Acids and bases SL (answers)

IB CHEMISTRY SL

8.1 Theories of acids and bases

Understandings:

- A Brønsted–Lowry acid is a proton/H^+ donor and a Brønsted–Lowry base is a proton/H^+ acceptor.
- Amphiprotic species can act as both Brønsted–Lowry acids and bases
- A pair of species differing by a single proton is called a conjugate acid-base pair.

Applications and skills:

- Deduction of the Brønsted–Lowry acid and base in a chemical reaction.
- Deduction of the conjugate acid or conjugate base in a chemical reaction.

Guidance:

- Lewis theory is not required here.
- The location of the proton transferred should be clearly indicated.
- Students should know the representation of a proton in aqueous solution as both H^+ (aq) and H_3O^+ (aq).
- The difference between the terms amphoteric and amphiprotic should be covered.

8.2 Properties of acids and bases

Understandings:

- Most acids have observable characteristic chemical reactions with reactive metals, metal oxides, metal hydroxides, hydrogen carbonates and carbonates.
- Salt and water are produced in exothermic neutralization reactions.

Applications and skills:

- Balancing chemical equations for the reaction of acids.
- Identification of the acid and base needed to make different salts.
- Candidates should have experience of acid-base titrations with different indicators.

Guidance:

- Bases which are not hydroxides, such as ammonia, soluble carbonates and hydrogen carbonates should be covered.
- The colour changes of different indicators are given in the data booklet in section 22.

8.3 The pH scale

Understandings:

- $pH = -\log[H^+(aq)]$ and $[H^+] = 10^{-pH}$.
- A change of one pH unit represents a 10-fold change in the hydrogen ion concentration
- Distinguish between acidic, neutral and alkaline solutions.
- The ionic product constant, $K_w = [H^+][OH^-]$ at 298 K

Applications and skills:

- Solving problems including pH, $[H^+]$ and $[OH^-]$
  Students should be familiar with the use of a pH meter and universal indicator.
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Guidance:

- Students will not be assessed on pOH values.
- Students should be concerned only with strong acids and bases in this sub-topic.
- Knowing the temperature dependence of K_w is not required.
- Equations involving H_3O^+ instead of H^+ may be applied.

8.4 Strong and weak acids and bases
Understandings:

- Strong and weak acids and bases differ in the extent of ionization.
- Strong acids and bases of equal concentrations have higher conductivities than weak acids and bases.
- A strong acid is a good proton donor and has a weak conjugate base.
- A strong base is a good proton acceptor and has a weak conjugate acid.

Applications and skills:

- Distinction between strong and weak acids and bases in terms of the rates of their reactions with metals, metal oxides, metal hydroxides, metal hydrogen carbonates and metal carbonates and their electrical conductivities for solutions of equal concentrations.

Guidance:
- The terms ionization and dissociation can be used interchangeably.
- See section 21 in the data booklet for a list of weak acids and bases

8.5 Acid deposition
Understandings:

- Rain is naturally acidic because of dissolved CO_2 and has a pH of 5.6. Acid deposition has a pH below 5.6.
- Acid deposition is formed when nitrogen or sulfur oxides dissolve in water to form HNO_3, HNO_2, H_2SO_4 and H_2SO_3.
- Sources of the oxides of sulfur and nitrogen and the effects of acid deposition should be covered.

Applications and skills:
- Balancing the equations that describe the combustion of sulfur and nitrogen to their oxides and the subsequent formation of H_2SO_3, H_2SO_4, HNO_2 and HNO_3.
- Distinction between the pre-combustion and post-combustion methods of reducing sulfur oxides emissions.
- Deduction of acid deposition equations for acid deposition with reactive metals and carbonates.

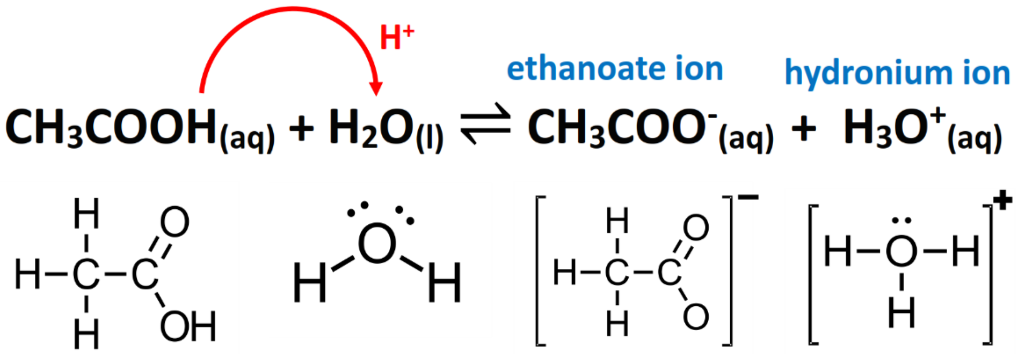
Names and formulae of common acid and bases

Name	Formulae	Weak or strong acid or base
Sulfuric acid	H_2SO_4	Strong acid
Hydrochloric acid	HCl	Strong acid
Nitric acid	HNO_3	Strong acid
Ethanoic acid	CH_3COOH	Weak acid
Methanoic acid	$HCOOH$	Weak acid
Carbonic acid	H_2CO_3	Weak acid
Phosphoric acid	H_3PO_4	Weak acid
Sodium hydroxide	$NaOH$	Strong base
Potassium hydroxide	KOH	Strong base
Barium hydroxide	$Ba(OH)_2$	Strong base
Ammonia	NH_3	Weak base

8.1 Theories of acids and bases

Brønsted–Lowry theory of acid and bases

- A Brønsted–Lowry acid is a proton (H^+) donor.
- A Brønsted–Lowry base is a proton (H^+) acceptor.
- A proton is a $H^+_{(aq)}$ ion, but exists in solution as $H_3O^+_{(aq)}$
- The reaction below shows ethanoic acid reaction with water to form the ethanoate ion and the hydronium ion.



