

What is green chemistry?

Green chemistry is both the chemistry of the future and the chemistry of today. It is based on a number of principles (see Appendix) that ensure that both processes and end products are clean and safe. Green chemistry aims to conserve both energy and raw materials. In practice, this means that 'green' processes are often cheaper than conventional methods. Some current processes are already 'green', and the use of green chemistry is growing because it is environmentally friendly, and also because of legislation and international agreements that aim to reduce pollution. One of the basic ideas of green chemistry is to *prevent* production of hazardous and polluting materials rather than producing them and then cleaning up.

Green chemistry:

- is safe;
- conserves raw materials and energy; and
- is more cost-effective than conventional methods.

Green chemistry in practice

Approaches to making chemical processes 'greener' include:

- redesigning production methods to use different starting materials;
- using different reaction conditions, catalysts, solvents *etc*; and
- using production methods with fewer steps.

Yield and atom economy

One of the key ideas of green chemistry is that of **atom economy**. This considers how much of the reactants in a chemical reaction end up in the final useful product or products. Ideally all the atoms of the reactants would end up incorporated into useful products – such a reaction would produce no waste at all – but this is rarely possible. The atom economy (also called **atom utilisation**) of a reaction is a measure of the percentage of the starting materials that actually ends up in the useful products.

The yield of a chemical reaction

Before looking at atom economy, we will look at a similar idea that you will probably already be familiar with, that of **yield**.

Much of the chemical industry is concerned with turning one material (the raw material) into another that is more useful and that is worth more (the product). This is why the chemical industry is useful and is how it makes a profit – by turning low value materials into high value ones. This process often requires several steps and is called a **chemical synthesis** ('synthesis' means 'building up'). Naturally, the chemists who design these syntheses wish to make the maximum amount of product that they can from a given amount of raw material. Unfortunately, few chemical reactions go 100% to completion. Firstly, the reaction may be reversible and form an equilibrium mixture, secondly there may be two or more alternative products that can be produced from the same starting materials. Furthermore, there will inevitably be losses during the process of separating the desired product from other waste materials (called by-products).

Example 1 Formation of an equilibrium mixture – making the ester ethyl ethanoate ($\text{CH}_3\text{COOC}_2\text{H}_5$) from ethanol ($\text{C}_2\text{H}_5\text{OH}$) and ethanoic acid (CH_3COOH)

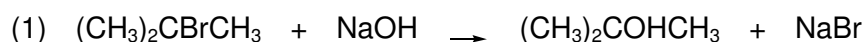
The following equilibrium is set up:



At room temperature, if we mix 1 mol of ethanol with 1 mol of ethanoic acid, we eventually produce a mixture containing 0.33 mol of ethyl ethanoate, 0.33 mol of water, 0.67 mol of ethanol and 0.67 mol of ethanoic acid. This means that the reaction has not gone to completion. If it had gone to completion, we would have formed 1 mol of ethyl ethanoate and 1 mol of water and there would have been no ethanol and ethanoic acid left.

Example 2 Formation of alternative products - the reaction of 2-bromo-2-methylpropane ((CH₃)₂CBrCH₃) with sodium hydroxide

Here two reactions are possible, forming 2-methylpropan-2-ol ((CH₃)₂COHCH₃) and 2-methylpropene ((CH₃)₂C=CH₂) respectively:



Under certain conditions, 1 mol of 2-bromo-2-methylpropane produces 0.9 mol of methylpropene and 0.1 mol of 2-methylpropan-2-ol.

In these sorts of situations, chemists talk about the **yield** of a chemical reaction. This is the number of moles obtained of a specified product divided by the maximum number of moles that could have been obtained if all the reactant had been converted to product. It is usually expressed as a percentage. So

$$\text{Yield} = \frac{\text{actual no. of moles of product}}{\text{maximum no. of moles of product}} \times 100\%$$

So in example 1

$$\text{Yield of ethyl ethanoate} = \frac{0.33 \text{ mol}}{1 \text{ mol}} \times 100\% = 33\%$$

In example 2

$$\text{Yield of methylpropene} = \frac{0.9 \text{ mol}}{1 \text{ mol}} \times 100\% = 90\%$$

Q 1. (a) What is the yield of water in example 1?

(b) What is the yield of 2-methylpropan-2-ol in example 2?

There is a complication with the idea of yield. In both the above examples we mixed the reactants in exactly the right ratios to react as shown by the equation - one mole of each reactant in each case. If we have more of one reactant than is needed then we must work out the yield with respect to the reactant that is in short supply (we call this the **limiting reactant**) because it is this reactant that governs the maximum amount of product we can make.

