Catalysis: an overview of different types of catalysis

Sections 8.4 and 8.5 in the book demonstrated how catalysts alter the rate of a reaction by finding an alternative mechanistic route with a lower activation energy. So, although zinc reacted with acid, when copper is attached to the zinc more hydrogen is released in a given time (i.e. the rate of reaction increases). The hydrogen can be seen coming from the copper as well as zinc, but the copper remains chemically intact. Zinc appears to vanish as it gradually dissolves, forming zinc ions that are solvated by water.

Types of catalyst: homogeneous, heterogeneous and enzyme

Catalysts work in many different ways. Some catalysts use their surface, where there are often unattached electrons available to form transient bonds with the reactants. These are called **heterogeneous catalysts**, where the reaction takes in a different phase from the catalyst. The catalyst is in the solid phase and the reaction occurs in the gas, or liquid, phase. With **homogeneous catalysts**, the catalyst is in the same phase as the reactants. Esters are prepared from carboxylic acid and alcohols by using a strong acid or alkaline ion exchange resin (heterogeneous), or the addition of sulfuric acid or sodium hydroxide solution (homogeneous). The other method by which catalysts work is using a change in oxidation number. The advantage of heterogeneous catalysts in industry is that they can by filtered off and reused.

How does the chemist classify enzyme catalyst? The enzyme molecules may dissolve, or be in suspension in water, and the reacting molecules find (by the enormous number of random collisions) a convenient surface site on which the reaction takes place. So, it can be classified as both as heterogeneous and homogeneous.

Homogeneous acid catalysts and enzymes can be immobilised so that they act as heterogeneous catalysts. Ionic exchange resins can immobilise acid catalysts, and enzymes can be immobilised in alginate beads.

Activity: Decomposition of hydrogen peroxide solution

Finding catalysts for slow reactions can be treated as a guided investigation, depending upon which substances the school has available. One such slow reaction is the thermal decomposition of hydrogen peroxide solutions, which takes place at room temperature. This also decomposes photochemically with ultraviolet light.

$$H_2O_2(aq) \rightarrow H_2O\,(l) + \tfrac{1}{2}O_2(g)$$

The investigation can be carried out on a polypropylene plastic folder. The worksheet (Figure 1 below is a possible version and available to download separately) is prepared in a PowerPoint A4 landscape format. Teachers can rearrange this to suit the materials that they have at hand.

