



2022 JC1 H2 CHEMISTRY (9729)

ORGANIC CHEMISTRY

Topic 8: INTRODUCTION TO ORGANIC CHEMISTRY

Name: _____

Civics Group: _____

Introduction

Students should be able to:

- (a) interpret, and use the nomenclature, general formulae and displayed formulae of the following classes of compound:
- (i) hydrocarbons (alkanes, alkenes and arenes)
 - (ii) halogen derivatives (halogenoalkanes and halogenoarenes)
 - (iii) hydroxyl compounds (alcohols and phenols)
 - (iv) carbonyl compounds (aldehydes and ketones)
 - (v) carboxylic acids and derivatives (acyl chlorides and esters)
 - (vi) nitrogen compounds (amines, amides, amino acids and nitriles)
- (b) interpret, and use the following terminology associated with organic reactions:
- (i) functional group
 - (ii) degree of substitution: primary, secondary, tertiary, quaternary
 - (iii) homolytic and heterolytic fission
 - (iv) carbocation
 - (v) free radical, initiation, propagation, termination
 - (vi) electrophile (Lewis acid), nucleophile (Lewis base)
 - (vii) addition, substitution, elimination, condensation, hydrolysis
 - (viii) oxidation and reduction
- [in equations for organic redox reactions, the symbols [O] and [H] are acceptable]
- (c) interpret, and use the following terminology associated with organic reactivities:
- (i) delocalisation
 - (ii) electronic effect (electron-donating and electron-withdrawing effect)
 - (iii) steric effect (steric hindrance)
- (d) describe sp^3 hybridisation, as in ethane molecule, sp^2 hybridisation, as in ethene and benzene molecules, and sp hybridisation, as in ethyne molecule
- (e) explain the shapes of, and bond angles in, the ethane, ethene, benzene, and ethyne molecules in relation to σ and π carbon-carbon bonds
- (f) predict the shapes of, and bond angles in, molecules analogous to those specified in (e)
- (g) apply (b) and (c) to the understanding of mechanisms in terms of organic structure and bonding
- (h) recognise that the mechanisms of polar reactions involve the flow of electrons from electron-rich to electron-poor sites

Isomerism

Students should be able to:

- (a) describe constitutional (structural) isomerism
- (b) describe *cis-trans* isomerism in alkenes, and explain its origin in terms of restricted rotation due to the presence of π bonds
[use of *E*, *Z* nomenclature is **not** required]
- (c) explain what is meant by a chiral centre
- (d) deduce whether a given molecule is chiral based on the presence or absence of chiral centres and/or a plane of symmetry
- (e) recognise that an optically active sample rotates plane-polarised light and contains chiral molecules
- (f) recognise that enantiomers have identical physical properties except in the direction in which they rotate plane-polarised light
[usage of the term diastereomers is **not** required]
- (g) recognise that enantiomers have identical chemical properties except in their interactions with another chiral molecule
- (h) recognise that different stereoisomers exhibit different biological properties, for example in drug action
- (i) deduce the possible isomers for an organic molecule of known molecular formula
- (j) identify chiral centres and/or *cis-trans* isomerism in a molecule of given structural formula

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REFERENCES

1. **Chemistry (for CIE AS Texts) by David G. Morris & A Level) by Peter Cann & Peter Hughes**
2. **Cambridge International AS and A Level Chemistry Revision Guide** by Judith Potter and Peter Cann
3. **Organic Chemistry (Eleventh Edition)** by Graham Solomons, Craig Fryhle & Scott Snyder
4. **Organic Chemistry** by John McMurry
5. **Keynotes in Organic Chemistry (Second Edition)** by Andrew F. Parsons
6. **Guidebook to Mechanism in Organic Chemistry (Sixth Edition)** by Peter Skyes
7. **Stereochemistry (RSC Tutorial Chemistry)**

1 Introduction

Organic chemistry, one of the major branches of chemistry, is concerned with

“the study of the *structure, properties, composition, reactions, and preparation* of **carbon-containing compounds**, which include not only hydrocarbons but also compounds with any number of other elements, such as hydrogen (most compounds contain at least one carbon–hydrogen bond), nitrogen, oxygen, halogens, phosphorus, silicon, and sulfur”.

Carbon is special in that

- it has a strong tendency to form long chains and/or rings of carbon atoms due to strength of the carbon–carbon bond
- it can form four bonds with neighbouring atoms which allows for significant branching on carbon chains
- It forms strong π -bonds, making double and triple bonds possible within the structures

Hence, it can form a vast array of compounds, from the simple methane with one carbon atom, to the complex DNA with tens of billions of carbon atoms.

