8.4 The pH Scale

The term pH was invented by Danish chemist Søren Sørenson in 1909, and stands for *pondus hydrogenii*, or 'potential hydrogen'. The phrase refers to the potential of a solution to produce hydrogen ions, as Sørenson recognised that the hydrogen ions were critical to the behaviour of enzymes he was investigating. Strictly speaking, pH is a measure of what is known as the 'activity' of hydrogen ions, though for the types of problems that we will encounter, the concentration of hydrogen ions is quite sufficient. When Sørenson was recording the results of his experiments, he needed to record the exact hydrogen ion concentration every time. He soon tired of writing, for example, $10^{-6.4}$ M, and slipped into the habit of simply writing the exponent of the concentration, which in the example given is 6.4. His colleagues quickly followed suit and, as a result, a convenient and practical way of recording the relative acidity of solutions came into widespread use and acceptance.

Water Dissociation and pH

Water has the ability to break up a substance into ions. This process is called dissociation or ionization. The water molecules themselves can also break up into ions although only to a very small extent. About one water molecule in about 500 million actually dissociates.

The reaction for the dissociation of water according to Arrhenius's theory is:

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

According to Bronsted-Lowry Theory water can also react with itself. More about this later.

$$H_2O\ (l) + H_2O\ (l) \leftrightarrow H_3O^+\ (aq) + OH^-\ (aq)$$

Each water molecule that dissociates contributes one H^+ and one OH^- ion to the solution. The concentration of H^+ and OH^- is very small. Normally we say that the concentration of H^+ and OH^- are the same:

i.e. $[H^+] = [OH^-] = \text{very small}$

[ ] stands for concentration in mol dm^{-3}

Chemists have actually worked out the concentration of H^+ and OH^- ions in pure water and found it to be 1 x 10^{-14} mol^2 dm^{-6} at 25°C.

$$\text{i.e.} \quad K_w = [H^+] \times [OH^-] = 1.0 \times 10^{-14}\ mol^2\ dm^{-6}$$

This number is called K_w, the dissociation constant or ionic product of water.

$$\text{Therefore } [OH^-] = [H^+] = 1 \times 10^{-7}\ mol\ dm^{-3}$$

Acid Solutions

An acid when added to water will donate H^+ ions to the water. This means that the $[H^+]$ of the water will increase and the $[H^+]$ and $[OH^-]$ will no longer be equal.

Although the $[H^+]$ has increased K_w always remains the same at 1.0 x 10^{-14} mol^2 dm^{-6}. Therefore the $[OH^-]$ will decrease.

In any acid solution the $[H^+] > [OH^-]$

$[H^+] > 10^{-7}$ mol^2 dm^{-3}
$[OH^-] < 10^{-7}$ mol^2 dm^{-3}

Alkaline Solutions

A base when added to water will donate OH^- ions to the water. This means that the $[OH^-]$ will increase and the $[H^+]$ and $[OH^-]$ will no longer be equal.

In any basic solution the $[H^+] < [OH^-]$

$[H^+] < 10^{-7}$ mol^2 dm^{-3}
$[OH^-] > 10^{-7}$ mol^2 dm^{-3}

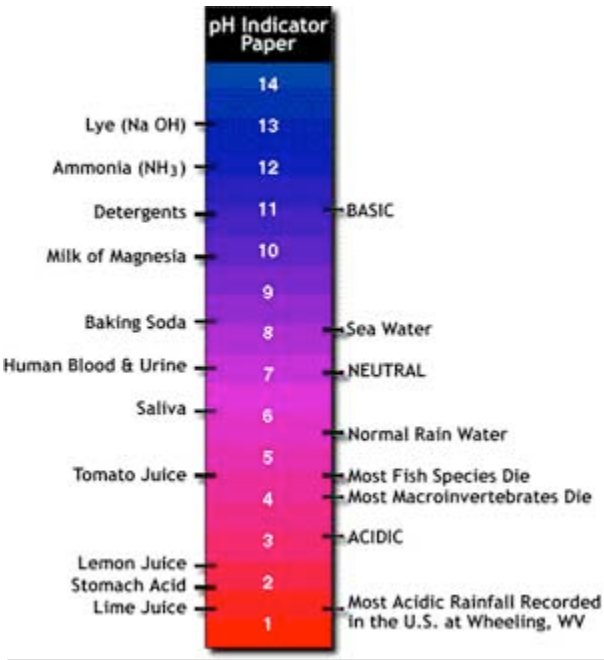
Neutral Solutions

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

$[H^+] = 10^{-7}$ mol^2 dm^{-3}
$[OH^-] = 10^{-7}$ mol^2 dm^{-3}

The pH Scale

The concentration of hydrogen ions in aqueous solutions varies widely between about 10 mol dm^{-3} and 1 x 10^{-16} mol dm^{-3}. The pH scale is a logarithmic scale used to overcome the problem of using such a large range of these numbers.



pH is defined as minus the logarithm to the base ten of the hydrogen ion concentration.