- Ethanoic acid is behaving as a Bronsted-Lowry acid and water is behaving as a Bronsted-Lowry base.
- The reaction is shown in equation form below. Note that both equations show the same reaction.

$$CH_3COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons CH_3COO^-_{(aq)} + H_3O^+_{(aq)}$$
$$CH_3COOH_{(aq)} \rightleftharpoons CH_3COO^-_{(aq)} + H^+_{(aq)}$$

Exercise:

Identify the Brønsted–Lowry acid and base in the forward reaction and in the reverse reaction in the reaction below.

$$NH_{3(aq)} + H_2O_{(l)} \rightleftharpoons \underbrace{NH_4^+{}_{(aq)}}_{\text{ammonium ion}} + \underbrace{OH^-{}_{(aq)}}_{\text{hydroxide ion}}$$

Forward reaction:
BL acid: H_2O
BL base: NH_3

Reverse reaction:
BL acid: NH_4^+
BL base: OH^-

Conjugate acid-base pairs

- Conjugate acid-base pairs differ by a proton.
- In the reaction below, H_2O and OH^- are conjugate acid-base pairs, as are NH_4^+ and NH_3.

conjugate acid-base pair

acid conjugate base

$$NH_{3(aq)} + H_2O_{(l)} \rightleftharpoons NH_4^+{}_{(aq)} + OH^-{}_{(aq)}$$

base conjugate acid

conjugate acid-base pair

Example:

Identify the conjugate acid-base pairs in the following reaction:

$$CH_3COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons CH_3COO^-{}_{(aq)} + H_3O^+{}_{(aq)}$$

Exercises:

1) Define an acid and base according to the Brønsted–Lowry theory.

A Bronsted-Lowry acid is a proton (H^+) donor.

A Bronsted-Lowry base is a proton (H^+) acceptor.

2) What is meant by a proton in the Brønsted–Lowry theory?

A proton is a H^+ ion. An aqueous hydrogen ion in solution can be represented as $H^+{}_{(aq)}$ or $H_3O^+{}_{(aq)}$

3) Identify the conjugate acid-base pairs in the following reactions:

a) $HClO_{4(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^+{}_{(aq)} + ClO_4^-{}_{(aq)}$

$HClO_{4(aq)}$	$H_2O_{(l)}$	$H_3O^+{}_{(aq)}$	$ClO_4^-{}_{(aq)}$
BL acid	BL base	conjugate acid	conjugate base

b) $H_2SO_{3(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^+{}_{(aq)} + HSO_3^-{}_{(aq)}$

$H_2SO_{3(aq)}$	$H_2O_{(l)}$	$H_3O^+{}_{(aq)}$	$HSO_3^-{}_{(aq)}$
BL acid	BL base	conjugate acid	conjugate base

c) $H_2S_{(g)} + H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq)} + HS^-_{(aq)}$

$H_2S_{(g)}$	$H_2O_{(l)}$	$H_3O^+_{(aq)}$	$HS^-_{(aq)}$
BL acid	BL base	conjugate acid	conjugate base

Amphiprotic species:

- An amphiprotic species is a substance that can act as a Bronsted-Lowry acid or Bronsted-Lowry base.
- An amphiprotic species must be able to donate a proton (H^+) to another species and be able to accept a proton (H^+) from another species.
- In the two examples below, H_2O is acting as both a Bronsted-Lowry acid and a Bronsted-Lowry base; it is amphiprotic.

$$CH_3COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons CH_3COO^-_{(aq)} + H_3O^+_{(aq)}$$

$$NH_{3(aq)} + H_2O_{(l)} \rightleftharpoons NH_4^+{}_{(aq)} + OH^-_{(aq)}$$

Amphiprotic and amphoteric

- Amphiprotic refers to any substance that can both accept and donate a proton (Bronsted-Lowry theory).
- Amphoteric refers to any species that can act like an acid or a base. All amphiprotic species are also amphoteric.
- The term amphoteric can be applied in different theories of acids and bases (Lewis theory).

Exercises:

1) Using H_2O as an example, explain what is meant by an amphiprotic species.

An amphiprotic species is able to donate or accept a proton therefore acting as a Bronsted-Lowry acid or a Bronsted-Lowry base. H_2O is able to donate a proton to form $OH^-_{(aq)}$ or accept a proton to form $H_3O^+_{(aq)}$, therefore acting as a Bronsted Lowry acid or a Bronsted-Lowry base.

2) Write equations for the following amphiprotic species reacting with the hydronium ion (H_3O^+) and the hydroxide ion (OH^-).

a) Hydrogen sulfate ion $HSO_4^-{}_{(aq)}$

(i) $HSO_4^-{}_{(aq)}$ reacting with $H_3O^+{}_{(aq)}$
$HSO_4^-{}_{(aq)} + H_3O^+{}_{(aq)} \rightleftharpoons H_2SO_{4(aq)} + H_2O_{(l)}$
Conjugate acid-base pairs (differ by a H^+):
$HSO_4^-{}_{(aq)}$ and $H_2SO_{4(aq)}$ $H_3O^+{}_{(aq)}$ and $H_2O_{(l)}$

(ii) $HSO_4^-{}_{(aq)}$ reacting with $OH^-{}_{(aq)}$
$HSO_4^-{}_{(aq)} + OH^-{}_{(aq)} \rightleftharpoons SO_4^{2-}{}_{(aq)} + H_2O_{(l)}$
Conjugate acid-base pairs:
$HSO_4^-{}_{(aq)}$ and $SO_4^{2-}{}_{(aq)}$ $OH^-{}_{(aq)}$ and $H_2O_{(l)}$

(iii) Identify the conjugate acid-base pairs in the above reactions.

b) Dihydrogen phosphate ion $H_2PO_4^-{}_{(aq)}$

(i) $H_2PO_4^-{}_{(aq)}$ reacting with $H_3O^+{}_{(aq)}$

$H_2PO_4^-{}_{(aq)} + H_3O^+{}_{(aq)} \rightleftharpoons H_3PO_{4(aq)} + H_2O_{(l)}$
Conjugate acid-base pairs:
$H_2PO_4^-{}_{(aq)}$ and $H_3PO_{4(aq)}$ $H_3O^+{}_{(aq)}$ and $H_2O_{(l)}$

(ii) $H_2PO_4^-{}_{(aq)}$ reacting with $OH^-{}_{(aq)}$
$H_2PO_4^-{}_{(aq)} + OH^-{}_{(aq)} \rightleftharpoons HPO_4^{2-}{}_{(aq)} + H_2O_{(l)}$
Conjugate acid-base pairs:
$H_2PO_4^-{}_{(aq)}$ and $HPO_4^{2-}{}_{(aq)}$ $OH^-{}_{(aq)}$ and $H_2O_{(l)}$

(iii) Identify the conjugate acid-base pairs in the above reactions.

