the properties of acids in terms of taste, their action as solvents, and how they changed the colour of certain vegetable extracts (similar to red cabbage juice seen in Figure 6.1.4). He also noticed that alkalis could reverse the effect that acids had on these extracts.



**FIGURE 6.1.4** Natural acid–base indicators are found in plants such as red cabbage. Red cabbage extract turns a different colour in (from left to right) concentrated acid, dilute acid, neutral solution, dilute base and concentrated base.

It was not until the late 18th century that attempts were made to define acids and bases on the basis of the nature of their constituent elements. Antoine Lavoisier, a French chemist, thought that acidic properties were due to the presence of oxygen. While this explanation applied to sulfuric acid ( $\text{H}_2\text{SO}_4$ ), nitric acid ( $\text{HNO}_3$ ) and phosphoric acid ( $\text{H}_3\text{PO}_4$ ), it did not explain why hydrochloric acid ( $\text{HCl}$ ) was an acid.

In about 1810, Humphrey Davy suggested that the acid properties of substances were associated with hydrogen and not oxygen. He came to this conclusion after producing hydrogen gas by reacting acids with metals. Davy also suggested that acids react with bases to form salts and water.

### The Arrhenius theory of acids and bases

The ideas of Lavoisier and Davy were further developed by the Swedish scientist Svante Arrhenius. In 1887 the **Arrhenius theory** defined acids and bases as follows.

- Acids are substances that **dissociate** (break apart) and **ionise** (form ions) in water. They produce hydrogen ions ( $\text{H}^+$ ).
- Bases dissociate in water to produce **hydroxide ions** ( $\text{OH}^-$ ).

In 1923, Danish physical chemist Johannes Brønsted and English chemist Thomas Lowry were working independently on acids and bases. They each came up with the theory that now bears both of their names. The Brønsted–Lowry theory is more general than the one proposed by Arrhenius and provides an explanation for some observed acid–base behaviours that cannot be explained by the earlier theories.

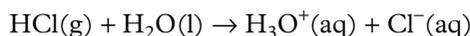
## THE BRØNSTED–LOWRY THEORY OF ACIDS AND BASES

According to the **Brønsted–Lowry theory**, a substance behaves as an acid when it donates a proton ( $\text{H}^+$ ) to a base. A substance behaves as a base when it accepts a proton from an acid.

In summary:

- acids are **proton donors**
- bases are **proton acceptors**
- an **acid–base reaction** involves an exchange of protons from an acid to a base.

For example, hydrogen chloride (HCl) is a gaseous molecular compound that is very soluble in water. The molecules dissociate in water according to the following reaction:



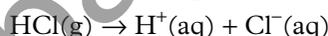
In an aqueous solution of hydrogen chloride, nearly all the hydrogen chloride is present as ions—virtually no molecules of hydrogen chloride remain. This solution is known as hydrochloric acid.

In this reaction, each HCl molecule has donated a proton to a water molecule, forming the **hydronium ion**,  $\text{H}_3\text{O}^+(\text{aq})$ . According to the Brønsted–Lowry theory, the HCl has acted as an acid. The water molecule has accepted a proton from the HCl molecule, so the water has acted as a base. This is outlined in Figure 6.1.5.

The hydronium ion can be represented as either  $\text{H}_3\text{O}^+(\text{aq})$  or  $\text{H}^+(\text{aq})$ . The reaction of HCl(g) with water can be written as either:

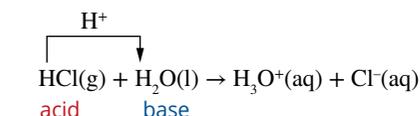


or

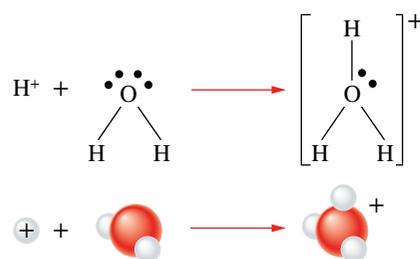


Writing the hydronium ion as  $\text{H}^+(\text{aq})$  in an equation makes it harder to see that a proton transfer has occurred. The hydronium ion is therefore usually written as  $\text{H}_3\text{O}^+(\text{aq})$  in this chapter.

The structural formulae of the hydronium ion and a water molecule are shown in Figure 6.1.6.



**FIGURE 6.1.5** The reaction between hydrochloric acid and water is an example of an acid–base reaction, which involves a transfer of protons from an acid to a base.



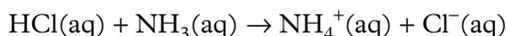
**FIGURE 6.1.6** Formation of the hydronium ion

**i** Remember that  $\text{H}^+(\text{aq})$  is often used interchangeably with  $\text{H}_3\text{O}^+(\text{aq})$  when discussing the nature of acids.

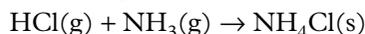
### Advantages of the Brønsted–Lowry theory

Acid–base reactions are not restricted to aqueous solutions. A reaction between two gases can be an acid–base reaction. For example, the **salt** ammonium chloride can be formed by a reaction between:

- solutions of hydrochloric acid and ammonia:



- gaseous hydrogen chloride and gaseous ammonia:



The Brønsted–Lowry theory classifies both of these reactions as acid–base reactions, because in each case the acid donates a proton to the base.

## PROPERTIES OF ACIDS AND BASES

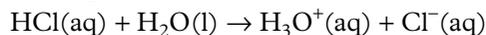
All acids have some properties in common. Bases also have common properties. The properties of acids and bases are summarised in Table 6.1.3.