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

The pH scale runs from 0 to 14. Because it depends on the power of ten a change in one pH unit represents a tenfold change in the hydrogen ion concentration.

Note that either $[H_3O^+]$ or $[H^+]$ may be used in the expression for pH.

A 0.1 mol dm^{-3} solution of a strong monoprotic acid will have a pH of 1, a 0.001 mol dm^{-3} solution of the same acid will have a pH of 3. Can you explain why?

Misconceptions about pH "limits". The pH scale does not have absolute limits of 0 and 14. Such limits would imply that it is impossible to have a hydrogen ion concentration greater than 1 mol dm^{-3} or less than 0.01 picomol dm^{-3}. Concentrated sulfuric acid, which is approximately 18 mol dm^{-3} has a pH of -1.25. Therefore the pH scale is constructed to work over a convenient, but limited, range that is useful for most acids and bases.

What does a pH value mean?

- A low value of $[H^{+}_{(aq)}]$ matches a high value of pH that is closer to 7
- A high value of $[H^{+}_{(aq)}]$ matches a low value of pH that is closer to 0
- Decreasing pH mean the pH number is getting smaller (pH 8 → 1). Increasing the pH means the pH number is getting larger (pH 1 → 8)
- A change of 1 pH unit corresponds to a 10 fold or factor of 10 change in the $[H^{+}_{(aq)}]$. For example an acid of pH 4 contains 10 times as many hydrogen ions as an acid of pH 5 and 100 times as many hydrogen ions as an acid of pH 6. (10^{x} = factor pH has changed, where x = new pH)

Calculating the pH of strong acids and bases

For a strong acid:

- We assume that the acid completely dissociated into ions
- Therefore the concentration of the acid equals the concentration of the hydrogen ions
- Take care with diprotic acids like H_2SO_4 which produce two moles of hydrogen ions when they dissociate (triprotic three moles of hydrogen ions.

Example:
A strong monoprotic acid has a concentration of 0.010 mol dm^{-3}. What is its pH?

Assuming complete dissociation of the acid $[HA] = [H^{+}]$ so $[H^{+}] = 0.010$ mol dm^{-3}

$pH = -\log_{10}[H^{+}] = -\log_{10} 0.010 = 2.0$

For a strong base:

- We assume that the base completely dissociated into ions
- That the concentration of the base equals the concentration of the hydroxide ions
- Using the appropriate equations calculate the pH from the hydroxide ion concentration

Determination of pH

The pH of a solution can be determined by using a pH meter or by universal indicator, which gives a range of colours at different pH values. Universal indicator is made up of a mixture of different indicators.

pH	$[H^+]$ / mol dm^{-3}	$[OH^-]$ / mol dm^{-3}	Description	Colour in universal indicator
0	1	1×10^{-14}	Very acidic	Red
4	1×10^{-4}	1×10^{-10}	Acidic	Orange
7	1×10^{-7}	1×10^{-7}	neutral	Green
10	1×10^{-10}	1×10^{-4}	basic	Blue
14	1×10^{-14}	1	Very basic	purple

Describe the relationships (patterns) between the pH, $[H^+]$ and $[OH^-]$ in the above table?

Important pH equations

These equations are not in the IB data booklet, so you will need to remember them.

1. $[H^+] \times [OH^-] = 1.0 \times 10^{-14}$ mol^2 L^{-2}

   and then be able to rearrange to give:

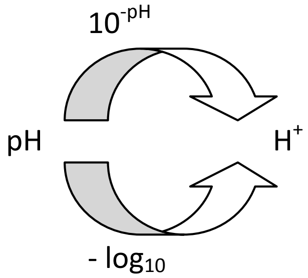
   $$[H^+] = \frac{1.0 \times 10^{-14}}{[OH^-]}$$

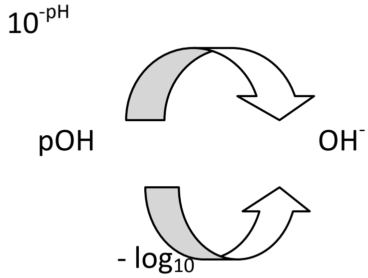
   $$[OH^-] = \frac{1.0 \times 10^{-14}}{[H^+]}$$