3) Explain the difference between the terms amphiprotic and amphoteric.

Amphiprotic is used to describe a species that can donate or accept a proton and is specific to the Bronsted-Lowry theory of acids and bases. All amphiprotic species are also amphoteric. Amphoteric refers to substances that can act as acids and bases and can be used in other theories of acids and bases where there is no proton transfer.

8.2 Properties of acids and bases

- Acids react with bases in neutralisation reactions to produce a salt and water.
- Examples are shown below.

$$\text{acid + base} \longrightarrow \text{salt + water}$$

$$HCl_{(aq)} + NaOH_{(aq)} \longrightarrow NaCl_{(aq)} + H_2O_{(l)}$$

$$CH_3COOH_{(aq)} + NaOH_{(aq)} \longrightarrow NaCH_3COO_{(aq)} + H_2O_{(l)}$$

- Acids also react with reactive metals (those above hydrogen on the activity series) to produce a salt and hydrogen gas.

$$\text{acid + metal} \longrightarrow \text{salt + hydrogen}$$

$$2HNO_{3(aq)} + Mg_{(s)} \longrightarrow Mg(NO_3)_2 + H_{2(g)}$$

- Acids react with metal carbonates and hydrogen carbonates to produce a salt, carbon dioxide and water.

$$\text{acid + carbonate} \longrightarrow \text{salt + carbon dioxide + water}$$

$$2HCl_{(aq)} + CaCO_{3(s)} \longrightarrow CaCl_{2(aq)} + CO_{2(g)} + H_2O_{(l)}$$

$$\text{acid + hydrogen carbonate} \longrightarrow \text{salt + carbon dioxide + water}$$

$$HCl_{(aq)} + NaHCO_{3(s)} \longrightarrow NaCl_{(aq)} + CO_{2(g)} + H_2O_{(l)}$$

Exercises:

1) Complete and balance the following equations:

a) $Zn_{(s)} + 2HCl_{(aq)} \rightarrow ZnCl_{2(aq)} + H_{2(g)}$

b) $Mg_{(s)} + H_2SO_{4(aq)} \rightarrow MgSO_{4(aq)} + H_{2(g)}$

c) $Ca_{(s)} + 2HNO_{3(aq)} \rightarrow Ca(NO_3)_2 + H_{2(g)}$

d) $Ni_{(s)} + 2HCl_{(aq)} \rightarrow NiCl_{2(aq)} + H_{2(g)}$

2) Complete and balance the following equations:

a) $CaCO_{3(s)} + 2HCl_{(aq)} \rightarrow CaCl_{2(aq)} + CO_{2(g)} + H_2O_{(l)}$

b) $CaCO_{3(s)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(aq)} + CO_{2(g)} + H_2O_{(l)}$

c) $MgCO_{3(aq)} + 2HNO_{3(aq)} \rightarrow Mg(NO_3)_{2(aq)} + CO_{2(g)} + H_2O_{(l)}$

3) Complete and balance the following equations:

a) $NaOH_{(aq)} + HCl_{(aq)} \rightarrow NaCl_{(aq)} + H_2O_{(l)}$

b) $KOH_{(aq)} + HNO_{3(aq)} \rightarrow KNO_{3(aq)} + H_2O_{(l)}$

c) $2LiOH_{(aq)} + H_2SO_{4(aq)} \rightarrow Li_2SO_4 + 2H_2O_{(l)}$

d) $NH_{3(aq)} + HCl_{(aq)} \rightarrow NH_4Cl_{(aq)}$

e) $NH_{3(aq)} + H_2SO_{4(aq)} \rightarrow (NH_4)_2SO_{4(aq)}$

f) $CH_3COOH_{(aq)} + NaOH_{(aq)} \rightarrow NaCH_3COO_{(aq)} + H_2O_{(l)}$

g) $CH_3COOH_{(aq)} + NH_{3(aq)} \rightarrow NH_4CH_3COO_{(aq)}$

4) Complete and balance the following equations:

a) $CuO_{(s)} + 2HCl_{(aq)} \rightarrow CuCl_{2(aq)} + H_2O_{(l)}$

b) $MgO_{(s)} + 2HNO_{3(aq)} \rightarrow Mg(NO_3)_2 + H_2O_{(l)}$

c) $CaO_{(s)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(aq)} + H_2O_{(l)}$

5) Complete and balance the following equations:

a) $2NaHCO_{3(s)} + H_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)} + 2CO_{2(g)} + 2H_2O_{(l)}$

b) $Mg(HCO_3)_{2(s)} + 2HNO_{3(aq)} \rightarrow Mg(NO_3)_{2(aq)} + 2CO_{2(g)} + 2H_2O_{(l)}$