**TABLE 6.1.3** Properties of acids and bases

Properties of acids	Properties of bases
<ul style="list-style-type: none"> <li>• turn litmus indicator (purple litmus) red</li> <li>• tend to be corrosive</li> <li>• taste sour</li> <li>• react with bases</li> <li>• solutions have a pH below 7.0</li> <li>• solutions conduct an electric current</li> </ul>	<ul style="list-style-type: none"> <li>• turn litmus indicator (purple litmus) blue</li> <li>• are caustic and feel slippery</li> <li>• taste bitter</li> <li>• react with acids</li> <li>• solutions have a pH above 7.0</li> <li>• solutions conduct an electric current</li> </ul>

## CONJUGATE ACID–BASE PAIRS

A **conjugate acid–base pair** is two molecules or ions that differ by one proton ( $\text{H}^+$ ). Consider the reactants and products when hydrochloric acid dissociates in water:



$\text{HCl}$  and  $\text{Cl}^-$  differ by one proton, so they are a conjugate acid–base pair. Similarly,  $\text{H}_3\text{O}^+$  and  $\text{H}_2\text{O}$  are also a conjugate acid–base pair. Because  $\text{Cl}^-$  is formed from  $\text{HCl}$  by the loss of a single proton, it is called the **conjugate base** of  $\text{HCl}$ . Similarly,  $\text{HCl}$  is the **conjugate acid** of  $\text{Cl}^-$ . Conjugate acid–base pairs are written in the format of acid/base; for example,  $\text{HCl}/\text{Cl}^-$ .

The relationship between acid–base conjugate pairs is represented in Figure 6.1.7.

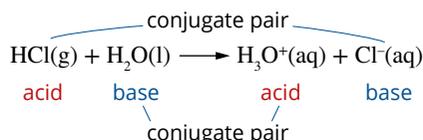


FIGURE 6.1.7 Conjugate acid–base pairs are formed when an acid donates a proton to a base.

In the reaction between  $\text{NH}_3$  and  $\text{H}_2\text{O}$  shown in Figure 6.1.8, the conjugate acid–base pairs are  $\text{NH}_4^+/\text{NH}_3$  and  $\text{H}_2\text{O}/\text{OH}^-$  because each acid differs from its corresponding base by one proton.

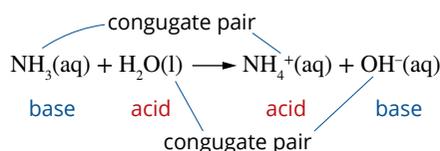


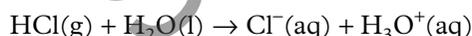
FIGURE 6.1.8 The reaction between ammonia and water, showing the conjugate acid–base pairs.

Figure 6.1.9 shows the formulae of some common acids and bases and their conjugates.

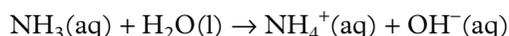
## AMPHIPROTIC SUBSTANCES

Some substances can either donate or accept protons, depending on the substance they are reacting with. This means they can behave as either an acid or a base. Such substances are called **amphiprotic**.

For example, in an aqueous solution of  $\text{HCl}$ , water gains a proton from  $\text{HCl}$  and therefore acts as a base.



However, in the reaction below, water donates a proton to  $\text{NH}_3$  and therefore acts as an acid.



These reactions are represented in Figure 6.1.10.

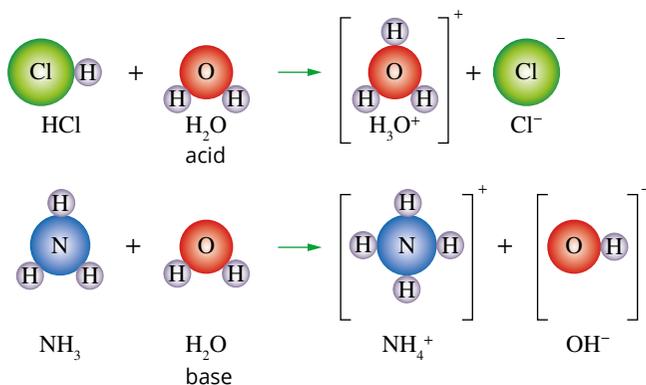
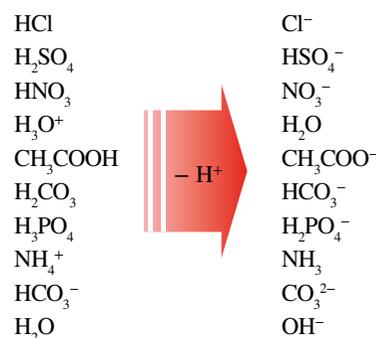


FIGURE 6.1.10 The amphiprotic nature of water is demonstrated by its reactions with  $\text{HCl}$  and  $\text{NH}_3$ .

Acids ... donate a proton to form:



Bases ... accept a proton to form:

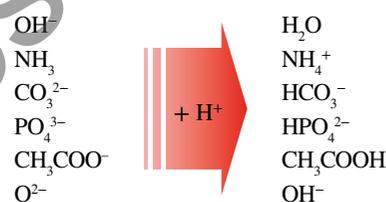


FIGURE 6.1.9 Some common acid–base conjugate pairs.

**i** When acids react with water, hydronium ( $\text{H}_3\text{O}^+$ ) ions are produced. When bases react with water, hydroxide ( $\text{OH}^-$ ) ions are produced.

It is evident that water can act as either an acid or a base, depending on the **solute** present.

If the solute is a stronger acid than water, then water will react as a base. If the solute is a stronger base than water, then water will react as an acid.

Some common amphoteric substances are listed in Figure 6.1.11.

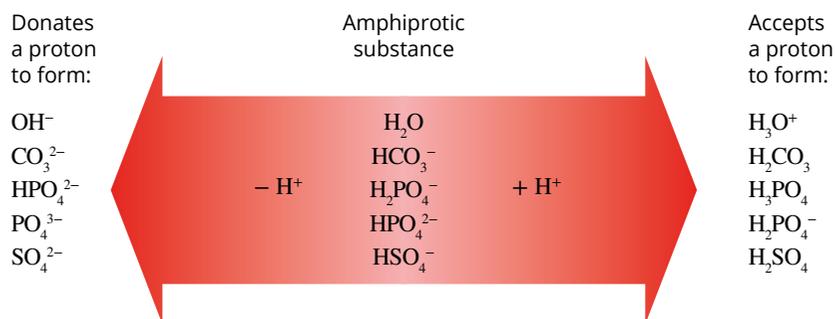
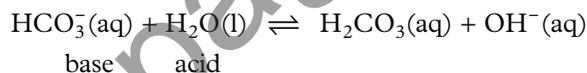


FIGURE 6.1.11 Substances that are amphoteric.

