Acids and bases SL

IB CHEMISTRY SL

25	16		6	2	25
Mn	S	J	C	He	Mn
Manganese	Sulfur		Carbon	Helium	Manganese
54.938045	32.065		12.0107	4.002602	54.938045

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.

Syllabus checklist

Objective	I am confident with this	I need to review this	I need help with this
Outline the Brønsted–Lowry theory of acids and bases			
Deduce the Brønsted–Lowry acid and base in a chemical reaction			
Identify the conjugate acid-base pair in a chemical reaction.			
Outline the difference between amphiprotic and amphoteric species			

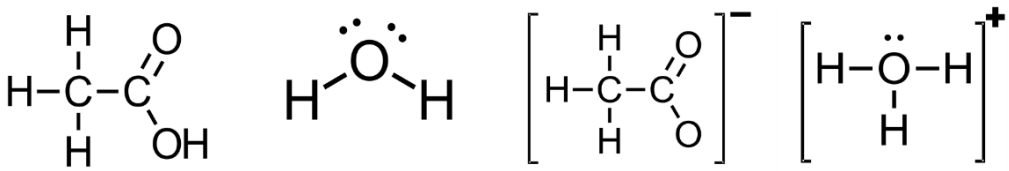
Names and formulae of common acid and bases

Name	Formula	Weak or strong acid or base
Sulfuric acid		
Hydrochloric acid		
Nitric acid		
Ethanoic acid		
Methanoic acid		
Carbonic acid		
Phosphoric acid		
Sodium hydroxide		
Potassium hydroxide		
Barium hydroxide		
Ammonia		
Phenylamine		

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 reacting with water to form the ethanoate ion and the hydronium ion.

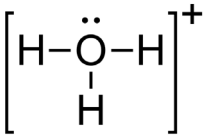
$$CH_3COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons \underset{\text{ethanoate ion}}{CH_3COO^-_{(aq)}} + \underset{\text{hydronium ion}}{H_3O^+_{(aq)}}$$



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

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

- The H^+ ion exists in solution as $H_3O^+_{(aq)}$ (the hydronium ion); the Lewis structure is shown below.



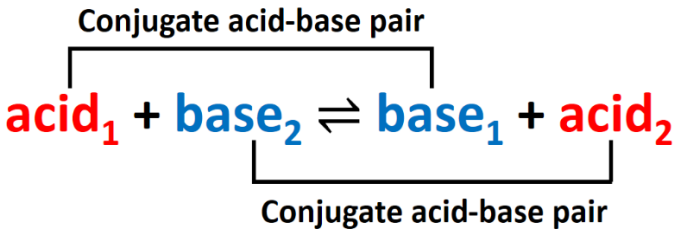
$H_3O^+_{(aq)}$ / $H^+_{(aq)}$

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

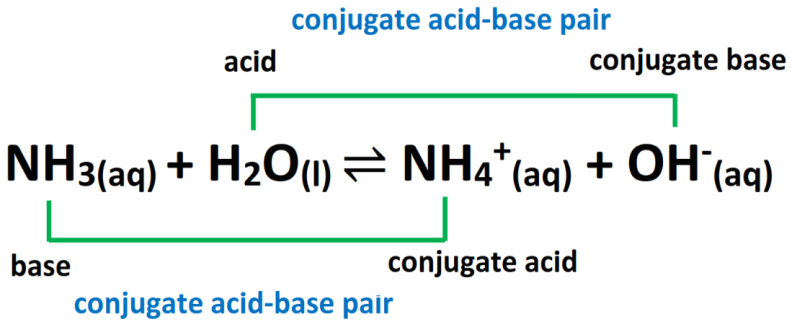
$$NH_{3(aq)} + H_2O_{(l)} \rightleftharpoons \underset{\text{ammonium ion}}{NH_4^+{}_{(aq)}} + \underset{\text{hydroxide ion}}{OH^-_{(aq)}}$$

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.



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.