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

3. $pH + pOH = 14$

4. $pOH = -\log_{10} [OH^-]$ and $[OH^-] = 10^{-pOH}$





Helpful hints for pH calculations

pH calculations are easy once you have learnt how to use your calculator correctly. Try the equations above until you can remember the order to press the keys. Write the order down. Try reversing the process and go back to the original value. Repeat this process several times until you have this process drilled. Finally look at the answer and decide whether it looks sensible. Different brands of calculators may need the keys pressed in a different order so make sure you stick to your own calculator.

Complete the following table

H^+ concentration (mol dm^{-3})		**pH**
0.0000001	1×10^{-7}	7

How does a change in one pH unit change the hydrogen ion concentration? Express your answer to the power of ten.

Can you describe the pattern between the pH and the $[H^+]$? This is a useful pattern to remember but it only works for those pH values that are whole numbers.

Do negative pH values exist? Explain your answer.

pH calculation practice problems

1. Determine the pH of
   a) Red wine with a hydrogen ion concentration of 1.6×10^{-2} mol dm^{-3}.

   b) Rain water with a hydrogen ion concentration of 5.0×10^{-5} mol dm^{-3}.

   c) 0.256 mol dm^{-3} HCl

   d) 0.256 mol dm^{-3} H_2SO_4

   e) 0.025 mol dm^{-3} NaOH

   h) 1.45×10^{-2} mol dm^{-3} LiOH

2. Laboratory HCl is usually 1.0 mol dm^{-3} but concentrated HCl can be 20. mol dm^{-3} (and higher). What is the pH of the concentrated HCl? What would the pH of sulfuric acid be at the same concentration?

3. Calculate the pH of the solutions made by dissolving the following in distilled water and making up to 500.0 cm^3 of solution:
   a) 3.00g of hydrogen chloride, HCl

   b) 4.50 g of Chloric (VII) acid, $HClO_4$

4. Calculate the hydrogen ion concentration of

a) Beer with a pH of 4.5

b) Coffee with a a pH of 5.3

c) battery acid H_2SO_4 with a pH of 1.57

d) NaOH with a pH of 12.87

5. Calculate the pOH from the following solutions

a) 2.5 mol dm^{-3} sodium hydroxide used to unblock a drain

b) Milk of Magnesia containing 0.034 mol dm^{-3} $Mg(OH)_2$

7. Calculate the pH for the solutions in 6 a) and b)

Acid Rain

The atmosphere contains low concentrations of a number of non-metal oxides, including carbon dioxide, nitrogen dioxide, sulfur dioxide and sulfur trioxide. While these oxides exist in the atmosphere from natural sources, their concentrations have increased as a result of human activity, particularly during the past 100 years. Some of these acidic oxides are responsible for acid rain, a serious form of air pollution.

All rain contains dissolved carbon dioxide, so even unpolluted rain is slightly acidic. The carbon dioxide reacts with water to form carbonic acid.

$$CO_2(g) + H_2O(l) \rightarrow H_2CO_3(aq)$$

Rain is usually described as acid rain if it has a pH lower than 5. The worst examples of acid rain occur in densely populated and highly industrialized regions. Acid rain is usually the result of rain dissolving sulfur oxides (SO_2 and SO_3) and nitrogen dioxide (NO_2) to produce a dilute solution of acids such as sulfurous (H_2SO_3), sulfuric (H_2SO_4) and nitric (HNO_3) acid.

In addition to the natural sources of sulfur oxides such as volcanic eruptions, emission of sulfur oxides into the atmosphere is often the result of burning fossil fuels in electricity generating power stations, and the smelting of sulfide ores in metal-smelting plants. The sulfur dioxide produced is readily oxidized (gain oxygen) in the air to form sulfur trioxide. Nitrogen oxide emissions are usually the result of high temperature combustion processes such as those in motor vehicles and airplane emissions. Nitrogen oxides can also be formed naturally in the vicinity of lightning which provides enough energy to allow nitrogen to be oxidized to NO and further to NO_2. When dissolved in rain, these sulfur and nitrogen oxides produce acids and, subsequently, acid rain.