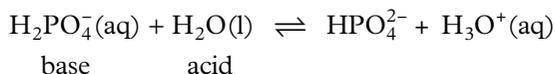
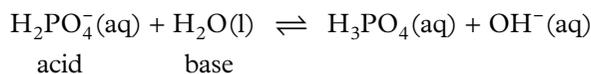
When an amphoteric substance is placed in water, it reacts as both an acid and a base. For example, the hydrogen carbonate ion ( $\text{HCO}_3^-$ ) reacts according to the equations:



Since  $\text{HCO}_3^-$  can act as both an acid and a base, it is amphoteric.

Although both reactions are possible for all amphoteric substances in water, generally one of these reactions dominates. The dominant reaction can be identified by measuring the pH (a measure of the amount of hydronium ion in solution) of the solution. (You will look more closely at pH in Chapter 7.)

Salts that contain such ions are said to be amphoteric in nature. Examples of these include sodium hydrogen carbonate ( $\text{NaHCO}_3$ ) and potassium dihydrogen phosphate. The dihydrogen phosphate ion ( $\text{H}_2\text{PO}_4^-$ ) reacts according to the following equations:



## MONOPROTIC ACIDS

**Monoprotic acids** can donate only one proton. These acids include hydrochloric acid ( $\text{HCl}$ ), hydrofluoric acid ( $\text{HF}$ ), nitric acid ( $\text{HNO}_3$ ) and ethanoic acid ( $\text{CH}_3\text{COOH}$ ).

Although ethanoic (acetic) acid contains four hydrogen atoms, each molecule can donate only one proton to produce an ethanoate (acetate) ion ( $\text{CH}_3\text{COO}^-$ ), so ethanoic acid is monoprotic. Only the hydrogen that is part of the highly polar O–H bond is donated. This hydrogen is called the **acidic proton** (Figure 6.1.12).

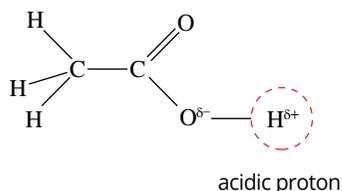


FIGURE 6.1.12 The structure of ethanoic acid. Each molecule can donate only one proton to a water molecule when ethanoic acid reacts with water.

## POLYPROTIC ACIDS

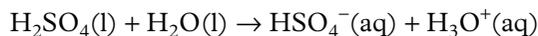
Acids that can donate more than one proton from each molecule are called **polyprotic acids**. The number of hydrogen ions an acid can donate depends on the structure of the acid. Polyprotic acids do not donate all of their protons at once, but do so in steps when reacting with a base.

**GO TO >** Section 7.2 page 167

## Diprotic acids

**Diprotic acids**, such as sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and carbonic acid ( $\text{H}_2\text{CO}_3$ ), can donate two protons. A diprotic acid, for example sulfuric acid, dissociates in two stages.

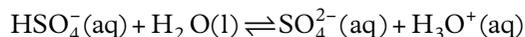
Stage 1:



Sulfuric acid is described as a **strong acid** in water because it readily donates a proton, so this stage occurs almost to completion. Virtually no  $\text{H}_2\text{SO}_4$  molecules are found in an aqueous solution.

Stage 2:

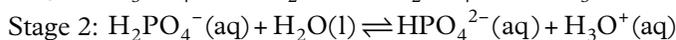
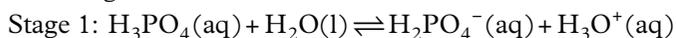
The  $\text{HSO}_4^-$  ion formed can also act as an acid. In a  $1.0 \text{ mol L}^{-1}$  solution, only a small proportion of those ions reacts further to produce  $\text{H}_3\text{O}^+$  ions and  $\text{SO}_4^{2-}$  ions.



$\text{HSO}_4^-$  is described as a **weak acid** because it is only partially dissociated. A double (reversible) arrow indicates that an incomplete reaction occurs. (You will learn more about strong and weak acids later in this chapter.) Therefore a solution of sulfuric acid contains hydrogen ions, hydrogen sulfate ions and sulfate ions.

## Triprotic acids

**Triprotic acids** can donate three protons. These include phosphoric acid ( $\text{H}_3\text{PO}_4$ ) and boric acid ( $\text{H}_3\text{BO}_3$ ). A triprotic acid, such as phosphoric acid, dissociates in three stages.



Phosphoric acid is a weak acid in water, so in a  $1.0 \text{ mol L}^{-1}$  solution only a small proportion of the protons is donated at each dissociation stage. The extent of the dissociation decreases progressively from stage 1 to stage 3. You will learn more about how the extent of dissociation is quantified in Chapter 8.

**GO TO**  Section 8.5 page 220

## NAMING ACIDS

To name a simple acid composed of hydrogen and another element, take the element's name and change the '-ide' ending to '-ic acid'. For example:

- hydrogen chloride becomes hydrochloric acid, and the anion is a chloride ion.

For acids that contain oxygen (oxyacids), the acid name often ends in '-ic acid'.

The name of the anion of the acid often ends in '-ate'. For example:

- sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and the anion, sulfate ( $\text{SO}_4^{2-}$ )
- nitric acid ( $\text{HNO}_3$ ) and the anion, nitrate ( $\text{NO}_3^-$ )
- ethanoic acid ( $\text{CH}_3\text{COOH}$ ) and the anion, ethanoate ( $\text{CH}_3\text{COO}^-$ ).

For some oxyacids, the acid name ends in '-ous acid'. These oxyacids have fewer O atoms than the corresponding '-ic acid'. The anion name will end in '-ite'.