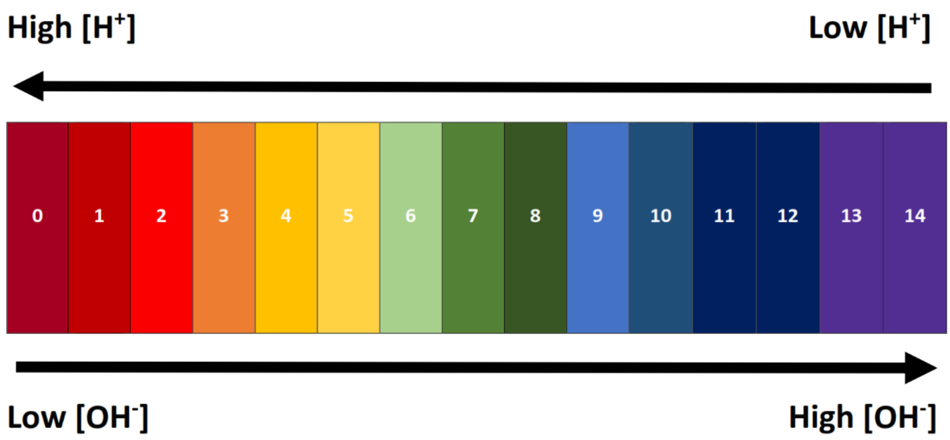
8.3 The pH scale

- The pH scale measures how acidic or basic a substance is.

$$pH = -\log_{10}[H^+]$$

$$[H^+] = 10^{-pH}$$

- The pH scale is inverse; a high concentration of hydrogen ions (H^+) in solution results in a low pH value.
- Conversely a low concentration of hydrogen ions in solution (H^+) results in a high pH value.

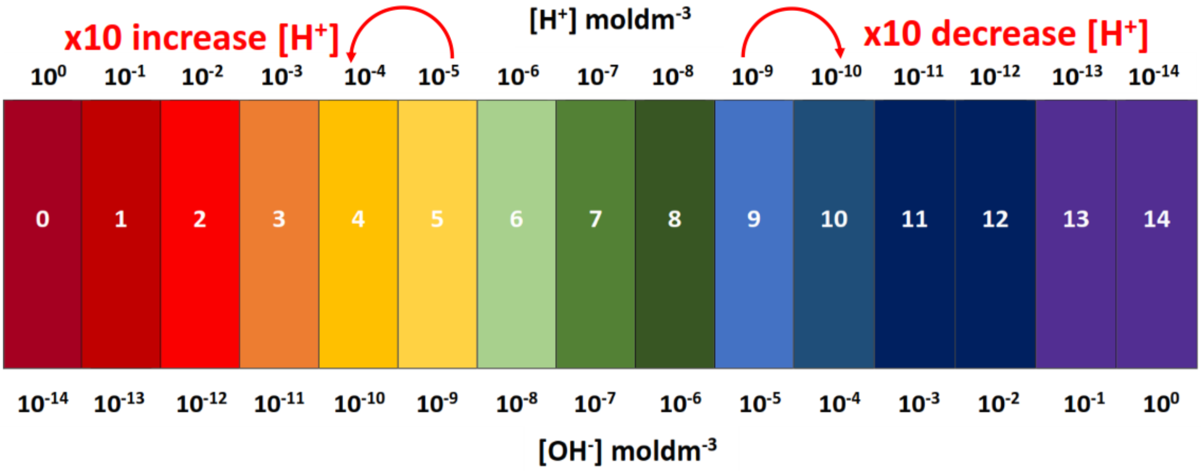


Complete the following table:

	Acidic, basic or neutral	pH at 298 K
$[H^+] = [OH^-]$	Neutral	7
$[H^+] > [OH^-]$	Acidic	<7
$[OH^-] > [H^+]$	Basic	>7

Changes in pH

- A change in one unit of pH represents a ten-fold change in hydrogen ion concentration $[H^+]$.



Example: Black coffee has a pH of 5 and toothpaste has a pH of 8. Identify which is more acidic and deduce how many times the $[H^+]$ is greater in the more acidic product.

Black coffee is more acidic, with a 1000 times higher $[H^+]$ than toothpaste.

Exercises:

1) Define the term pH.

$pH = -\log[H^+]$

2) Calculate the following:

a) the pH of a solution that has $[H^+] = 3.2 \times 10^{-5}$ moldm^{-3}

$pH = -\log[H^+]$

$pH = -\log(3.2 \times 10^{-5})$

$pH = 4.49$

b) the $[H^+]$ of a solution that has a pH of 4.6

$[H^+] = 10^{-pH}$

$[H^+] = 10^{-4.6}$

$[H^+] = 2.51 \times 10^{-5}$ mol dm^{-3}

3) Describe the relationship between the pH value and the $[H^+]$.

Inverse relationship - the lower the pH value, the higher the $[H^+]$. The higher the pH value, the lower the $[H^+]$

4) The pH of a solution is 2. If its pH is increased to 6, how many times greater is the $[H^+]$ of the original solution?

pH =2

$[H^+] = 10^{-2}$

$[H^+] = 1 \times 10^{-2}$ moldm^{-3}

pH = 6

$[H^+] = 10^{-6}$

$[H^+] = 1 \times 10^{-6}$ moldm^{-3}

The original solution is 10000 times more acidic.

Ionic product constant (K_w)

- Water ionizes but only very slightly; the equilibrium in the reaction below lies to the left.
- The Kw is the ionic product constant of water. It has a value of 1.00×10^{-14} at 298 K.

$$H_2O_{(l)} \rightleftharpoons H^+_{(aq)} + OH^-_{(aq)}$$

$$K_c = \frac{[H^+][OH^-]}{[H_2O]}$$

$$K_w = [H^+][OH^-]$$

$$K_w = 1.00 \times 10^{-14} \text{ at } 298K$$

Example: Calculate the pH of pure water at 298 K.
See video for solution.

Exercises:
1) Write the expression for the ionic product constant of water and state its value at 298 K.

$K_w = [H^+][OH^-]$

$K_w = 1.00 \times 10^{-14}$ at 298 K

2) Complete the following table (assume 298 K)

$[H^+]$ ($mol dm^{-3}$)	$[OH^-]$ ($mol dm^{-3}$)	pH	Acidic or Basic
3.2×10^{-8}	3.1×10^{-7}	7.49	basic
6.3×10^{-5}	1.6×10^{-10}	4.20	acidic
3.2×10^{-9}	3.2×10^{-6}	8.50	basic
1.3×10^{-13}	7.8×10^{-2}	12.89	basic

3) Lemon juice has a pH of 2.90 at 298 K. Calculate its $[H^+]$ and $[OH^-]$.