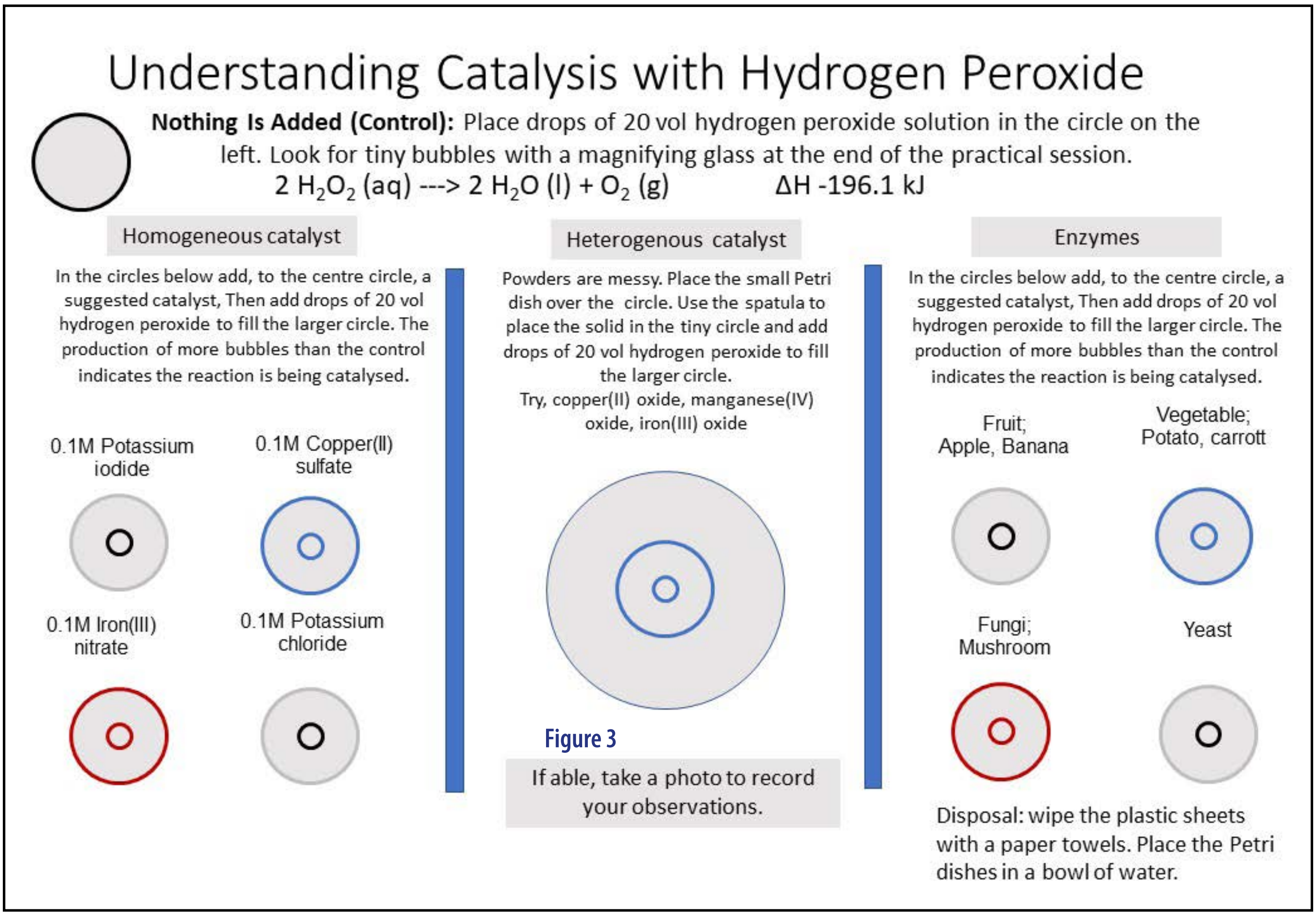

Figure 1

Outline requirements

- 20 vol hydrogen peroxide
- In dropping bottles, 0.1 M solution of potassium iodide, copper(II) sulfate, iron(III) nitrate, potassium chloride
- In vials: Solid copper(II) oxide, manganese(IV) oxide, iron(III) oxide
- Fruits such as apples and bananas
- Vegetables such as diced potato, carrot
- Fungi such as mushrooms and yeast
- Small plastic Petri dishes (The lids could also be used)
- Transfer pipettes
- Worksheets and polypropylene folder
- (Micro)spatulas for the solids. (An alternative is to cut a channel from the stem of a 3 cm^3 transfer pipette and use this a scoop)
- Hand lens

Outline method

1. Wear eye protection and insert the paper worksheet into the plastic folder.
2. Fill the 'control reaction' circle with 20 vol peroxide.
3. Examine the liquid at various intervals through the lesson for the formation of tiny bubbles of oxygen, as in Figure 2.

Figure 2

Homogeneous catalysts

1. To the centre circle of the two circles, add the solution of a suggested catalyst.
2. Add drops of 20 vol hydrogen peroxide to fill the larger circle. The production of more bubbles than the control indicates that the reaction is being catalysed. One example is shown in Figure 3. Lots of tiny form as well, rather like in Figure 2, but in a shorter timeline of 5 to 10 minutes.
3. Try one drop of 0.1 M iron IIIII) nitrate, copper(II) sulfate, cobalt(II) chloride potassium chloride[i], 0.05 M silver nitrate, 0.4 M sodium hydroxide, etc., as potential catalysts.
4. Other liquids can be tried. Transition metal salt solutions are a good source.
5. After the observations, wipe the plastic with a paper towel.