For example:

- sulfurous acid ( $\text{H}_2\text{SO}_3$ ) and the anion, sulfite ( $\text{SO}_3^{2-}$ )
- nitrous acid ( $\text{HNO}_2$ ) and the anion, nitrite ( $\text{NO}_2^-$ ).

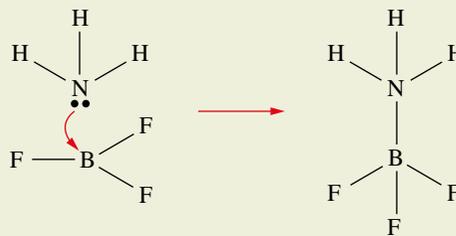
## + ADDITIONAL

# Lewis acids and bases

Not all acids are substances that can be easily defined by the donation of a proton. In the same year that the Brønsted–Lowry theory was published, Gilbert N. Lewis (of Lewis dot diagrams fame) defined an acid as being a substance that can accept a lone electron pair from another molecule. By contrast, Lewis bases are substances that donate a lone pair of electrons. Brønsted–Lowry bases are also Lewis bases because they donate a pair of electrons in order to accept a proton.

Lewis acids and bases are a diverse group of compounds. An example of a Lewis acid is boron trifluoride ( $\text{BF}_3$ ). When it interacts with a Lewis base, such as ammonia ( $\text{NH}_3$ ),

it accepts a pair of electrons from the nitrogen, which creates a bond with the ammonia molecule.



**FIGURE 6.1.13** The lone-pair interaction between ammonia ( $\text{NH}_3$ ) and boron trifluoride ( $\text{BF}_3$ )

## 6.1 Review

### SUMMARY

- The Brønsted–Lowry model describes acid–base properties in terms of proton transfer. In this model, an acid is a proton donor and a base is a proton acceptor.
- When an acid donates a proton, it forms its conjugate base. When a base accepts a proton, it forms its conjugate acid.
- Conjugate acid–base pairs are molecules or ions that differ from each other by one proton ( $\text{H}^+$ ).
- A proton or hydrogen ion in solution can be represented by the hydronium ion,  $\text{H}_3\text{O}^+(\text{aq})$ , or simply as  $\text{H}^+(\text{aq})$ .
- Amphiprotic substances can act as either acids or bases, depending on the substance with which they are reacting.
- A polyprotic acid can donate more than one proton to a base.
- The first dissociation of a diprotic acid occurs to a greater extent than the second dissociation. In a triprotic acid, the third dissociation occurs to the least extent.

### KEY QUESTIONS

- 1 An acidic solution is formed when hydrogen bromide gas ( $\text{HBr}$ ) is mixed with water ( $\text{H}_2\text{O}$ ). Write an equation for this reaction.
- 2 In the following reaction, what are the two acid–base conjugate pairs?  
$$\text{H}_2\text{SO}_4(\text{l}) + \text{HNO}_3(\text{l}) \rightarrow \text{HSO}_4^-(\text{l}) + \text{H}_2\text{NO}_3^+(\text{l})$$
- 3 For each of the following equations, give the conjugate of the acid or base that is in bold.
  - a  $\text{HF}(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{H}_2\text{O}(\text{l}) + \text{F}^-(\text{aq})$
  - b  $\text{HCOOH}(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{H}_3\text{O}^+(\text{aq}) + \text{HCOO}^-(\text{aq})$
  - c  $\text{CH}_3\text{NH}_2(\text{aq}) + \text{HCl}(\text{aq}) \rightarrow \text{CH}_3\text{NH}_3^+(\text{aq}) + \text{Cl}^-(\text{aq})$
- 4 What is the conjugate acid of each of the following bases?
  - a  $\text{NH}_3$
  - b  $\text{CH}_3\text{COO}^-$
  - c  $\text{HPO}_4^{2-}$
  - d  $\text{CO}_3^{2-}$
  - e  $\text{O}^{2-}$
- 5 Show that the reaction between solutions of sodium hydroxide and hydrochloric acid is a Brønsted–Lowry acid–base reaction.
- 6 Write an equation to show each of the following acting as an acid and a base with water.
  - a  $\text{HCO}_3^-$
  - b  $\text{HPO}_4^{2-}$
  - c  $\text{HSO}_4^-$
  - d  $\text{H}_2\text{O}$

## 6.2 Reactions of acids and bases

Brønsted–Lowry acid–base reactions involve the exchange of a proton ( $\text{H}^+$  ion), but there are other acid and base reactions that need to be considered to fully understand their properties and the products formed from such reactions.

In this section you will learn to use the patterns in the reactions of acids and bases to predict the products that are formed, calculate quantities of acids or bases required for neutralisation to occur, calculate the pH of the resultant solution when an acid or base is in excess after mixing, and develop an understanding of the enthalpy of neutralisation.

The general reaction types explored in this section include acids reacting with:

- metal hydroxides
- metal carbonates (including hydrogen carbonates)
- reactive metals.

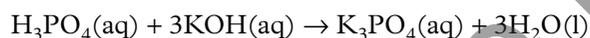
### ACIDS AND METAL HYDROXIDES

In the previous section you learnt that a Brønsted–Lowry acid is a proton donor and that a Brønsted–Lowry base is a proton acceptor. Bases that contain hydroxide ions will accept the protons from an acidic solution to form water. The metal cation and conjugate base anion of the acid thus become the salt.

This can be expressed generally as:



For example, solutions of phosphoric acid and potassium hydroxide react to form a potassium phosphate salt and water. This can be represented by the full (or overall) equation:



Experimentally you can confirm the presence of the salt by evaporating the water, leaving the solid salt behind.

### NEUTRALISATION REACTIONS

When a basic solution is added to an acidic solution, a reaction takes place that usually forms a salt and water. The solutions are said to have been **neutralised** when the concentrations of the hydronium and hydroxide ions within the mixture become equal.

#### Worked example 6.2.1

##### CALCULATING THE AMOUNT OF BASE NEEDED TO NEUTRALISE AN ACID

What volume of a  $0.20 \text{ mol L}^{-1}$  solution of barium hydroxide ( $\text{Ba}(\text{OH})_2$ ) would be required to neutralise 150 mL of a  $0.15 \text{ mol L}^{-1}$  solution of nitric acid ( $\text{HNO}_3$ )?