$[H^+] = 10^{-pH}$

$[H^+] = 10^{-2.90}$

$[H^+] = 1.26 \times 10^{-3}$ mol dm^{-3}

$K_w = [H^+][OH^-] = 1.00 \times 10^{-14}$ at 298 K

$1.00 \times 10^{-14} = 1.26 \times 10^{-3} [OH^-]$

$[OH^-] = 1.00 \times 10^{-14} \div 1.26 \times 10^{-3}$

$[OH^-] = 7.94 \times 10^{-12}$ mol dm^{-3}

8.4 Strong and weak acids and bases

- Strong acids and bases completely ionize (or dissociate) in solution.
- For example, HCl is a strong acid and the equation for its dissociation is shown below.

$$HCl_{(aq)} \longrightarrow H^{+}_{(aq)} + Cl^{-}_{(aq)}$$

- Weak acids partially ionize (or dissociate) in solution.
- CH_3COOH is a weak acid; the equilibrium sign is used to show its dissociation (the equilibrium lies to the left).

$$CH_3COOH_{(aq)} \rightleftharpoons CH_3COO^{-}_{(aq)} + H^{+}_{(aq)}$$

- Strong acids are good proton donors and have weak conjugate bases.
- The conjugate base of HCl, the Cl^- ion, is a weak conjugate base.

$$HCl_{(aq)} + H_2O_{(l)} \longrightarrow H_3O^{+}_{(aq)} + Cl^{-}_{(aq)}$$

- Weak acids are poor proton donors and have stronger conjugate bases.
- CH3COO$^-$, the conjugate base of CH_3COOH is a stronger conjugate base than Cl^-

$$CH_3COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons CH_3COO^{-}_{(aq)} + H_3O^{+}_{(aq)}$$

Strong and weak bases

- Strong bases completely ionize (or dissociate) in solution.
- NaOH is a strong base that dissociates completely in solution, as shown below.

$$NaOH_{(aq)} \longrightarrow Na^{+}_{(aq)} + OH^{-}_{(aq)}$$

- Weak bases such as NH_3 partially ionize (or dissociate) in solution.
- The equilibrium sign is used to show its dissociation (the equilibrium lies to the left).

$$NH_{3(aq)} + H_2O_{(l)} \rightleftharpoons NH_4^{+}{}_{(aq)} + OH^{-}_{(aq)}$$

- Strong bases are good proton acceptors and have weak conjugate acids.
- OH^- is a weak conjugate acid.

$$NaOH_{(aq)} \longrightarrow Na^{+}_{(aq)} + OH^{-}_{(aq)}$$

- Weak bases are poor proton acceptors and have stronger conjugate acids.
- NH_4^+ is a stronger conjugate acid than OH^-.

$$NH_{3(aq)} + H_2O_{(l)} \rightleftharpoons NH_4^+{}_{(aq)} + OH^-{}_{(aq)}$$

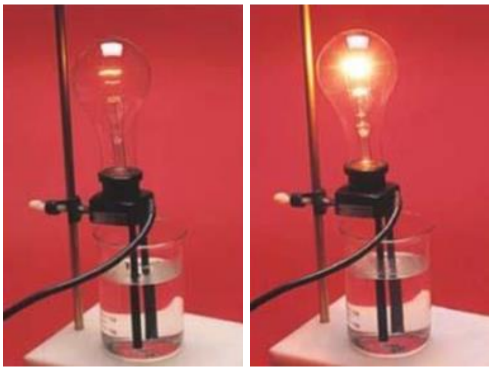
Complete the following table:

	Degree of dissociation/ ionization	Strength of conjugate acid or base
Strong acid	complete	weaker
Weak acid	partial	stronger
Strong base	complete	weaker
Weak base	partial	stronger

Distinguish between strong and weak acids and bases

Electrical conductivity

- Strong acids and bases have a higher concentration of mobile ions in solution, therefore they have higher electrical conductivity than weak acids and bases of equal concentration.



Reactions with active metals

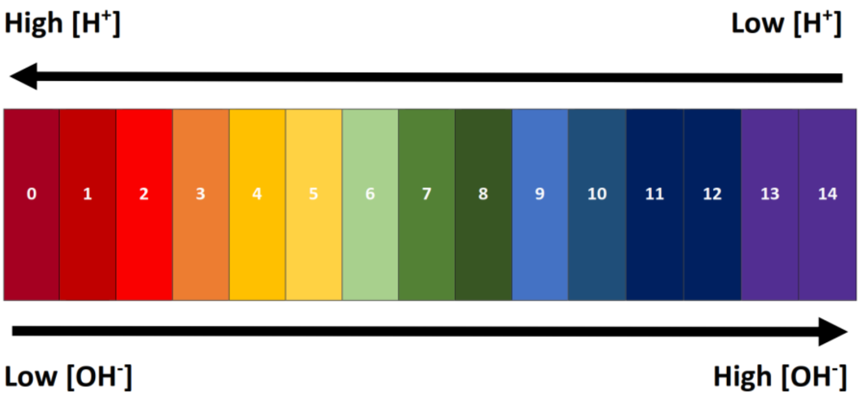
- Strong acids have a higher rate of reaction with reactive metals than weak acids of equal concentration because they have a higher concentration of H^+ ions in solution.

$$Mg_{(s)} + HCl_{(aq)} \longrightarrow MgCl_{2(aq)} + H_{2(g)}$$

$$Mg_{(s)} + 2CH_3COOH_{(aq)} \longrightarrow Mg(CH_3COO)_2 + H_{2(g)}$$

pH

- Strong acids have a lower pH than weak acids of equal concentration because they have a higher concentration of H^+ ions in solution.
- Recall that a higher $[H^+]$ equals a lower pH value.



Exercises:

1. Describe **two** different methods, one chemical and one physical, other than measuring the pH, that could be used to distinguish between ethanoic acid and hydrochloric acid solutions of the same concentration.