In the study of organic chemistry, we will make use of concepts that we have learnt in **Chemical Bonding** related to **covalent bonding** (e.g., sigma (σ) and pi (π) bonds, dative bonds, polarity of bonds and molecules) and **intermolecular forces** (e.g., instantaneous dipole–induced dipole attraction, permanent dipole–permanent dipole attraction, hydrogen bonds).

Before we go further into the topic, use Self Check 1A below to do a quick self-assessment of your grasp of these essential concepts.

Self-Check 1A

Are the following statements true or false?

(a)	A covalent bond is formed when electrons are shared between two atoms.	True / False
(b)	σ bonds can be formed from either the head-on or side-on overlaps of orbitals.	True / False
(c)	A double bond is composed of two π bonds.	True / False
(d)	The longer the bond, the stronger the bond.	True / False
(e)	A dative bond is formed when one atom donates both electrons that are shared between two atoms.	True / False
(f)	The donor atom in a dative bond has a filled orbital, while the acceptor atom has an accessible vacant orbital.	True / False
(g)	CCl_4 is a polar molecule as the C–Cl bond is polar.	True / False
(h)	The more polar a bond, the stronger the bond.	True / False
(i)	$\text{CH}_3\text{CH}_2\text{OH}$ forms intermolecular hydrogen bonds.	True / False
(j)	CH_3CHO forms intermolecular hydrogen bonds.	True / False

2 Representations in Organic Chemistry

LO (a) interpret, and use the nomenclature, general formulae and displayed formulae of hydrocarbons, halogen derivatives, hydroxyl compounds, carbonyl compounds, carboxylic acids and derivatives, nitrogen compounds

2.1 Formulae of Organic Compounds

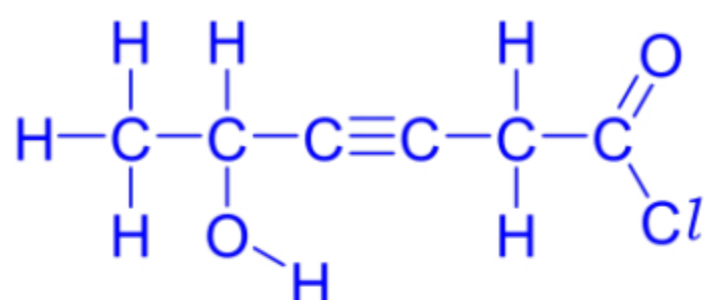
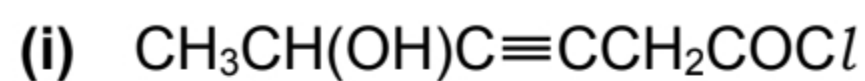
We can show the elements present in an organic compound and their relative proportions in a few different ways.

The following different formulae are illustrated using **lactic acid**, $\text{C}_3\text{H}_6\text{O}_3$.

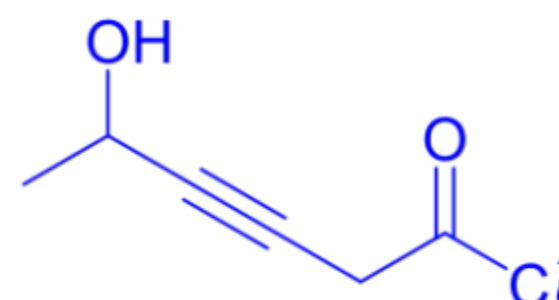
	type of formula	what it shows	representation of lactic acid
1	empirical formula	- shows the simplest ratio of the number of atoms of the elements present in one molecule of a compound - order usually follows alphabetical order of symbols. However, for organic compounds, because carbon and hydrogen are always present, C is always cited first, H second and then the rest, in alphabetical order.	CH_2O
2	molecular formula	shows the actual number of atoms of the elements present in one molecule	$\text{C}_3\text{H}_6\text{O}_3$
3	constitutional formula	shows how the constituent atoms of a molecule are joined together with minimal detail, using conventional groups, for an unambiguous structure	$\text{CH}_3\text{CH}(\text{OH})\text{CO}_2\text{H}$
4	full structural or displayed formula	detailed structure of molecule showing the relative position of atoms and the number of bonds between them	
5	skeletal formula	simplified representation of an organic formula derived from the structural formula by removing hydrogen atoms bonded to carbon atoms (and their associated bonds) and carbon atoms, leaving just the carbon-carbon bonds in the carbon skeleton and the associated functional groups	
6	stereochemical formula	shows spatial arrangement of bonds, atoms and groups in molecule in 3-dimension	

