CHEM1002 Worksheet 10: Making a Perfect Snowball

Model 1: Addition of a Strong Base to a Weak Acid

In Worksheet 8, you used an "ICE" approach to work out the pH of a solution containing a weak acid. For example, you worked out that a 0.500 M solution of $CH_3COOH(aq)$ has a pH of 2.531.

If a strong base, such as NaOH, is added to this solution, it will react with the weak acid.

$$CH_3COOH(aq) + OH^-(aq) \rightarrow CH_3COO^-(aq) + H_2O(aq)$$

As long as the amount of $OH^-(aq)$ added is *less* than the amount of $CH_3COOH(aq)$ present, the solution will contain both $CH_3COO^-(aq)$ and left over $CH_3COOH(aq)$. A solution like this containing both a weak acid and its conjugate base is a buffer and its pH is given by the *Henderson-Hasselbalch* equation:

$$\mathrm{pH} = \mathrm{p}K_\mathrm{a} + \log\frac{[\mathrm{base}]}{[\mathrm{acid}]} = \mathrm{p}K_\mathrm{a} + \log\frac{[\mathrm{CH_3COO^-(aq)}]}{[\mathrm{CH_3COOH(aq)}]}$$

Critical thinking questions

1. If 0.100 mol of NaOH(s) is added to a 1.00 L solution of 0.500 M CH_3COOH, it will react to form a solution which is 0.100 M in $CH_3COO^-(aq)$ and 0.400 M $CH_3COOH(aq)$. What is the pH of this solution? ($\mathrm{p}K_\mathrm{a}$ (CH_3COOH) = 4.756).

2. Complete the table below showing the concentrations of $CH_3COOH(aq)$ and $CH_3COO^-(aq)$ and the pH of the solution as more NaOH(s) is added to this solution.

Amount of NaOH(s) added (mol)	0.000	0.100	0.200	0.300	0.400	0.500
$[CH_3COOH(aq)]$ (M)	0.500	0.400				
$[CH_3COO^-(aq)]$ (M)	0.000	0.100				
pH	2.531					

3. To react completely with the original CH_3COOH, 0.500 mol of NaOH must be added. What is the pH of the solution when exactly *half* this amount is added?

4. How can you obtain the value for $\mathrm{p}K_\mathrm{a}$ for an acid?

Model 2: Neutralizing a Weak Acid

Model 1 describes the pH changes as a strong base is added to a solution containing a weak acid. The strong base reacts with the weak acid leading to a solution containing the conjugate base of the weak acid and any left over acid. The *equivalence* point occurs when enough base has been added so that there is no acid left.

At this point, the solution contains the conjugate base and essentially none of the original acid.

The conjugate base will then set up its own equilibrium:

$$CH_3COO^-(aq) + H_2O(l) \rightleftharpoons CH_3COOH(aq) + OH^-(aq) \qquad K_b = \frac{[CH_3COOH(aq)][OH^-(aq)]}{[CH_3COO^-(aq)]}$$

From the chemical equation:

$$[CH_3COOH(aq)]_{equilirium} = [OH^-(aq)]_{equilirium}$$

As hardly any base reacts, $[CH_3COO^-(aq)]_{equilibrium} \approx [CH_3COO^-(aq)]_{initial}$ and so:

$$K_b = \frac{[OH^-(aq)]^2}{[CH_3COO^-(aq)]_{initial}} \qquad \text{and} \qquad [OH^-(aq)] = \sqrt{K_b \times [CH_3COO^-(aq)]_{initial}}$$

After working out $[OH^-(aq)]$, the pOH can be calculated:

$$pOH = -\log[OH^-(aq)]$$

Finally, the pH can then be calculated using pH = 14.00 – pOH.

Critical thinking questions

1. To react completely with the original CH_3COOH in Model 1, 0.500 mol of NaOH must be added. What will be $[CH_3COO^-(aq)]$ when this occurs?

2. Calculate the pH of the solution the reaction produced in Q1. (*Hint*: remember that $pK_a + pK_b = 14.00$ or $K_a \times K_b = 10^{-14.00}$)

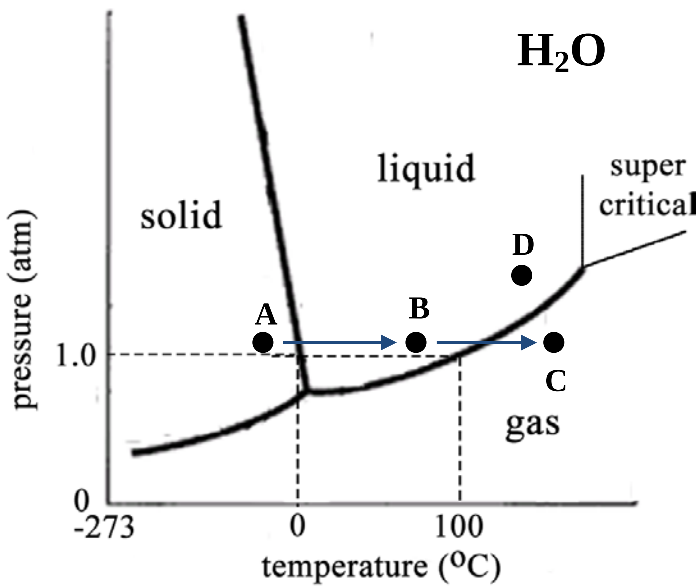
3. Correct your entry in the final column of the table in Model 1 if required!