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

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

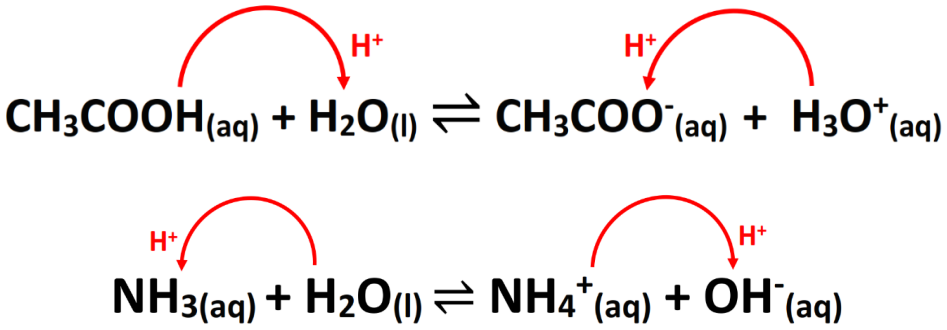
a. $HClO_{4(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq)} + ClO_4^-{}_{(aq)}$

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

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

Amphiprotic species:

- An amphiprotic species is a substance that can act as a Brønsted-Lowry acid or Brønsted-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 Brønsted-Lowry acid and a Brønsted-Lowry base; it is amphiprotic.



Amphiprotic and amphoteric

- Amphiprotic refers to any substance that can both accept and donate a proton (Brønsted-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.

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 $H_3O^+{}_{(aq)}$

(ii) $HSO_4^-{}_{(aq)}$ reacting with $OH^-{}_{(aq)}$

(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 $H_3O^+{}_{(aq)}$

(ii) $H_2PO_4^-{}_{(aq)}$ reacting with $OH^-{}_{(aq)}$

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

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

8.2 Properties of acids and bases

Understandings:

- Most acids have observable characteristic chemical reactions with reactive metals, metal oxides, metal hydroxides, hydrogencarbonates 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.

8.2 Syllabus checklist

Objective	I am confident with this	I need to review this	I need help with this
Write balanced chemical equations for the reactions of: Acids with metal hydroxides, metal oxides, metal carbonates and hydrogencarbonates			
Identify the parent acid and base from the formula of a salt			

Properties of acids and bases

- Acids react with bases in neutralisation reactions to produce a salt and water.

acid + metal hydroxide → salt + water

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

- Acids react with metal oxides to produce a salt and water:

acid + metal oxide → salt + water

$$2HCl_{(aq)} + MgO_{(s)} \rightarrow MgCl_{2(aq)} + H_2O_{(l)}$$

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

acid + metal → salt + hydrogen

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

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

acid + metal hydrogen carbonate → salt + water + carbon dioxide

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

acid + metal carbonate → salt + water + carbon dioxide

$$2HCl_{(aq)} + Na_2CO_{3(s)} \rightarrow 2NaCl_{(aq)} + H_2O_{(l)} + CO_{2(g)}$$

Exercises:

1) Complete and balance the following equations:

a) $Zn_{(s)} + HCl_{(aq)} \rightarrow$

b) $Mg_{(s)} + H_2SO_{4(aq)} \rightarrow$

c) $Ca_{(s)} + HNO_{3(aq)} \rightarrow$

d) $Ni_{(s)} + HCl_{(aq)} \rightarrow$

2) Complete and balance the following equations:

a) $CaCO_{3(s)} + HCl_{(aq)} \rightarrow$

b) $CaCO_{3(s)} + H_2SO_{4(aq)} \rightarrow$

c) $MgCO_{3(s)} + HNO_{3(aq)} \rightarrow$

3) Complete and balance the following equations:

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

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

c) $LiOH_{(aq)} + H_2SO_{4(aq)} \rightarrow$

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

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

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

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

4) Complete and balance the following equations:

a) $CuO_{(s)} + HCl_{(aq)} \rightarrow$

b) $MgO_{(s)} + HNO_{3(aq)} \rightarrow$

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

5) Complete and balance the following equations:

a) $NaHCO_{3(s)} + H_2SO_{4(aq)} \rightarrow$

b) $Mg(HCO_3)_{2(s)} + HNO_{3(aq)} \rightarrow$

8.3 The pH scale

Understandings:

- pH = −log[H^+] 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.

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.