Q 2. Suggest why it might make sense to use more of one of the reactants than is actually needed as shown in the chemical equation for the reaction.

In the second example, we could have mixed 1 mol of 2-bromo-2-methylpropane with 2, 3, or even 10 mol of sodium hydroxide and the maximum possible amount of methylpropene would still have been 1 mol. But if we had used 0.5 mol of sodium hydroxide, and 1 mol of 2-bromo-2-methylpropane, the sodium hydroxide would have become the **limiting reactant** and the maximum possible amount of methylpropene would have become 0.5 mol.

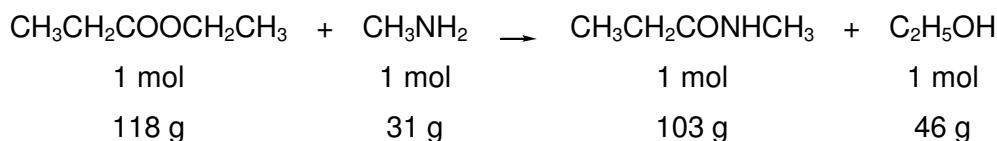
In practice, no chemical reaction ever produces a 100% yield. Even if the reaction goes to completion and there is only a single possible product, there are always losses involved in the practical processes of separating the required product from the rest of the reaction mixture. For example when filtering there will always be some material left on the filter paper, when pouring there will always be droplets left behind in the original container and so on. In the laboratory much of the skill of the practical chemist is in increasing the yield of a reaction by careful manipulation of the apparatus so as to minimise losses such as these. Industrially, good design of the process will minimise losses of this type.

- Q 3. Consider the reaction of ethanoic acid with sodium hydroxide:
 $\text{CH}_3\text{COOH} + \text{NaOH} \rightarrow \text{CH}_3\text{COONa} + \text{H}_2\text{O}$
- (a) How many moles of sodium hydroxide could react with one mole of ethanoic acid?
- (b) Work out the relative molecular masses of
- (i) ethanoic acid
 - (ii) sodium hydroxide.
- (c) If 2 mol of ethanoic acid are mixed with 1 mol of sodium hydroxide, what is the limiting reactant?
- (d) If 3.0 g of ethanoic acid are mixed with 4.0 g of sodium hydroxide, what is the limiting reactant?
- (e) In the reaction described in (d), what is the maximum mass of sodium ethanoate that could be produced?
- (f) In the reaction described in (d), 3.6 g of sodium ethanoate was separated from the reaction mixture. What is the yield?
- Q 4. Consider the reaction of sulfuric acid with sodium hydroxide:
 $\text{H}_2\text{SO}_4 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O}$
- (a) How many moles of sodium hydroxide could react with one mole of sulfuric acid?
- (b) Work out the relative molecular masses of
- (i) sulfuric acid
 - (ii) sodium hydroxide.
- (c) If 2 mol of sulfuric acid are mixed with 2 mol of sodium hydroxide, what is the limiting reactant?
- (d) If 6.0 g of sulfuric acid are mixed with 4.0 g of sodium hydroxide, what is the limiting reactant?
- (e) In the reaction described in (d), what is the maximum mass of sodium sulfate that could be produced?
- (f) In the reaction described in (d), 5.0 g of sodium sulfate was separated from the reaction mixture. What is the yield?
- Q 5. Consider the oxidation of ethanol ($\text{C}_2\text{H}_5\text{OH}$) to ethanal (CH_3CHO) by acidified potassium dichromate(VI) ($\text{K}_2\text{Cr}_2\text{O}_7$) solution.
- (a) Write an equation for the reaction. Use [O] to represent the oxidising agent potassium dichromate(VI).
- (b) What other organic product is possible?
- (c) Explain why this reaction will not have a 100% yield.

Atom economy

The idea of yield is a useful one but, from the point of view of green chemistry, it does not tell the whole story. This is because it concentrates only on one reactant (the limiting reactant) and one product (the product that we want). One of the key principles of green chemistry is that processes should be designed to incorporate the maximum amount of *all* the raw materials into the final product, thus reducing waste products. A reaction with a high percentage yield does not necessarily fulfil this principle.