$$SO_2(g) + H_2O(l) \rightarrow H_2SO_3(aq)$$

$$SO_3(g) + H_2O(l) \rightarrow H_2SO_4(aq)$$

$$4NO_2(g) + 2H_2O(l) + O_2(g) \rightarrow 4HNO_3(aq)$$

Although a solution with a pH of 4 or 5 would be described as only weakly acidic, these solutions can cause a lot of damage over long periods of time. Acid rain can cause several problems. Surface waters and lakes can become acidic, decreasing the numbers of aquatic species that can't tolerate these acidic conditions. Many lakes in Europe, Scandinavia and North America are now too acidic to support fish life. Acid rain can also cause damage to plants, including crops and forests. This occurs through the direct effect of the acid rain, but also indirectly because of its effects on soil. Another problem is the damage caused to metal and stone buildings and structures. In particular, many historical statues are slowly dissolving due to the effect of acid rain on the limestone of which they are composed. The reaction involved is:

$$CaCO_3(s) + 2H^+(aq) \rightarrow Ca^{2+}(aq) + H_2O(l)$$

Questions

Please don't use a calculator for the multiple choice questions.

1. (N00/S) When the pH of a solution changes from 2.0 to 4.0, the hydrogen ion concentration
   - A. increases by a factor of 100
   - B. increases by a factor of 2
   - C. decreases by a factor of 2
   - D. decreases by a factor of 100

2. (M02/S) Solutions P, Q, R and S have the following properties:
   - P: pH = 8
   - Q: $[H^+] = 1 \times 10^{-3}$ mol dm^{-3}
   - R: pH = 5
   - S: $[H^+] = 2 \times 10^{-7}$ mol dm^{-3}

   Which of these solutions are arranged in order of increasing acidity (least acidic first), the correct order is
   - A. P, S, R, Q
   - B. Q, R, S, P
   - C. S, R, P, Q
   - D. R, P, Q, S

3. Which one of the following aqueous solutions would you expect to have a pH significantly different to the rest?
   - A. mol dm^{-3} CO_2
   - B. 0.001 mol dm^{-3} HNO_3
   - C. 0.001 mol dm^{-3} H_2SO_4
   - D. 0.001 mol dm^{-3} HCl

4. (N06/S) Lime is added to a lake to neutralize the effects of acid rain. The pH value of the lake water rises from 4 to 7. What is the change in concentration of the hydrogen ions in the lake water?

A. increase by a factor of 3
B. increase by a factor of 1000
C. decrease by a factor of 3
D. decrease by a factor of 1000

5. (M05/S) The pH of a solution X is 1 and that of Y is 2. Which statement is correct about the hydrogen ion concentration in the two solutions?

A. $[H^+]$ in X is half that of Y.
B. $[H^+]$ in X is twice that of Y.
C. $[H^+]$ in X is one tenth that of Y.
D. $[H^+]$ in X is ten times that of Y.

6. (N03/S) Four aqueous solutions, I, II, III and IV, are listed below.

I. 0.100 mol dm^{-3} HCl
II. 0.010 mol dm^{-3} HCl
III. 0.100 mol dm^{-3} NaOH
IV. 0.010 mol dm^{-3} NaOH

What is the correct order of increasing pH of these solutions?

A. I, II, III, IV
B. I, II, IV, III
C. II, I, III, IV
D. II, I, IV, III

7. Spec/S(1) A solution, which has a pH of 5.5, would be described as

A. very acidic
B. slightly acidic
C. slightly basic
D. very basic

8. M98/S(1) A student prepared separate 0.1 M solutions of the monoprotic acids X and Y. The pH=3 for the solution of acid X and the pH=2 for the solution of the acid Y. Acid X

A. is stronger than acid Y
B. is more dilute than acid Y
C. contains a higher concentration of H+ than acid Y.
D. contains more undissociated molecules than acid Y.

9. $2 H_2O (l) \leftrightarrow H_3O^+ (aq) + OH^- (aq)$

(M00/S) The equilibrium constant for the reaction above is 1.0×10^{-14} at 25°C and 2.1×10^{-14} at 35°C. What can be deduced from this information?

A. $[H_3O^+]$ decreases as the temperature is raised
B. $[H_3O^+]$ is greater than $[OH^-]$ at 35°C
C. Water is a stronger electrolyte at 25°C
D. The ionization of water is endothermic

10. $10 cm^3$ of an HCl solution with a pH value of 2 was mixed with $90 cm^3$ of water. What will be the pH of the resulting solution?