Thinking	Working
Write the general reaction and identify the products.	acid + metal hydroxide $\rightarrow$ salt + water Products of this reaction are barium nitrate in solution and water.
Write a balanced chemical equation.	$2\text{HNO}_3(\text{aq}) + \text{Ba}(\text{OH})_2(\text{aq}) \rightarrow \text{Ba}(\text{NO}_3)_2(\text{aq}) + 2\text{H}_2\text{O}(\text{l})$
Calculate the amount, in mol, of known substance using the following relationship: $n = c \times V$	$n(\text{HNO}_3) = c \times V$ $= 0.150 \times 0.15$ $= 0.023 \text{ mol}$

<p>Calculate the amount of substance, in mol, of the unknown chemical species using the mole ratio between known and unknown chemical species:</p> $\text{mole ratio} = \frac{\text{coefficient of unknown chemical}}{\text{coefficient of known chemical}}$	$\frac{n(\text{Ba}(\text{OH})_2)}{n(\text{HNO}_3)} = \frac{1}{2}$ $n(\text{Ba}(\text{OH})_2) = \frac{1}{2} \times n(\text{HNO}_3)$ $= \frac{1}{2} \times 0.023 \text{ mol}$ $= 0.011 \text{ mol}$
<p>Knowing the concentration, calculate the required volume for neutralisation using the following relationship:</p> $V = \frac{n}{c}$	$V(\text{Ba}(\text{OH})_2) = \frac{n}{c}$ $= \frac{0.01125}{0.20}$ $= 0.056 \text{ L}$ $= 56 \text{ mL}$

### Worked example: Try yourself 6.2.1

#### CALCULATING THE AMOUNT OF BASE NEEDED TO NEUTRALISE AN ACID

What volume of a  $0.100 \text{ mol L}^{-1}$  solution of barium hydroxide ( $\text{Ba}(\text{OH})_2$ ) would be required to neutralise  $75.0 \text{ mL}$  of a  $0.0500 \text{ mol L}^{-1}$  solution of sulfuric acid ( $\text{H}_2\text{SO}_4$ )?

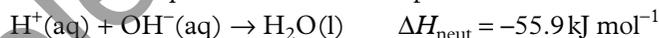
### Enthalpy of neutralisation

**Enthalpy of neutralisation** is the thermal energy change in the reaction when an acid and a base react in stoichiometric proportions to make a salt and 1 mol of water. It is represented by the symbol  $\Delta H_{\text{neut}}$ .

The reaction is exothermic ( $\Delta H$  is negative). In the reaction of strong acids with strong bases, the hydrogen and hydroxide ions that react to form water are already within solution.

The formation of 1 mol of water releases  $55.9 \text{ kJ}$  of energy.

The thermochemical equation thus can be represented as:



#### Measuring the enthalpy of neutralisation using simple calorimetry

The enthalpy of neutralisation can be measured using simple **calorimetry**. By measuring the temperature change of the salt solution formed, the energy released by the **neutralisation reaction** can be measured using the formula:

$$q = m \times c \times \Delta T$$

where

$q$  is the amount of energy released by the neutralisation reaction (in J)

$m$  is the mass of the salt solution = the combined mass of the acid and base (in g)

$c$  is the specific heat capacity of water ( $4.18 \text{ J g}^{-1} \text{ K}^{-1}$ )

$\Delta T$  is the temperature change of the mixture of the acid and base (in K or  $^{\circ}\text{C}$ ).

A number of assumptions are made when determining the amount of energy released by the neutralisation reaction using this method:

- The salt solution formed from the reaction has the same specific heat capacity as that of water. This is a reasonable assumption because the salt solution is dilute, so it contains mostly water.
- All thermal energy released by the reaction is transferred to the salt solution. There is no energy loss.
- If the mass of the salt solution formed was not measured, it can be assumed that the salt solution has the same density as that of water, i.e.  $1 \text{ g mL}^{-1}$ . This is another reasonable assumption because the salt solution is dilute, so it contains mostly water.

Once the energy released by the neutralisation reaction has been determined, the enthalpy of neutralisation can be calculated by the following expression:

$$H_{\text{neut}} = \frac{q}{n(\text{H}_2\text{O})}$$

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where

$\Delta H_{\text{neut}}$  is the enthalpy of neutralisation (in  $\text{kJ mol}^{-1}$ )

$q$  is the amount of energy released by the neutralisation reaction (in kJ)

$n(\text{H}_2\text{O})$  is the amount of water produced by the neutralisation reaction (in mol).



### Worked example 6.2.2

#### DETERMINING THE ENTHALPY OF NEUTRALISATION

50.0 mL of a diluted standard sodium hydroxide solution ( $\text{NaOH}$ ) was added to neutralise 50.0 mL of a  $2.0 \text{ mol L}^{-1}$  solution of ethanoic acid ( $\text{CH}_3\text{COOH}$ ).

The temperature of the mixture rose from  $22.0^\circ\text{C}$  to a maximum temperature of  $33.7^\circ\text{C}$ .

Determine the enthalpy of neutralisation.