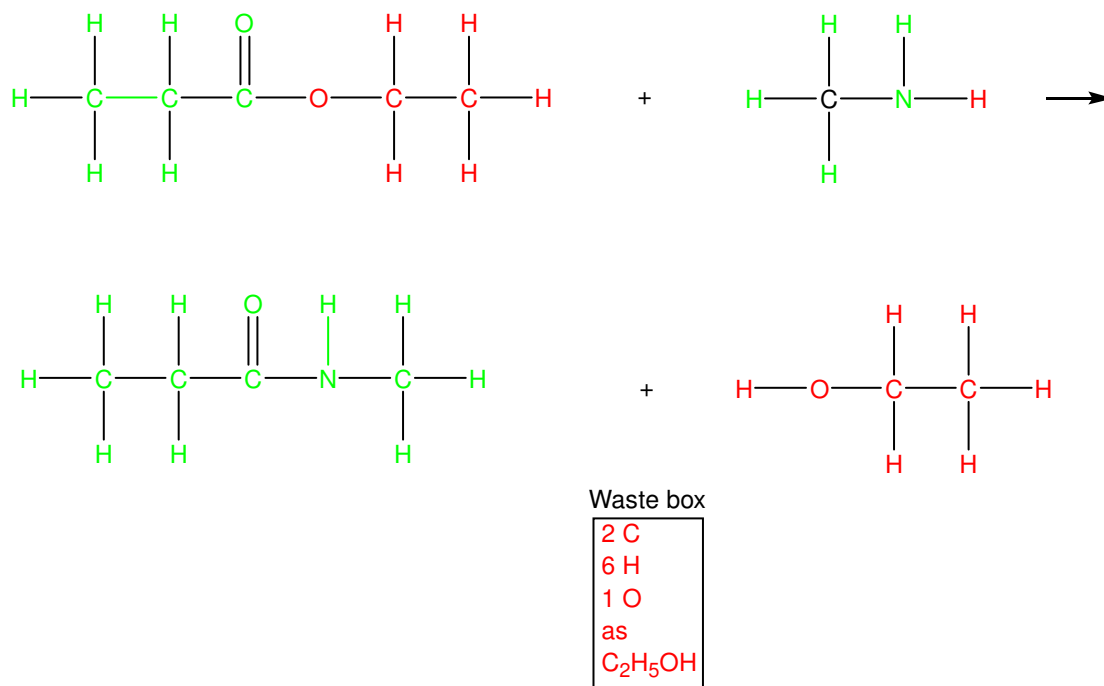
Take as an example the reaction between ethyl propanoate ($\text{CH}_3\text{CH}_2\text{COOCH}_2\text{CH}_3$) and methylamine (CH_3NH_2) to form N-methylpropanamide ($\text{CH}_3\text{CH}_2\text{CONHCH}_3$) and ethanol ($\text{C}_2\text{H}_5\text{OH}$). 1 mol of each reactant and product is involved. The mass of 1 mol of each reactant (*ie* the relative molecular mass in grams) is given, but you might like to check these in a data book or by adding up the relative atomic masses for each compound.



Imagine that the reaction has a 100% yield and then look at the quantities involved. Assuming that N-methylpropanamide is the product we want, we have started with 149 g of starting materials (118 g + 31 g) yet the mass of the required product is only 103 g. The rest, 46 g of ethanol, is wasted. Looking at it another way, we have lost 2 atoms of carbon, 6 of hydrogen and one of oxygen. These are wasted and have to be disposed of. This, of course, is before we have taken into account any losses associated with the reaction not going to completion, alternative products and practical manipulation.

Note. If the reaction were being used industrially, and it was economically viable to collect and purify the ethanol for use, then the picture would change; the atom economy could then be considered to be 100%.

It may be easier to see what has happened if we look at the displayed formulae of the molecules involved and colour code the atoms. Those coloured in green are incorporated into the final product and those in red are wasted. We could imagine a 'waste box' containing two atoms of carbon, six atoms of hydrogen and one atom of oxygen.



Green chemists have developed the idea of atom economy or atom utilization. This is defined as

$$\% \text{ Atom economy} = \frac{\text{mass of desired product}}{\text{mass of desired product plus waste products}} \times 100\%$$

or

$$\% \text{ Atom economy} = \frac{\text{mass of desired product}}{\text{total mass of reactants}} \times 100\%$$

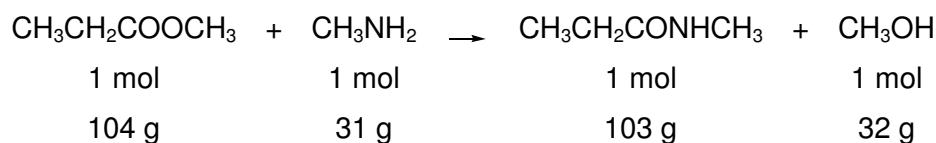
which amounts to exactly the same thing, see question 6.