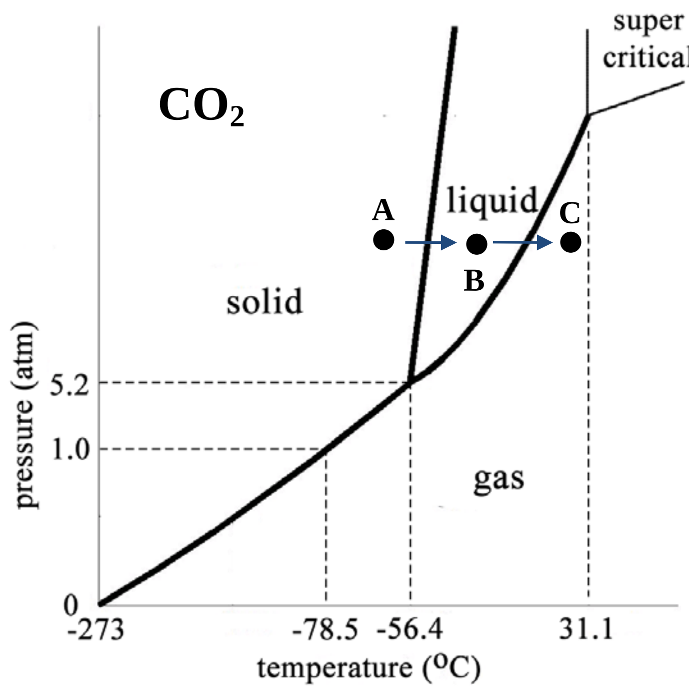
4. What is the pH at the equivalence point of the titration of a *strong* acid with a strong base?

5. Is the pH at the equivalence point of the titration of a *weak* acid with a strong base less than or higher than 7?

Model 3: Phase Diagrams for Water and Carbon Dioxide

The *phase diagrams* for H_2O and CO_2 are shown below. A phase diagram summarizes the behaviour of a substance and different temperatures (*x* axis) and pressures (*y* axis). The different areas of the diagram represent conditions under which the material is a gas, liquid or solid. The thick, solid lines represent the transitions between these phases.





For example, point **A** on both diagrams represents a temperature and pressure in which the substance is a solid (*ice*). If the temperature is increased and the pressure is not changed, the substance moves to point **B** (liquid) and then to point **C** (gas). Along the way it passes through the solid line separating 'solid' from 'liquid' (*melting*) and through the solid line separating 'liquid' from 'gas' (*boiling* or *vapourizing*).

Critical thinking questions

1. Water in a car radiator when the engine overheats is both very hot and under pressure. Point **D** on the water phase diagram represents this situation. What phase is water in at point **D**?

2. If the radiator cap is removed, the pressure will decrease to atmospheric pressure. What is likely to happen to the water? Draw another point (**E**) and an arrow on the phase diagram to illustrate this process.

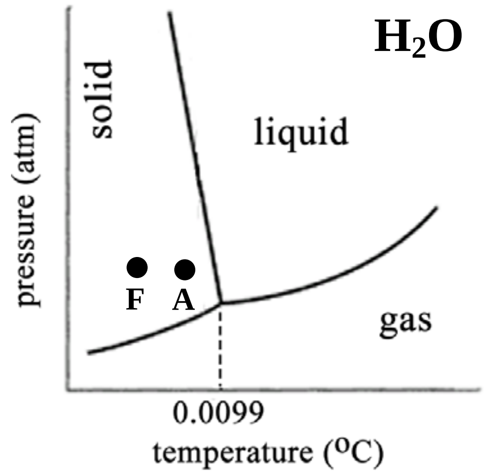
3. Sequestration involves storing CO_2, produced by burning fossil fuels, underground as a liquid. How could this be done? Draw two points and an arrow on the phase diagram of CO_2 to illustrate this process occurring at 25 °C.

Model 4: Under Pressure

Snow is very loose and there is an art to make it into a snowball capable to being thrown. To make a perfect snowball, you scoop up snow in a gloved hand and squeeze it between your cupped hands.

The explanation for this lies in the almost unique* phase diagram of water. The thick line representing the solid-liquid transition slopes to the left for water. As shown in Model 1 for CO_2, it normally slopes to the right.

This peculiarity is associated with the lower density of solid water compared to liquid water: water ice floats in a glass of water but dry ice sinks in liquid CO_2.



Critical thinking questions

1. On a particular winter's day, the temperature is just below freezing. The snow you pick up is at point **A** on the phase diagram. When you squeeze the snow, what will happen to it? Draw another point (**G**) and an arrow on the phase diagram to illustrate this process.

2. Before throwing the snowball, you release the pressure. Describe what will happen and add another arrow to the phase diagram to illustrate this process.

3. The temperature even on a summer's day at the South Pole is very cold (around -25 °C). On worlds such as Ganymede, Pluto or Mars, the temperature can be a low as -120 °C. Point **F** represents snow on a very cold day. Can ice be welded by hand compression from this point?

4. Mars is usually so cold that CO_2 exists as a solid. By first predicting what happens if you squeeze dry ice at point **A** on its phase diagram (see Model 1), suggest whether it is possible to make a snowball of dry ice.

* There are other materials that have solid-liquid transition lines that slope to the left but these tend to be under conditions where humans cannot survive. You could, for example, make a plutonium snowball by squeezing plutonium dust at 640 °C. Just don't take too big a handful.