8.3 Syllabus checklist

Objective	I am confident with this	I need to review this	I need help with this
Calculate the pH of an acid or base given the hydrogen ion concentration [H^+]			
Calculate the hydrogen ion concentration [H^+] from the pH value			
Distinguish between acidic, basic and neutral solutions from [H^+] and [OH^-]			
Deduce the change in hydrogen ion concentration from changes in pH and vice-versa.			
Solve problems using the ionic product constant of water, K_w			

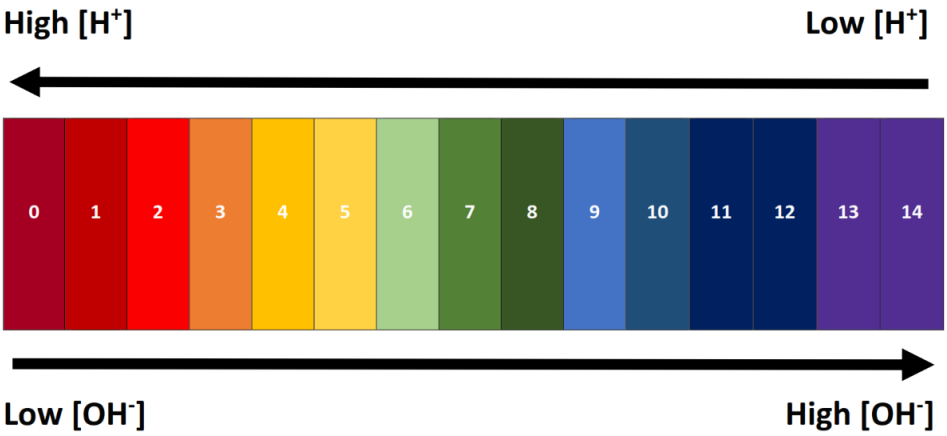
The pH scale

- The pH scale measures the concentration of H^+ ions $[H^+]$ in solution.

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

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

- 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.



Exercises:

1. Complete the following table:

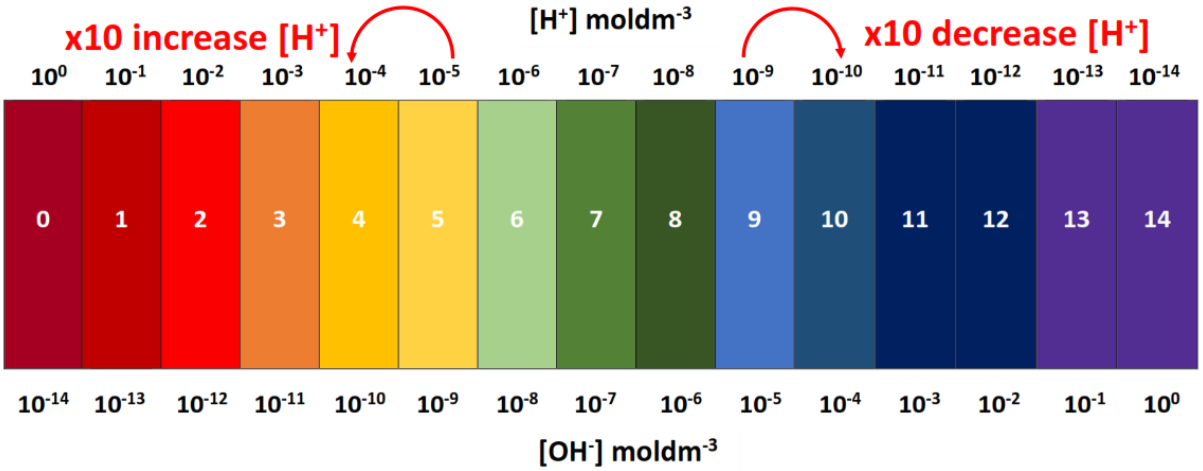
	Acidic, basic or neutral	pH at 298 K
$[H^+] = [OH^-]$		
$[H^+] > [OH^-]$		
$[OH^-] > [H^+]$		

2. Complete the sentences below:

   If the $[H^+] = [OH^-]$, the pH is _____ at 298 K.
   If the $[H^+] > [OH^-]$, the pH is _____ than 7 at 298 K.
   If the $[H^+] < [OH^-]$, the pH is _____ than 7 at 298 K.

Changes in pH

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



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.