Q 6. Explain why 'mass of desired product plus waste products' and 'total mass of reactants' have exactly the same value.

In the example above of the reaction between ethyl propanoate and methylamine, the atom economy = $\frac{103}{149} \times 100\% = 69.1\%$

So 69.1% of the starting materials are incorporated into the desired product, the rest is lost or, worse, has to be disposed of.

Now consider a similar reaction but starting with *methyl* propanoate (CH₃CH₂COOCH₃) rather than ethyl propanoate. This gives the same product, N-methylpropanamide, but with methanol as a by-product.



$$\text{Atom economy} = \frac{103}{135} \times 100 = 76.3\%$$

In this case, the 'waste box' contains one atom of carbon, four atoms of hydrogen and one atom of oxygen.

So a small change in the design of the synthesis (just shortening the carbon chain of one of the starting materials in this case) can lead to a significant improvement in the atom economy. In this case a molecule of methanol (mass 32 g mol^{-1}) is the unwanted product rather than a molecule of ethanol (mass 46 g mol^{-1}).

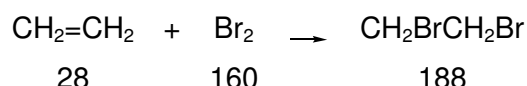
- Q 7. (a) Write out the equation for the reaction of propanoic acid ($\text{CH}_3\text{CH}_2\text{COOH}$) and methylamine to form N-methylpropanamide ($\text{CH}_3\text{CH}_2\text{CONHCH}_3$).
- (b) (i) What molecule is the unwanted product?
(ii) Therefore what atoms are in the 'waste box'?
- (c) Without doing a calculation, predict how the atom economy will compare with the above reaction.
- (d) Now check your answer by calculating the atom economy.

Reaction type and atom economy

Chemical reactions are often classified as addition, elimination, substitution or re-arrangement. Some examples of each of these reaction types follow, with their atom economies calculated. In each case, the mass of 1 mol (the relative molecular mass in grams) of each species is given below its formula.

(You may find it a useful exercise to check that you can correctly name each of the organic compounds whose formulae appear in the four equations below.)

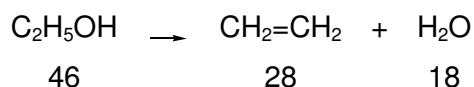
Addition



$$\text{Atom economy} = \frac{188}{(28 + 160)} \times 100\% = 100\%$$

You should be able to see without doing a calculation that the atom economy of *all* addition reactions is 100% because there is only one product and nothing is wasted.

Elimination



$$\text{Atom economy} = \frac{28}{46} \times 100 = 60.9\%$$

The atom economy of an elimination reaction can *never* be 100% because there is *always* a molecule wasted.

Substitution

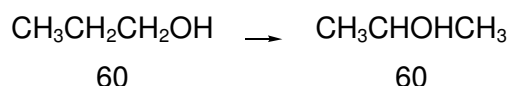


$$\text{Atom economy} = \frac{88}{(78.5 + 46)} \times 100\% = 70.7\%$$

The atom economy of a substitution reaction must always be less than 100% because there is always a molecule wasted. The atom economy is relatively low in this case because of the heavy chlorine atom that is ejected as part of the HCl.

- Q 8. (a) The main product of the reaction above is ethyl ethanoate ($\text{CH}_3\text{COOC}_2\text{H}_5$). Write the equation for the reaction of ethanoic acid with ethanol that also produces ethyl ethanoate as the main product.
- (b) Work out the atom economy of the reaction you have suggested, to confirm that it is greater than that of the reaction above that starts with ethanoyl chloride (CH_3COCl).
- (c) Explain why this reaction has a greater atom economy.
- (d) What disadvantages does the reaction starting from ethanoic acid have if you wish to prepare ethyl ethanoate?

Rearrangement



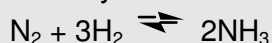
$$\text{Atom economy} = \frac{60}{60} \times 100\% = 100\%$$

The atom economy of all re-arrangement reactions is 100% as nothing is lost.