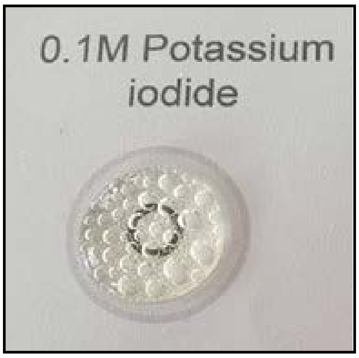

Figure 3

Heterogeneous catalysts

1. Powders are messy, so place a small Petri dish over the circle. Use the spatula to place the solid in the tiny circle and add drops of 20 vol hydrogen peroxide to fill the larger circle.
2. Look for bubbles of gas appearing (see Figure 4), which shows manganese(IV) oxide as the catalyst.
3. The Petri dish can be washed under a tap, dried and used again,
4. Try copper(II) oxide, manganese(IV) oxide, iron(III) oxide, etc. as a potential catalyst.

Figure 4

Enzyme catalysis

1. To the centre circle of the two circles, add a suggested catalyst.
2. Add drops of 20 vol hydrogen peroxide to fill the larger circle. The production of more bubbles than the control indicates that the reaction is being catalysed. One example is shown in Figure 5.
3. Try small samples of potato, carrot, mushroom, apple, banana, yeast, etc. as a potential catalyst.
4. After the observations, wipe the plastic with a paper towel.

Figure 5

The decomposition of hydrogen peroxide solution

Using *Heats of Formation* from a data book (kJ mol^{-1}), the enthalpy change for the reaction is found at 298 K.

$$H_2O_2(aq) \rightarrow H_2O(l) + \tfrac{1}{2}O_2(g)$$

$$-187.6 \quad -285.9 \quad 0 \qquad \Delta H_{dec} \text{ is } -98.3 \text{ kJ mol}^{-1}$$

The entropy change for the reaction (ΔSdec) is +62.9 J K^{-1}.

The energy profile (Figure 6 (top)) shows an exothermic reaction, which is accompanied by an increase in entropy. Hydrogen peroxide is thermodynamically unstable and really should not exist at room temperature. However, it is kinetically stable because the activation energy for the decomposition is quite large. The reaction occurs, but is very slow, as shown by the control reaction. The reaction (see Figure 2) occurs because the energy carried by radiation (light) can split the oxygen/oxygen single bond. Dust in the atmosphere carries fungal spores[ii], which contain enzymes.

The activation energy of the reaction is about 75 kJ mol^{-1} in the absence of catalyst[iii]. Platinum metal catalysts can lower the activation energy to about 49 kJ mol^{-1}. The enzymes in yeast lower it further to about 23 kJ mol^{-1}. The enzyme found in blood lowers the activation energy to below 8 kJ mol^{-1} (see Figure 6 (bottom)), which corresponds to an increase in the rate of reaction at room temperature by a factor of 2×10^{11} or more.

Pure hydrogen peroxide cannot be purchased, but aqueous solutions can. The most concentrated solution available is 100 vol solution[iv], also sold as 30% (w/w) or 8.3 mol dm^{-3} solution[v]. It is also available from local pharmacies at concentrations of 3% and 6% (w/w).