Exercises:

1. Define the term pH.

2. Calculate the following:

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

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

3. Describe the relationship between the pH value and 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?

Ionic product constant (K_w)

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

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

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

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

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

Example: Calculate the pH of pure water at 298 K.

Exercises:

1. Write the expression for the ionic product constant of water and state its value 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}			
	1.6×10^{-10}		
3.2×10^{-9}			
	7.8×10^{-2}		

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

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 ionisation and dissociation can be used interchangeably.
- See section 21 in the data booklet for a list of weak acids and bases.

Syllabus checklist

Objective	I am confident with this	I need to review this	I need help with this
State the degree of dissociation (or ionisation) for a weak and strong acid or base.			
Distinguish between weak and strong acids and bases based on their rates of reactions with metals, metal oxides, metal hydroxides, metal hydrogen carbonates and metal carbonates and their electrical conductivities for solutions of equal concentrations.			

Strong and weak acids and bases

- Strong acids and bases completely ionise (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 ionise (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.
- CH_3COO^-, 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 ionise (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 ionise (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.
- Weak bases are poor proton acceptors and have stronger conjugate acids.

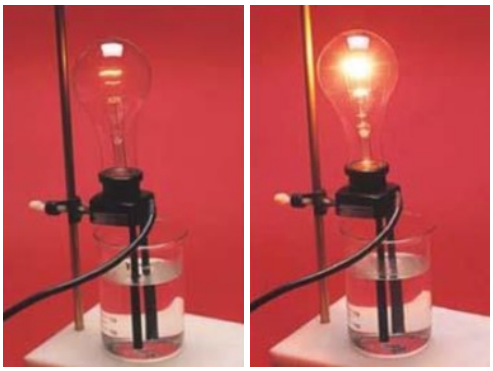
Complete the following table:

	Degree of dissociation/ ionization	Strength of conjugate acid or base
Strong acid		
Weak acid		
Strong base		
Weak base		

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

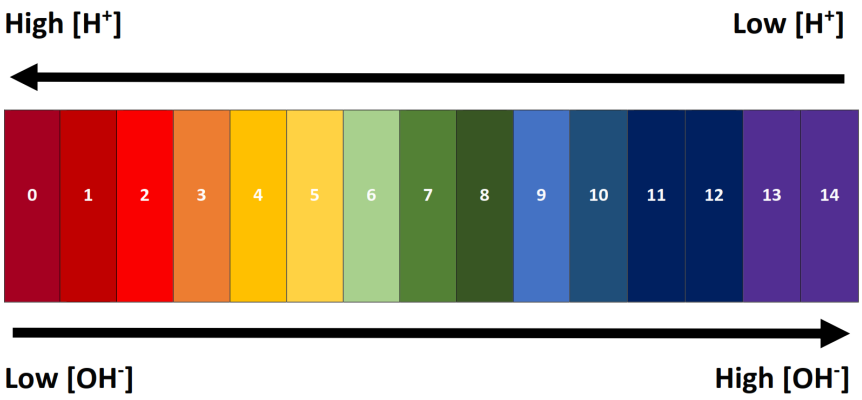
- Strong acids have a higher rate of reaction with reactive metals than weak acids of equal concentration because they have a higher $[H^+]$ in solution.

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

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

pH

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



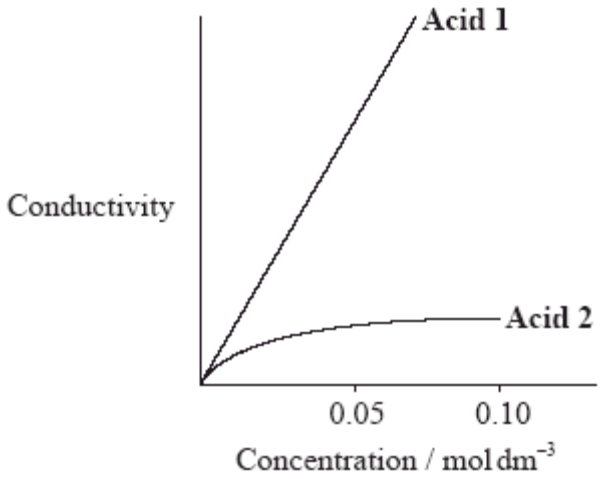
Exercises:

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.