- Q 9. The above rearrangement reaction cannot easily be carried out in one step but it can be done in two.
- (a) Suggest a reaction scheme for bringing it about in two steps.
- (b) What is the probable effect on the yield of having to use two steps rather than one? Explain your answer.
- Q 10. (a) For each of the reactions below, draw the displayed formula (a formula showing every atom and every bond) of each reactant and product. Colour each atom that appears in the final product in green and each atom that does not in red. For each reaction, say what atoms would be in the 'waste box'. (Check also that you can name each of the organic compounds.)
- (i) $\text{C}_2\text{H}_5\text{OH} \longrightarrow \text{CH}_3\text{OCH}_3$
- (ii) $\text{CH}_3\text{COCH}_3 + \text{I}_2 \longrightarrow \text{CH}_3\text{COCH}_2\text{I} + \text{HI}$
- (iii) $\text{C}_6\text{H}_6 + 3\text{H}_2 \longrightarrow \text{C}_6\text{H}_{12}$
- (iv) $\text{C}_2\text{H}_5\text{I} \longrightarrow \text{CH}_2=\text{CH}_2 + \text{HI}$
- (b) Work out the atom economy for each of the reactions above. In each case assume that the first mentioned product (if there is more than one) is the one that is required.
- (c) Classify each reaction as one of the following types - addition, elimination, substitution and re-arrangement
- (d) (i) For reaction 10 (a) (iv), suggest a different starting material that would lead to the same organic product but with better atom economy.

(ii) Work out the atom economy of your proposed reaction to confirm that its value is lower than that for the reaction in 10 (a) (iv).

Q 11. The key reaction in the Haber process for the manufacture of ammonia is



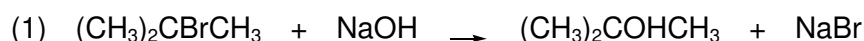
(a) Work out the atom economy for this reaction. (You should not need to do a calculation.)

(b) What does the symbol \rightleftharpoons suggest about the likely yield for the reaction?

Selectivity

Another concept, related to yield and atom economy that is used in synthetic organic chemistry is that of selectivity. Selectivity is concerned with controlling reactions so that the desired product is produced rather than competing side products.

The reaction of 2-bromo-2-methylpropane ((CH₃)₂CBrCH₃) with sodium hydroxide discussed above illustrates this idea. As we have seen, there are two possible products: 2-methylpropan-2-ol ((CH₃)₂COHCH₃) and methylpropene ((CH₃)₂C=CH₂). By changing the conditions of the reaction, it is possible to control the proportions of each that are produced. Carrying out the reaction at a relatively low temperature in **aqueous solution** favours the formation of the alcohol by reaction (1) while at high temperature and in alcoholic solution the formation of the alkene predominates by reaction (2).



Q 12. Classify each of the above reactions as addition, elimination, substitution or re-arrangement.

With the conditions under which 90% of methylpropene and 10% of 2-methylpropan-2-ol are produced, this is a fairly selective reaction. If 50% of each product were formed, it would be entirely unselective. Clearly, chemists favour selective reactions when designing syntheses.

Chemists distinguish different types of selectivity.

Chemoselectivity is the ability of a reagent to react with one functional group rather than another. For example sodium tetrahydridoborate(III) (sodium borohydride, NaBH₄) is a selective reducing agent; it will reduce C=O but not C=C. Hydrogen with a platinum or nickel catalyst is less selective; it will reduce both these functional groups.

Q 13. (a) Predict the products when CH₂=CHCH₂CHO is reduced with (i) sodium tetrahydridoborate(III) and (ii) hydrogen with a nickel catalyst.

(b) Sodium tetrahydridoborate(III) generates the ion H⁻ and it is this that carries out the first step of the reduction.

(i) Which of the functional groups C=O or C=C is polar?

(ii) Mark the polarity of this functional group using the symbols δ⁺ and δ⁻.

(iii) Use this to explain why sodium tetrahydridoborate(III) will reduce C=O but not C=C.

(iv) On the basis of your explanation predict whether sodium tetrahydridoborate(III) will reduce the -C≡N functional group.

Regioselectivity is the ability to produce one positional isomer rather than another. (Positional isomers differ in the point on the carbon chain where a functional group is attached.) The addition of reagents H-X across a double bond is an example of a regioselective reaction. Markovnikov's rule states that the hydrogen will add to the carbon that already has more hydrogen atoms bonded to it.

- Q 14. (a) What are the two possible products when hydrogen bromide adds on to propene ($\text{CH}_3\text{CH}=\text{CH}_2$)?
- (b) Which one does Markovnikov's rule predict will predominate? Hint: it will almost certainly help if you first draw out the displayed formulae (formulae showing every atom and every bond) of the two possible products.