Chemical
reaction with reactive metal/Mg/Zn/carbonate/hydrogen carbonate
hydrochloric acid would react faster/more vigorously / ethanoic acid would react slower/less vigorously

Physical – conductivity - hydrochloric acid will conduct more/higher /ethanoic acid will conduct less

2. (a) The nitrite ion is present in nitrous acid, HNO_2, which is a weak acid. The nitrate ion is present in nitric acid, HNO_3, which is a strong acid. Distinguish between the terms *strong* and *weak acid* and state the equations used to show the dissociation of each acid in aqueous solution.

strong acid completely dissociated/ionized and weak acid partially dissociated/ionized

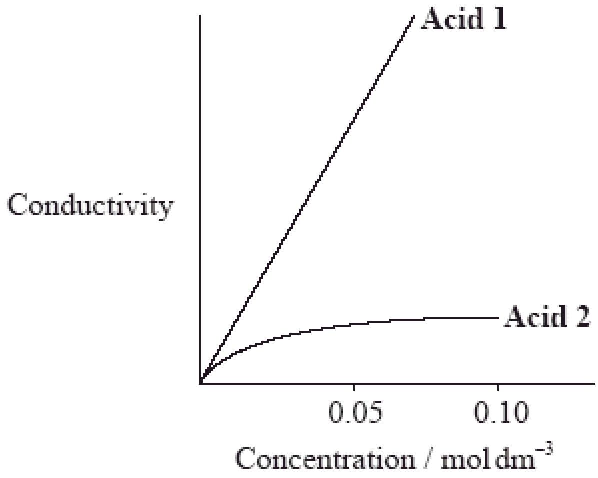
$HNO_{3(aq)} \rightarrow H^+_{(aq)} + NO_3^-{}_{(aq)}$

$HNO_{2(aq)} \rightleftharpoons H^+_{(aq)} + NO_2^-{}_{(aq)}$

(b) A small piece of magnesium ribbon is added to solutions of nitric and nitrous acid of the same concentration at the same temperature. Describe **two** observations that would allow you to distinguish between the two acids.

With HNO_3
faster rate of bubble/gas/hydrogen production
faster rate of magnesium dissolving
higher temperature change

(c) The graph below shows how the conductivity of the two acids changes with concentration.



Identify Acid 1 and explain your choice.

Acid 1 is HNO_3

HNO_3 has higher conductivity for solutions with same concentration as there are a higher concentration mobile ions in solution.

Calculating the pH of strong acids and bases

- Strong acids completely ionise in solution, so the concentration of H^+ ions, $[H^+]$, is assumed to be the same as the initial concentration.
- Strong bases also completely ionise in solution, so the assumption is the same as above (except that strong bases produce OH^- ions rather than H^+ ions).

Example 1: Calculate the pH of a 1.00 mol dm^{-3} solution of hydrochloric acid, HCl.

HCl dissociates as follows:

$$HCl\ (aq) \rightarrow H^+\ (aq) + Cl^-\ (aq)$$

A 1.00 mol dm^{-3} solution of HCl will produce $[H^+]$ of 1.00 mol dm^{-3}.

pH = - log$[H^+]$

pH = -log (1.00)

pH = 0

Example 2: Calculate the pH of a 1.00 mol dm^{-3} solution of potassium hydroxide, KOH.

KOH dissociates as follows:

$$KOH\ (s) \rightarrow K^+\ (aq) + OH^-\ (aq)$$

A 1.00 mol dm^{-3} solution of KOH will produce $[OH^-]$ of 1.00 mol dm^{-3}.

At 298 K, $K_w = 1.00 \times 10^{-14}$

$K_w = [H^+][OH^-]$

$1.00 \times 10^{-14} = [H^+][1.00]$

$[H^+] = 1.00 \times 10^{-14} / 1.00$

$[H^+] = 1.00 \times 10^{-14}$

pH = -log $[H^+]$

pH = -log($1.00 \times 10^{-14)}$

pH = 14

Exercise:

1. Calculate the pH of a 0.100 mol dm^{-3} solution of nitric acid, HNO_3.

   Nitric acid is a strong acid, so $[H^+]$ = 0.100 mol dm^{-3}.

   pH = -log$[H^+]$

   pH = -log(0.100)