A. 1
B. 3
C. 5
D. 7

11. Define the term pH. *[1]*

12. N02/S(2)
Carbonic acid can be used to treat wasp (an insect) stings.

(a) What does this claim suggest about the nature of wasp sting? *[1]*
(b) Name the type of reaction that occurs. *[1]*
(c) If this claim is true then explain why is hydrochloric acid not used to treat wasp stings? *[1]*

13. (M07/S) If a 1.0 $mol dm^{-3}$ solution of sodium hydroxide has a pH of 14 what would the concentration be if the pH was 13? *[2]*

14. (N06/S) The pH values of three acidic solutions X, Y and Z are shown in the following table.

Solution	Acid	pH
X	HCl	2
Y	HCl	4
Z	CH_3COOH	4

a) Solutions X and Z have the same acid concentration. Explain by reference to both acids why they have different pH values. *[2]*
b) Deduce by what factor the values of the hydrogen ion concentration in solutions X and Y differ. *[1]*

15. (N01/S/A) The pH of an aqueous caffeine solution is 12. An aqueous urea solution is 100,000 times more acidic than the caffeine solution. Estimate the pH of the urea solution and explain your answer. *[2]*

16. (M02/S) Solutions of 0.1 mol dm^{-3} sodium hydroxide and 0.1 mol dm^{-3} ammonia have different electrical conductivities.

a) State and explain which solution has the greatest conductivity. *[1]*

b) The pH value of 0.1 mol dm^{-3} ammonia solution is approximately 11. State and explain how the pH value of the 0.1 mol dm^{-3} sodium hydroxide solution would compare. *[2]*

17. M98/1(H) Separate solutions of HCl are prepared that have pH values of 2 and 4. How do the H^+ concentrations in them compare?

A. The $[H^+]$ in the pH=2 solution is 100 times as large as the $[H^+]$ in the pH=4 solution
B. The $[H^+]$ in the pH=4 solution is 100 times as large as the $[H^+]$ in the pH=2 solution
C. The $[H^+]$ in the pH=4 solution is twice as large as the $[H^+]$ in the pH=2 solution
D. The $[H^+]$ in the pH=2 solution is twice as large as the $[H^+]$ in the pH=4 solution

18. (N06/H) Water dissociated according to the equation

$$H_2O\ (l) \leftrightarrow H^+\ (aq) + OH^-\ (aq) \quad \Delta H = +56\ kJ$$

At 25°C water has a pH of 7. Which of the following occurs when water is heated to 30°C?

A. It remains neutral and its pH decreases
B. It becomes acidic and its pH decreases
C. It remains neutral and its pH increases
D. It becomes acidic and its pH increases.

19. (M05/H) Which values are correct for a solution of NaOH of concentration 0.010 mol dm^{-3} at 298K?

A. $[H^+] = 1.0 \times 10^{-2}$ mol dm^{-3} and pH = 2.00
B. $[OH^-] = 1.0 \times 10^{-2}$ mol dm^{-3} and pH = 12.00
C. $[H^+] = 1.0 \times 10^{-12}$ mol dm^{-3} and pOH = 12.00
D. $[OH^-] = 1.0 \times 10^{-12}$ mol dm^{-3} and pOH = 2.00

20. (N05/H) When the following 1.0 $moldm^{-3}$ solutions are listed in increasing order of pH (lowest first), what is the correct order?

A. $HNO_3 < H_2CO_3 < NH_3 < Ba(OH)_2$
B. $NH_3 < Ba(OH)_2 < H_2CO_3 < HNO_3$
C. $Ba(OH)_2 < H_2CO_3 < NH_3 < HNO_3$
D. $HNO_3 < H_2CO_3 < Ba(OH)_2 < NH_3$

21. (N05/H) An aqueous solution has a pH of 10. Which concentrations are correct for the ions below.

	$[H^+]$ mol dm^{-3}	$[OH^-]$ mol dm^{-3}
A.	10^{4}	10^{-10}
B.	10^{-4}	10^{-10}
C.	10^{-10}	10^{-4}
D.	10^{-10}	10^{4}

22. Advertisers often used science as a stamp of approval or guarantee of quality to sell their products. How could you determine if a claim made about the pH of a product is a scientific one?

23. Many people commonly believe the following about wasp and bee stings. Wasp sting venom is alkaline and so its effects can be neutralized with vinegar an acid and this neutralization then reduces the pain. Bee sting venom is acidic and so its effects can be neutralized with baking soda or alkali and this reaction reduces the pain.

    Consider the following claim made in an IB Chemistry exam

    "Carbonic acid can be used to treat wasp stings"
    - Paper 2, Nov 2002 IB Chemistry SL Exam

    Discuss the issues associated with this claim.

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