Enantioselectivity is the ability of a reaction to produce one optical isomer rather than another. Optical isomers are pairs of mirror image isomers – they have virtually identical physical and chemical properties but often differ in their biological effects. (They can be distinguished by the fact that they rotate the plane of polarisation of polarised light in different directions.)

Most chemical reactions that make optical isomers produce a mixture containing equal amounts of the two isomers (called a **racemic mixture**), but reagents have been developed that can produce one rather than another. This is important in pharmaceutical chemistry because there are many cases where one of a pair of optical isomers is a safe and useful drug and the other has no activity or is even toxic. Ibuprofen (sold under the brand names Nurofen, Cuprofen and others) is a good example; one of the two **enantiomers** (called the *S*-form) is an effective pain-killing drug, the other (the *R*-form) is inactive. Because of the difficulty of separating the two, the drug is normally supplied as racemic (50 : 50) mixture of the two forms – an obvious source of waste which could be avoided if an enantioselective synthesis were used. There is more information about the synthesis of ibuprofen in *Ibuprofen – a case study in green chemistry*.

There are even more extreme examples where one optical isomer is a useful drug and the other is toxic. An example of this is penicillamine (not to be confused with penicillin). One optical isomer is an anti-arthritis drug, while its mirror image is toxic. Penicillamine is currently available as a racemic mixture but must be used with caution because one isomer is toxic to the heart and nervous system.

Enantioselective reactions are important for green chemistry because even if a racemic mixture can be separated, the unwanted component normally has to be thrown away.

Recently an enantioselective synthesis of the anti-inflammatory drug Naproxen has been developed using a special catalyst to add hydrogen across the double bond of a starting material in such a way that only one of the two possible optical isomers is produced, see Figure 1.

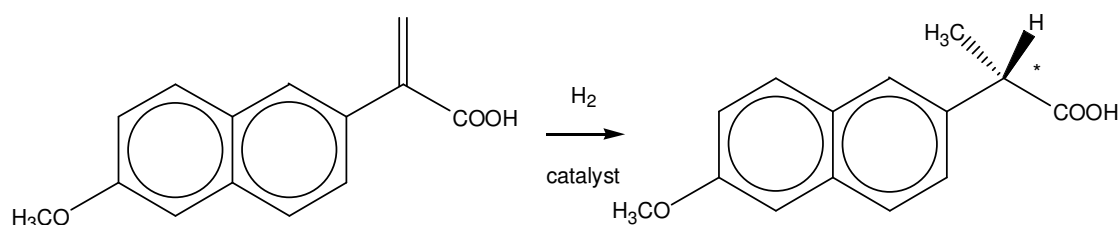


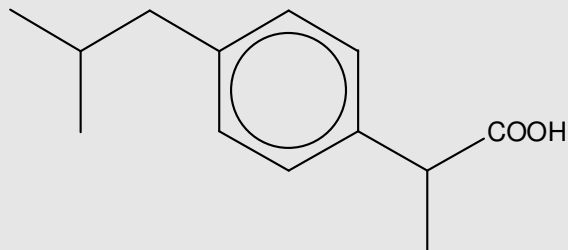
Figure 1 Part of the synthesis of Naproxen

However, at present, Naproxen is still made by a non-selective route and sold as a racemic mixture because changing the synthetic route would require expensive and time-consuming toxicological tests to be repeated.

Other chiral drugs, such as the penicillins, are made and sold as single optical isomers but they are made from naturally-occurring starting materials that are already single optical isomers.

Q 15. If an organic molecule has a carbon atom to which four different atoms or groups are bonded, it will exist as a pair of optical isomers. Such a carbon atom is called a chiral centre.

The skeletal formula of ibuprofen is given below.



(a) Draw the displayed formula (a formula showing every atom and every bond) of ibuprofen.

(b) Identify the chiral centre and mark it with a * on the formula.

Appendix

The principles of green chemistry

1. Prevention is better than cure – it is better to design processes that produce no waste than to produce waste and clean it up.
2. Processes should be designed to incorporate the maximum amount of the raw materials into the final product, thus reducing waste products.
3. Raw materials should come from renewable sources.
4. Energy requirements of processes should be minimised.
5. Catalysts are better than reagents that are used up in a process.
6. Chemical products should be designed so that they break down at the end of their useful life to form harmless products.
7. Methods of making chemicals should be designed to make products that cause no harm to human health or to the environment and that do not cause accidents such as explosions and fires.
8. Methods of making chemicals should be monitored to prevent the formation of hazardous substances.