   pH = 1

2. Calculate the pH of a 0.500 mol dm^{-3} solution of sodium hydroxide, NaOH.

NaOH is a strong base, so $[OH^-] = 0.500$ mol dm^{-3}

At 298 K, $K_w = 1.00 \times 10^{-14}$

$K_w = [H^+][OH^-]$

$1.00 \times 10^{-14} = [H^+][0.500]$

$[H^+] = 1.00 \times 10^{-14} / 0.500$

$[H^+] = 2.00 \times 10^{-14}$

pH = -log $[H^+]$

pH = -log$(2.00 \times 10^{-14)}$

pH = 13.7

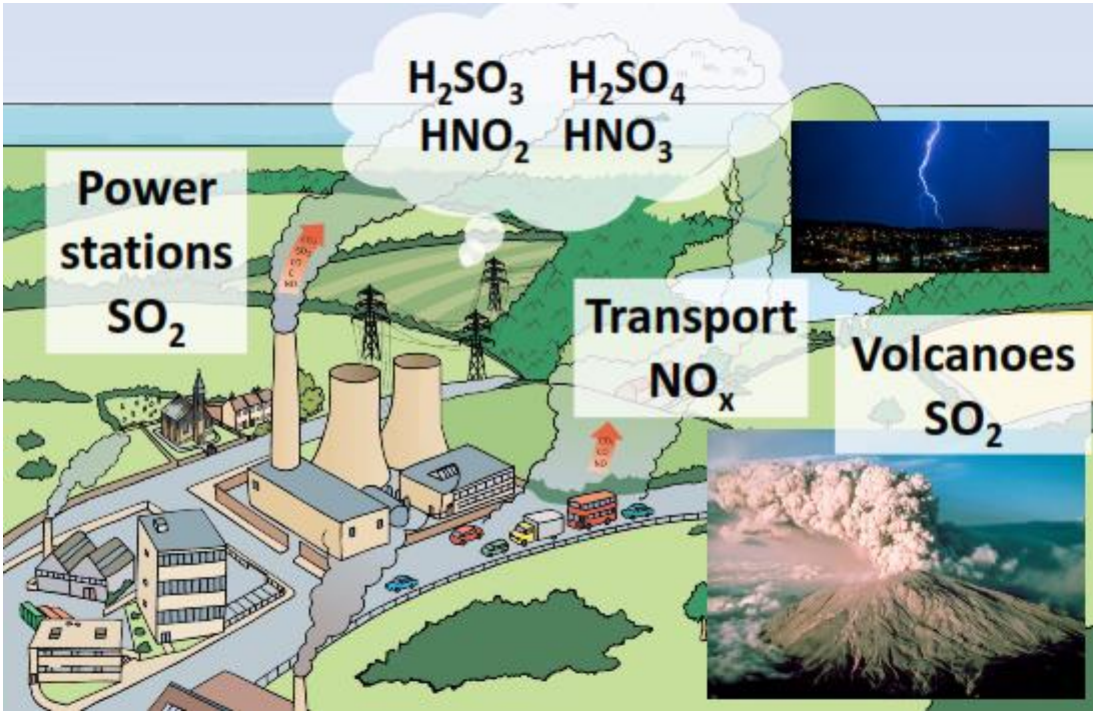
8.5 Acid deposition

- Rainwater is naturally acidic with a pH of 5.6
- The equation below shows that carbon dioxide dissolves in water to form carbonic acid H_2CO_3.

$$CO_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)}$$

- Acid rain has a pH of between 4.5 and 5.0
- Wet deposition includes acid rain, fog and snow.
- Dry deposition includes acidic gases and particles.

Sources of acid deposition



Exercise: From the diagram above, identify some natural and anthropogenic sources (caused by human activity) of acid deposition.

Anthropogenic:

NO_x – from the combination of atmospheric nitrogen and oxygen at high temperatures in internal combustion engines.

SO_2 – combustion of coal that contains sulfur.

Natural:

NO_x – lightning

SO_2 – volcanoes

Formation of acid rain

Sulfuric and sulphurous acid

- Sulfuric acid (H_2SO_4) and sulphurous acid (H_2SO_3) are formed by the combustion of coal that contains high levels of sulfur.
- Sulfur (S) burns in oxygen (O_2) to form sulfur dioxide (SO_2)
  $S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$
- SO_2 dissolves in water to form sulphurous acid (H_2SO_3)
  $SO_{2(g)} + H_2O_{(l)} \rightarrow H_2SO_{3(aq)}$
- SO_2 can react with O_2 to form sulfur trioxide (SO_3)
  $2SO_{2(g)} + O_{2(g)} \rightarrow 2SO_{3(g)}$
- SO_3 dissolves in water to form H_2SO_4
  $SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(aq)}$

Nitric and nitrous acid

- Nitric (HNO_3) and nitrous acid (HNO_2) are formed from the reaction of nitrogen (N_2) and oxygen (O_2) at high temperatures in internal combustion engines.
- Nitrogen (N_2) and oxygen (O_2) react at high temperatures in internal combustion engines to form nitrogen monoxide (NO)
  $N_{2(g)} + O_{2(g)} \rightarrow 2NO_{(g)}$
- NO reacts with O_2 to form nitrogen dioxide (NO_2)
  $2NO_{(g)} + O_{2(g)} \rightarrow 2NO_{2(g)}$
- NO_2 dissolves in water to form HNO_3 and HNO_2
  $2NO_{2(g)} + H_2O_{(l)} \rightarrow HNO_{3(aq)} + HNO_{2(aq)}$
  $4NO_{2(g)} + O_{2(g)} + 2H_2O_{(l)} \rightarrow 4HNO_{3(aq)}$

Exercises:

1. State an equation to show why rain water is naturally acidic.

$CO_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)}$

2. State a natural and man-made source of sulfur dioxide (SO_2) and nitrogen monoxide (NO).

SO_2

Man-made source: combustion of coal containing sulfur in power stations

Natural source: volcanoes

NO_x

Man-made source: reaction of nitrogen with oxygen at high temperatures in an internal combustion engine

Natural source: lightning

3. Acid rain has a pH of less than 5.0. Explain how the burning of coal can lead to the formation of acid rain.

Coal, containing sulfur, is burned in a power station to produce heat.

The sulfur reacts with oxygen to form sulfur dioxide

$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$

The sulfur dioxide then reacts with water to form sulfurous acid

$SO_{2(g)} + H_2O_{(l)} \rightarrow H_2SO_{3(aq)}$

The sulfur dioxide can react with oxygen to form sulfur trioxide which then reacts with water to form sulfuric acid.

$2SO_{2(g)} + O_{2(g)} \rightarrow 2SO_{3(g)}$

$SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(aq)}$

4. Outline the process responsible for the production of acid rain from the oxides of nitrogen.

Nitrogen reacts with oxygen at high temperatures inside an internal combustion engine to produce nitrogen monoxide.

$N_{2(g)} + O_{2(g)} \rightarrow 2NO_{(g)}$

The nitrogen monoxide reacts with oxygen to form nitrogen dioxide.

$2NO_{(g)} + O_{2(g)} \rightarrow 2NO_{2(g)}$

The nitrogen dioxide then reacts with water (or oxygen and water) to form nitrous and nitric acids.

$2NO_{2(g)} + H_2O_{(l)} \rightarrow HNO_{3(aq)} + HNO_{2(aq)}$

$4NO_{2(g)} + O_{2(g)} + 2H_2O_{(l)} \rightarrow 4HNO_{3(aq)}$

Effects of acid deposition

Effect on materials

- Acid rain reacts with calcium carbonate ($CaCO_3$) in statues

Exercise: Write equations for the reaction of calcium carbonate with sulfuric and nitric acid.