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.

(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.

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



Identify Acid 1 and explain your choice.

Calculating the pH of strong acids and bases

- Strong acids completely ionise in solution, so $[H^+]$ 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.

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

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 5.0.
- 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 HNO_3, HNO_2, H_2SO_4 and H_2SO_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.

Syllabus checklist

Objective	I am confident with this	I need to review this	I need help with this
Outline why rain is naturally acidic with a pH of 5.6			
Write balanced equations for the reactions for the formation of HNO_3, HNO_2, H_2SO_4 and H_2SO_3 in the atmosphere			
Outline pre- and post-combustion methods of reducing SO_2 emissions			
Deduce equations for the reactions of HNO_3 and H_2SO_4 with reactive metals and carbonates			

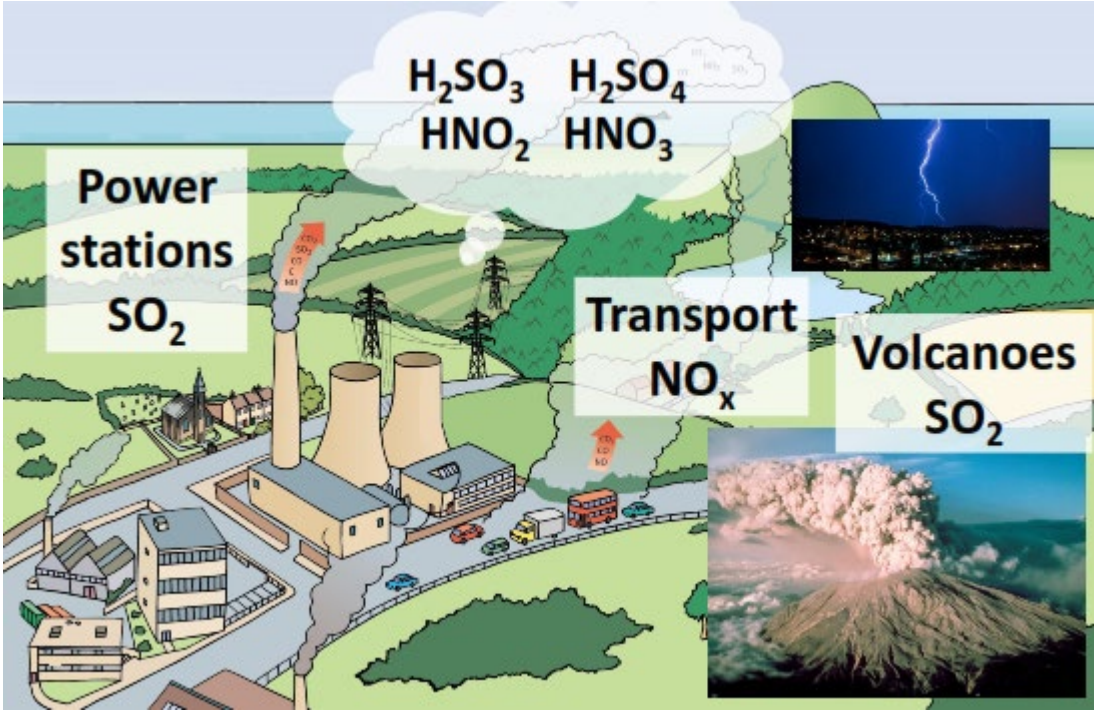
Acid deposition

- Unpolluted 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 less than 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.

Formation of acid rain

Sulfuric and sulfurous acid

- Sulfuric acid (H_2SO_4) and sulfurous 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)

- SO_2 dissolves in water to form sulphurous acid (H_2SO_3)

- SO_2 can react with O_2 to form sulfur trioxide (SO_3)

- SO_3 dissolves in water to form H_2SO_4

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).

- NO reacts with O_2 to form nitrogen dioxide (NO_2)

- NO_2 dissolves in water to form HNO_3 and HNO_2

Exercises:

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

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

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.

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

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 acid and nitric acid.

Reduction of 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.

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

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

Reducing acidity of water

- Powdered $CaCO_3$ 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. Outline one pre-combustion and one post-combustion method of reducing sulfur emissions.

2. Outline how acidic lake water can be neutralised.