Thinking	Working
Write a balanced chemical equation for the reaction.	$\text{NaOH}(\text{aq}) + \text{CH}_3\text{COOH}(\text{aq}) \rightarrow \text{NaCH}_3\text{COO}(\text{aq}) + \text{H}_2\text{O}(\text{l})$
Determine the amount, in mol, of acid using the expression: $n = c \times V$	$n(\text{CH}_3\text{COOH}) = c \times V$ $= 2.0 \times 0.0500$ $= 0.10 \text{ mol}$
Determine the temperature change of the mixture, $\Delta T$ .	$\Delta T = 33.7 - 22.0$ $= 11.7^\circ\text{C}$
Determine the amount of energy released by the reaction using the formula: $q = m \times c \times \Delta T$ Assume the density of the mixture is $1 \text{ g mL}^{-1}$ . Therefore the mass of the mixture is equivalent to the volume of the mixture.	$q = m \times c \times \Delta T$ $= 100.0 \times 4.18 \times 11.7$ $= 4.89 \times 10^3 \text{ J}$
Convert energy to kJ.	$\frac{4.89 \times 10^3}{1000}$ $= 4.89 \text{ kJ}$
Determine the amount of water, in mol, produced in the reaction, using the mole ratio with the limiting reactant.	$\frac{n(\text{H}_2\text{O})}{n(\text{CH}_3\text{COOH})} = \frac{1}{1}$ $n(\text{H}_2\text{O}) = n(\text{CH}_3\text{COOH})$ $= 0.10 \text{ mol}$
Determine $\Delta H_{\text{neut}}$ using: $H_{\text{neut}} = \frac{q}{n(\text{H}_2\text{O})}$ Because the temperature increased, the reaction was exothermic and hence $\Delta H_{\text{neut}}$ is negative.	$H_{\text{neut}} = \frac{q}{n(\text{H}_2\text{O})}$ $= \frac{-4.89}{0.10}$ $= -49 \text{ kJ mol}^{-1}$

### Worked example: Try yourself 6.2.2

#### DETERMINING THE ENTHALPY OF NEUTRALISATION

25.0 mL of a diluted standard barium hydroxide solution ( $\text{Ba}(\text{OH})_2$ ) was added to neutralise 50.0 mL of a  $1.5 \text{ mol L}^{-1}$  solution of ethanoic acid ( $\text{CH}_3\text{COOH}$ ).

The temperature of the solution rose from  $21.3^\circ\text{C}$  to a maximum temperature of  $34.0^\circ\text{C}$ .

Determine the enthalpy of neutralisation.

## ACIDS AND METAL CARBONATES

Metal carbonates and metal hydrogen carbonates (bicarbonates) react with acids to form the same products. These products include a salt, carbon dioxide and water.

The general equation for the reaction between acids and metal carbonates is:  
 $\text{acid} + \text{metal carbonate} \rightarrow \text{salt} + \text{water} + \text{carbon dioxide}$

For example, a solution of phosphoric acid reacting with sodium carbonate solution produces a solution of sodium phosphate, water and carbon dioxide gas. The reaction is represented by the equation:



Similarly, the reaction between phosphoric acid and sodium hydrogen carbonate can be represented as:



**i** Spectator ions are ions that do not participate in a chemical reaction but are still present within the reaction mixture. Spectator ions are therefore not listed in a net ionic equation.

### Worked example 6.2.3

#### WRITING IONIC EQUATIONS FOR REACTIONS BETWEEN ACIDS AND METAL CARBONATES

Thinking	Working
What products are formed when a dilute solution of hydrochloric acid is added to solid sodium carbonate? Write an ionic equation for this reaction.	
Write the general reaction and identify the products.	acid + metal carbonate $\rightarrow$ salt + water + carbon dioxide The products of this reaction are sodium chloride in solution, water, and carbon dioxide gas.
Identify the reactants and products. Indicate the state of each.	Reactants: Hydrochloric acid is dissociated in solution, forming $\text{H}^+(\text{aq})$ and $\text{Cl}^-(\text{aq})$ ions. Sodium carbonate is an ionic solid, $\text{Na}_2\text{CO}_3(\text{s})$ . Products: Sodium chloride is dissociated into $\text{Na}^+(\text{aq})$ and $\text{Cl}^-(\text{aq})$ ions. Water has the formula $\text{H}_2\text{O}(\text{l})$ . Carbon dioxide has the formula $\text{CO}_2(\text{g})$ .
Write the equation showing all reactants and products. (There is no need to balance the equation yet.)	$\text{H}^+(\text{aq}) + \text{Cl}^-(\text{aq}) + \text{Na}_2\text{CO}_3(\text{s}) \rightarrow \text{Na}^+(\text{aq}) + \text{Cl}^-(\text{aq}) + \text{H}_2\text{O}(\text{l}) + \text{CO}_2(\text{g})$
Identify the spectator ions.	$\text{Cl}^-(\text{aq})$
Rewrite the net ionic equation, without the spectator ions.	$\text{H}^+(\text{aq}) + \text{Na}_2\text{CO}_3(\text{s}) \rightarrow \text{Na}^+(\text{aq}) + \text{H}_2\text{O}(\text{l}) + \text{CO}_2(\text{g})$
Balance the equation with respect to number of atoms of each element and charge.	$2\text{H}^+(\text{aq}) + \text{Na}_2\text{CO}_3(\text{s}) \rightarrow 2\text{Na}^+(\text{aq}) + \text{H}_2\text{O}(\text{l}) + \text{CO}_2(\text{g})$  Note that if hydronium ions are represented as $\text{H}_3\text{O}^+(\text{aq})$ , rather than as $\text{H}^+(\text{aq})$ , this reaction would be written as: $2\text{H}_3\text{O}^+(\text{aq}) + \text{Na}_2\text{CO}_3(\text{s}) \rightarrow 2\text{Na}^+(\text{aq}) + 3\text{H}_2\text{O}(\text{l}) + \text{CO}_2(\text{g})$

### Worked example: Try yourself 6.2.3

#### WRITING IONIC EQUATIONS FOR REACTIONS BETWEEN ACIDS AND METAL CARBONATES

What products are formed when a solution of sulfuric acid is added to a solution of calcium hydrogen carbonate? Write an ionic equation for this reaction.

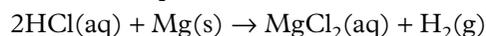
## ACIDS AND REACTIVE METALS

When acids are added to reactive metals, bubbles of hydrogen gas are released and a salt is formed. Because there is no transfer of protons, it is not a Brønsted–Lowry acid–base reaction. Instead, it is a redox reaction. Copper, silver and gold do not react with acids because their respective ions are stronger oxidising agents than hydrogen ions so a spontaneous reaction does not occur.