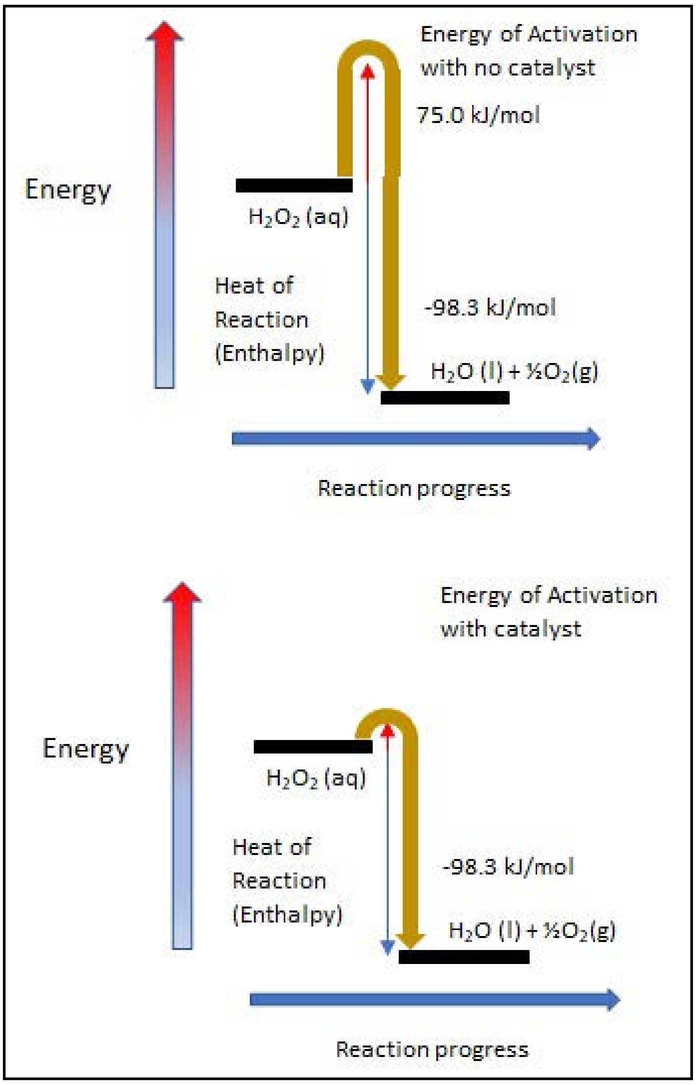

Figure 6

Activity: Mouse toothpaste

Many teachers enjoy performing the famous demonstration of the effect of catalysts on hydrogen peroxide decomposition called *The Elephant's Toothpaste*[vi]. This uses 100 vol hydrogen peroxide, which should not be used by students. Here is a smaller, safer version.

Outline requirements

- Goggles
- 20 vol hydrogen peroxide
- 250 cm^3 beaker
- Glass vial
- Small tray
- Detergent
- About 0.6 g potassium iodide

Disposal:

- Place the beaker with the vial into a sink and add lots of water.
- Gloves should not be necessary unless the student has abrasions on their skin. There is no reason to get hydrogen peroxide on the skin if transfer pipettes are used correctly.

Outline method

1. Wear goggles.
2. Put a glass vial in a beaker and on a tray.
3. Place about 5 cm^3 of 20 vol hydrogen peroxide (IRRITANT) in the vial using a transfer pipette.
4. Add 2 cm^3 detergent.
5. Add 0.5 to 0.7 g solid potassium iodide (see Figure 7).
6. Observe what happens (see Figure 8).

Figure 7

Figure 8

There is a delay as the oxygen saturates the solution. There is also a side reaction, which gives rise to a small amount of iodine (yellow colour in the bubbles). In acidic conditions, the iodide is oxide to iodine.

$$H_2O_2(aq) + 2I^-(aq) + 2H^+(aq) \rightarrow 2H_2O(l) + I_2(aq)$$

Once the small amount of acid used up and the liquid is neutral, the decomposition reaction occurs catalysed by the iodide ion.

Activities for teachers

Teachers might like to carry out the activities over several steps, so just devise your own version.

Footnotes

[i] I used potassium chloride to compare with potassium iodide to see which ion was the catalyst. There was no effect.

[ii] *What are fungal spores?* University Of Worcester: www.worcester.ac.uk/about/academic-schools/school-of-science-and-the-environment/science-and-the-environment-research/national-pollen-and-aerobiology-research-unit/What-are-fungal-spores.aspx

[iii] *The Catalytic Decomposition of Hydrogen Peroxide.* Chemistry LibreTexts: https://chem.libretexts.org/Ancillary_Materials/Demos_Techniques_and_Experiments/Lecture_Demonstrations/Additional_Demos/The_Catalytic_Decomposition_of_Hydrogen_Peroxide

[iv] 100 vol means that 1 cm^3 of solution will produce 100 cm^3 of oxygen at 0°C.

[v] Bottles of hydrogen peroxide come with a special cap that vents oxygen as the solution very slowly decomposes. The reasons are UV light and fungal spores, which enter the bottle when the cap is undone. It may take a year to notice this. Hydrogen peroxide also comes with an inhibitor to stop this happening, by removing the free radicals that form. When 100 vol is diluted to 10 vol, the inhibitor is diluted too. So, prepared 10 vol solutions soon lose their ability to produce oxygen even after a few weeks. It is better to prepare diluted solutions as and when required.

[vi] science.cleapss.org.uk/Resource-Info/SRA011-Spectacular-decomposition-of-hydrogen-peroxide-to-produce-a-foam-catalysed-by-potassium-iodide-elephant-s-toothpaste.aspx