Reaction with sulfuric and nitric acid:

$CaCO_{3(s)} + 2HNO_{3(aq)} \rightarrow Ca(NO_3)_{2(aq)} + H_2O_{(l)} + CO_{2(g)}$

$CaCO_{3(s)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(aq)} + H_2O_{(l)} + CO_{2(g)}$

Effects on plants

- Acid rain leaches important nutrients such as Mg^{2+}, Ca^{2+} and K^+ ions from the soil.
- Without these nutrients, plants are unable to grow.
- Acid rain releases Al^{3+} ions from rocks into soil.
- Al^{3+} ions damage roots of plants and prevents them from taking up water and nutrients.

Effects on water

- Fish cannot survive in acidic conditions below pH 5
- The Al^{3+} ions in rocks are released and interfere with the operation of a fish's gills and reduce their ability to take in oxygen.

$$Al(OH)_{3(s)} + 3H^+_{(aq)} \longrightarrow Al^{3+}_{(aq)} + 3H_2O_{(l)}$$

- The nitrates from nitric acid can cause eutrophication in lakes (the nitrate ions cause excessive plant growth).

Effects on human health

- Breathing acidic gases irritates the respiratory tract, from the mucous membranes in the nose and throat to the lung tissue.
- This can increase the risk of respiratory diseases such as asthma, bronchitis and emphysema.
- There is also a greater risk of poisonous metal ions such as Pb^{2+} and Cu^{2+} being released from water pipes.

Exercises:

1. Acid rain can cause damage to limestone buildings and marble statues. Write an equation to show the reaction of acid rain with limestone or marble (containing $CaCO_3$).

   $CaCO_{3(s)} + HNO_{3(aq)} \rightarrow Ca(NO_3)_{2(aq)} + H_2O_{(l)} + CO_{2(g)}$

   $CaCO_{3(s)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(aq)} + H_2O_{(l)} + CO_{2(g)}$

2. Outline how acid rain can damage the growth of trees and plants.

Acid rain can leach essential plant nutrient such as Mg^{2+}, Ca^{2+} and K^{+} from the soil. It can also release Al^{3+} ions from rocks which can damage plant roots, leaving them unable to uptake water and nutrients.

3. Describe the effects of acid rain on aquatic organisms such as fish.

The Al^{3+} ions released from rocks can damage fish's gills leaving them unable to take in oxygen.
Nitrates from nitric acid can cause eutrophication in lakes.

4. Describe 3 possible effects of acid rain on human health.

Breathing acidic gases can irritate the respiratory tract.
Increased risk of respiratory diseases such as asthma, bronchitis and emphysema.
Greater risk of poisonous metal ions such as Pb^{2+} and Cu^{2+} being released from water pipes.

Reduction of NO_x and SO_2 emissions

Pre-combustion methods (remove or reduce sulfur in oil or coal before combustion)

- Hydrodesulfurization is a chemical process that uses a catalyst to remove sulfur from natural gas and from refined petroleum products.
- The removal of sulfur reduces the SO_2 emissions when fuels are burned.
- In fluidized bed combustion, coal is mixed with powdered limestone ($CaCO_3$) **during combustion**.

$$CaCO_{3(s)} \longrightarrow CaO_{(s)} + CO_{2(g)}$$

$$CaO_{(s)} + SO_{2(g)} \longrightarrow CaSO_{3(s)}$$

$$2CaO_{(s)} + 2SO_{2(g)} + O_{2(g)} \longrightarrow 2CaSO_{4(s)}$$

Post-combustion methods (remove acidic gases by reacting with a base)

- Flu-gas desulfurization can remove up to 90% of SO_2 emissions from power stations.

$$CaO_{(s)} + SO_{2(g)} \longrightarrow CaSO_{3(s)}$$

$$CaCO_{3(s)} + SO_{2(g)} \longrightarrow CaSO_{3(s)} + CO_{2(g)}$$

$$2CaSO_{3(s)} + O_{2(g)} \longrightarrow 2CaSO_{4(s)}$$

Reducing acidity of water

- Powered $CaCO_3$ is added to lakes to reduce the acidity.
- CaO and $Ca(OH)_2$ are also used to neutralize acidic water.

$$CaO_{(s)} + H_2SO_{4(aq)} \longrightarrow CaSO_{4(aq)} + H_2O_{(l)}$$

$$Ca(OH)_2 + H_2SO_{4(aq)} \longrightarrow CaSO_{4(aq)} + 2H_2O_{(l)}$$

Exercises:

1. (a) Nitrogen monoxide is formed from the combination of nitrogen and oxygen at high temperatures in an internal combustion engine.

$$N_{2(g)} + O_{2(g)} \rightarrow 2NO_{(g)}$$

(b) Hot exhaust gases are reacted with air in the presence of a catalyst (Pt or Pd).

$$2NO_{(g)} + 2CO_{(g)} \rightarrow 2CO_{2(g)} + N_{2(g)}$$

(c) Exhaust gas recirculation – exhaust gases are recirculated into the engine which lowers the operating temperature and reduces emission of NO.

2. (a) $S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$

(b)

(i) Pre-combustion

Hydrodesulfurization uses a catalyst to remove sulfur from natural gas and refined petroleum products before combustion which reduces emissions of SO_2 when the fuels are combusted.

(ii) During combustion

Fluidized bed combustion

Coal is mixed with powered limestone during combustion

$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$

$CaO_{(s)} + SO_{2(g)} \rightarrow CaSO_{3(s)}$

$2CaO_{(s)} + SO_{2(g)} + O_{2(g)} \rightarrow 2CaSO_{4(s)}$

(iii) Post-combustion

Flu-gas desulfurization

$CaO_{(s)} + SO_{2(g)} \rightarrow CaSO_{3(s)}$

$CaCO_{3(s)} + SO_{2(g)} \rightarrow CaSO_{3(s)} + CO_{2(g)}$

$2CaSO_{3(s)} + O_{2(g)} \rightarrow 2CaSO_{4(s)}$

3. The addition of CaO and $Ca(OH)_2$ neutralises acidic water.

$CaO_{(s)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(aq)} + H_2O_{(l)}$

$Ca(OH)_{2(s)} + H_2SO_{4(aq)} \rightarrow CaSO_{4(aq)} + 2H_2O_{(l)}$