The general equation for the reaction is:



For example, the reaction between hydrochloric acid and magnesium metal can be represented by the chemical equation below.



### Worked example 6.2.4

#### WRITING IONIC EQUATIONS FOR REACTIONS BETWEEN ACIDS AND REACTIVE METALS

Write an ionic equation for the reaction that occurs when hydrochloric acid is added to a sample of iron metal.

Thinking	Working
Write the general reaction and identify the products formed.	acid + reactive metal $\rightarrow$ salt + hydrogen Hydrogen gas and iron(II) chloride solution are produced.
Identify the reactants and products. Indicate the state of each.	Reactants: iron is a solid, Fe(s). Hydrochloric acid is dissociated, forming $\text{H}^+(\text{aq})$ and $\text{Cl}^-(\text{aq})$ ions. Products: hydrogen gas, $\text{H}_2(\text{g})$ . Iron(II) chloride is dissociated into $\text{Fe}^{2+}(\text{aq})$ and $\text{Cl}^-(\text{aq})$ ions.
Write the equation showing all reactants and products. (There is no need to balance the equation yet.)	$\text{H}^+(\text{aq}) + \text{Cl}^-(\text{aq}) + \text{Fe}(\text{s}) \rightarrow \text{Fe}^{2+}(\text{aq}) + \text{Cl}^-(\text{aq}) + \text{H}_2(\text{g})$
Identify the spectator ions.	$\text{Cl}^-(\text{aq})$
Rewrite the equation without the spectator ions. Balance the equation with respect to number of atoms of each element and charge.	$2\text{H}^+(\text{aq}) + \text{Fe}(\text{s}) \rightarrow \text{Fe}^{2+}(\text{aq}) + \text{H}_2(\text{g})$

### Worked example: Try yourself 6.2.4

#### WRITING IONIC EQUATIONS FOR REACTIONS BETWEEN ACIDS AND REACTIVE METALS

Write an ionic equation for the reaction that occurs when aluminium is added to a solution of nitric acid.

## 6.2 Review

### SUMMARY

- General equations for reactions involving acids and bases:
  - acid + metal hydroxide → salt + water
  - acid + metal carbonate → salt + water + carbon dioxide
  - acid + reactive metal → salt + hydrogen
- Neutralisation reactions involve balancing the hydronium and hydroxide ion concentrations by adding a base to an acid, or vice versa, in stoichiometric proportions to produce a salt and water.
- The enthalpy of neutralisation is the heat released per mol of water produced during a neutralisation reaction and is given the symbol  $\Delta H_{\text{neut}}$  and has the unit  $\text{kJ mol}^{-1}$ .
- Neutralisation reactions are exothermic and as such  $\Delta H_{\text{neut}}$  is negative.

### KEY QUESTIONS

- 1 For the reactions between the following pairs of compounds, write:
  - i the balanced chemical equation
  - ii the balanced ionic equation.
  - a magnesium and nitric acid
  - b calcium and sulfuric acid
  - c zinc and hydrochloric acid
  - d aluminium and ethanoic acid.
- 2 Name the salt produced in each of the reactions in Question 1.
- 3 For the reactions between the following pairs, write:
  - i the balanced chemical equation
  - ii the balanced ionic equation.
  - a solid aluminium hydroxide and hydrofluoric acid
  - b solid iron(II) hydroxide and nitric acid
  - c solid zinc carbonate and ethanoic acid
  - d solid tin(II) hydrogen carbonate and hydrochloric acid.
- 4 25.0 mL of a  $1.00 \text{ mol L}^{-1}$  sodium hydroxide solution was completely neutralised by the addition of 12.5 mL of sulfuric acid. The temperature of the mixture rose from  $19.5^\circ\text{C}$  to  $28.3^\circ\text{C}$ . Assume the density of the mixture is  $1 \text{ g mL}^{-1}$ .
  - a Write a balanced equation for the reaction between sulfuric acid and sodium hydroxide.
  - b Calculate the amount of sodium hydroxide used in the neutralisation reaction.
  - c Calculate the amount of energy released in the neutralisation reaction.
  - d Calculate the amount of water, in mol, produced by the reaction.
  - e Calculate the enthalpy of neutralisation,  $\Delta H_{\text{neut}}$ .
- 5 Which one of the following best describes the species, apart from  $\text{H}_2\text{O}$ , that exist in an aqueous solution formed from the complete neutralisation of potassium hydroxide with nitric acid?
  - A  $\text{K}^+(\text{aq})$  and  $\text{NO}_3^-(\text{aq})$
  - B  $\text{K}^+(\text{aq})$ ,  $\text{OH}^-(\text{aq})$  and  $\text{H}^+(\text{aq})$
  - C  $\text{K}^+(\text{aq})$ ,  $\text{NO}_3^-(\text{aq})$  and  $\text{H}^+(\text{aq})$
  - D  $\text{K}^+(\text{aq})$ , and  $\text{H}^+(\text{aq})$

# Chapter review

## KEY TERMS

acid  
acid–base reaction  
acidic proton  
alkali  
amphiprotic  
Arrhenius theory  
base  
Brønsted–Lowry theory  
calorimetry

conjugate acid  
conjugate acid–base pair  
conjugate base  
diprotic acid  
dissociate  
dissociation  
enthalpy of neutralisation  
hydronium ion  
hydroxide ion

indicator  
ionise  
monoprotic acid  
neutralisation reaction  
neutralise  
polyprotic acid  
proton acceptor  
proton donor  
salt

# 06

solute  
solution  
strong acid  
triprotic acid  
weak acid

## REVIEW QUESTIONS

- Identify the reactant that acts as an acid in each of the following reactions.
  - $\text{NH}_4^+(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{NH}_3(\text{aq}) + \text{H}_3\text{O}^+(\text{aq})$
  - $\text{NH}_3(\text{g}) + \text{HCl}(\text{g}) \rightarrow \text{NH}_4\text{Cl}(\text{s})$
  - $\text{HCO}_3^-(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{H}_2\text{O}(\text{l}) + \text{CO}_3^{2-}(\text{aq})$
  - $\text{SO}_4^{2-}(\text{aq}) + \text{H}_3\text{O}^+(\text{aq}) \rightarrow \text{HSO}_4^-(\text{aq}) + \text{H}_2\text{O}(\text{l})$
  - $\text{CO}_3^{2-}(\text{aq}) + \text{CH}_3\text{COOH}(\text{aq}) \rightarrow \text{HCO}_3^-(\text{aq}) + \text{CH}_3\text{COO}^-(\text{aq})$
- Write balanced equations to show that in water:
  - $\text{PO}_4^{3-}$  acts as a base
  - $\text{H}_2\text{PO}_4^-$  acts as an amphiprotic substance
  - $\text{H}_2\text{S}$  acts as an acid.
- Write the formula for the conjugate of:
  - the acid  $\text{HCl}$
  - the base  $\text{OH}^-$
  - the base  $\text{O}^{2-}$
  - $\text{HSO}_4^-$  when it acts as an acid.
- Using suitable examples, distinguish between:
  - a diprotic and an amphiprotic substance
  - a strong and a weak acid.
- Draw a structural formula of the monoprotic ethanoic acid molecule. Identify which proton is donated in an acid–base reaction.
- Which of the following reactions are Brønsted–Lowry acid–base reactions?
  - $\text{HCl}(\text{aq}) + \text{KOH}(\text{aq}) \rightarrow \text{KCl}(\text{aq}) + \text{H}_2\text{O}(\text{l})$
  - $2\text{HNO}_3(\text{aq}) + \text{Mg}(\text{s}) \rightarrow \text{Mg}(\text{NO}_3)_2(\text{aq}) + \text{H}_2(\text{g})$
  - $\text{AgNO}_3(\text{aq}) + \text{NaCl}(\text{aq}) \rightarrow \text{AgCl}(\text{s}) + \text{NaNO}_3(\text{aq})$
  - $\text{CuO}(\text{s}) + \text{H}_2\text{SO}_4(\text{aq}) \rightarrow \text{CuSO}_4(\text{aq}) + \text{H}_2\text{O}(\text{l})$
- Chromic acid ( $\text{H}_2\text{CrO}_4$ ) is a diprotic acid.
  - Explain what is meant by a diprotic acid.
  - Write balanced chemical equations to represent the stages of dissociation for chromic acid.
- In polyprotic acids, do the dissociation stages of removal of protons occur to a greater extent, a lesser extent, or the same extent? Explain.
- Which of the following species is both diprotic and amphiprotic?
  - $\text{HCl}$
  - $\text{HSO}_4^-$
  - $\text{H}_2\text{SO}_3$
  - $\text{H}_2\text{PO}_4^-$
- Complete and balance the following reactions:
  - $\text{Fe}(\text{s}) + 2\text{HF}(\text{aq}) \rightarrow$
  - $\text{HClO}_4(\text{aq}) + \text{LiOH}(\text{aq}) \rightarrow$
  - $\text{HNO}_3(\text{aq}) + \text{KHCO}_3(\text{aq}) \rightarrow$
  - $\text{Li}_2\text{CO}_3(\text{aq}) + 2\text{CH}_3\text{COOH}(\text{aq}) \rightarrow$
- For each of the chemical equations in Question 10, write the corresponding net ionic equation.
- What volume of  $0.0010 \text{ mol L}^{-1}$  potassium hydroxide solution would be required to neutralise 30.0 mL of a  $0.0500 \text{ mol L}^{-1}$  hydrofluoric acid solution?
- 40.0 mL of a solution of  $\text{HClO}_4$  was added to neutralise 40.0 mL of a  $2.00 \text{ mol L}^{-1}$  solution of  $\text{NaOH}$ . The temperature of the mixture rose from  $22.3^\circ\text{C}$  to  $35.2^\circ\text{C}$ .
  - Write a balanced chemical equation for the reaction.
  - Calculate the enthalpy of neutralisation,  $\Delta H_{\text{neutr}}$  for this reaction.
  - If the standard enthalpy of neutralisation for this reaction is  $-57.3 \text{ kJ mol}^{-1}$ , account for possible reasons why there might be a difference.

## CHAPTER REVIEW CONTINUED

- 14** Hydrochloric acid is a key component in brick cleaner and sodium hydrogen carbonate is used in large quantities to neutralise acid spills.
- Write a balanced chemical equation for the reaction between sodium hydrogen carbonate and hydrochloric acid.
  - What is the minimum mass of sodium hydrogen carbonate required to neutralise 2.00 L of a  $12 \text{ mol L}^{-1}$  solution of hydrochloric acid solution used to clean bricks?
- 15** Define what is meant by a spectator ion, and explain why spectator ions are not listed in net ionic equations.
- 16 a** Write concise definitions for the following terms:
- Brønsted–Lowry acid
  - strong base
  - molarity
  - conjugate acid.
- b** Explain, with the aid of equations, why  $\text{HCO}_3^-$  is classified as amphiprotic.
- 17** In the following reactions, identify the conjugate acid–base pairs:
- $\text{HCl(aq)} + \text{NaOH(aq)} \rightarrow \text{NaCl(aq)} + \text{H}_2\text{O(l)}$
  - $\text{HNO}_3\text{(aq)} + \text{NH}_3\text{(aq)} \rightarrow \text{NH}_4\text{NO}_3\text{(aq)}$
  - $\text{HCO}_3^-\text{(aq)} + \text{H}_2\text{O(l)} \rightarrow \text{CO}_3^{2-}\text{(aq)} + \text{H}_3\text{O}^+\text{(aq)}$
- 18** Why can the hydrogen ion or proton ( $\text{H}^+$ ) be represented by the hydronium ion ( $\text{H}_3\text{O}^+$ ) when in solution?
- 19** Construct a concept map that demonstrates your understanding of the links between the following terms:  
acid, base, proton, hydrogen ion, hydronium ion, conjugate
- 20** Reflect on the Inquiry activity on page 144. What type of reaction was demonstrated?

Sample pages