Example 2A

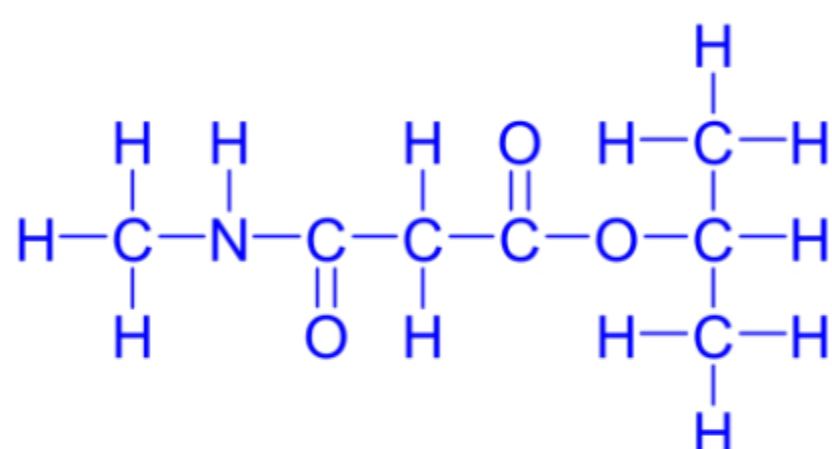
Write the **full structural** and **skeletal formulae** of the following compounds.



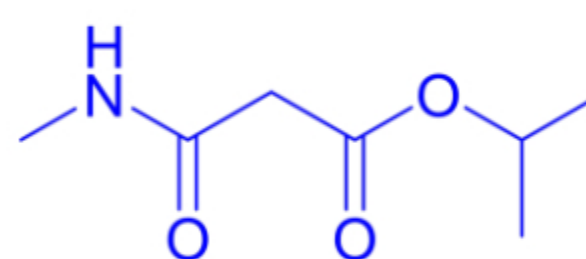
full structural formula



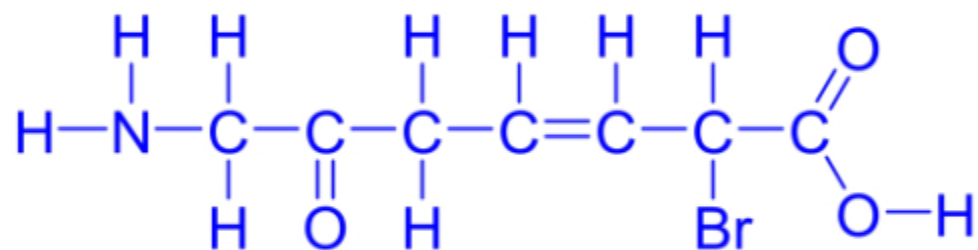
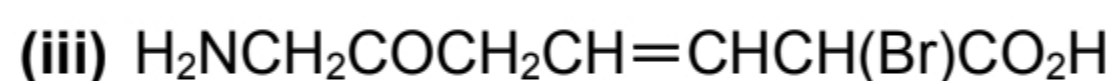
skeletal formula



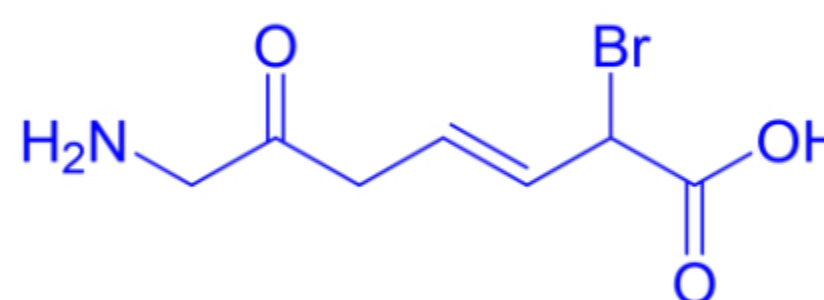
full structural formula



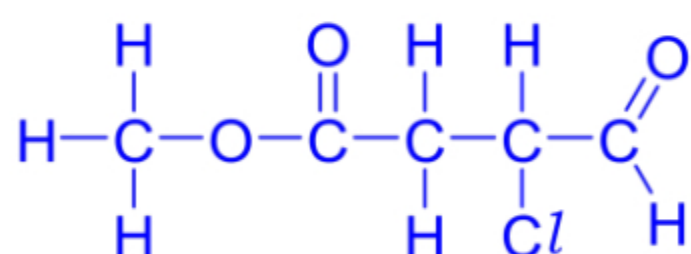
skeletal formula



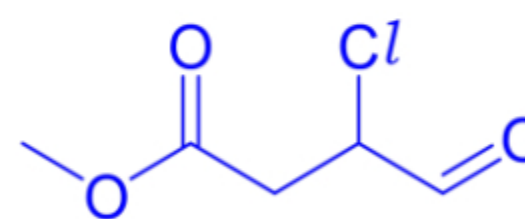
full structural formula



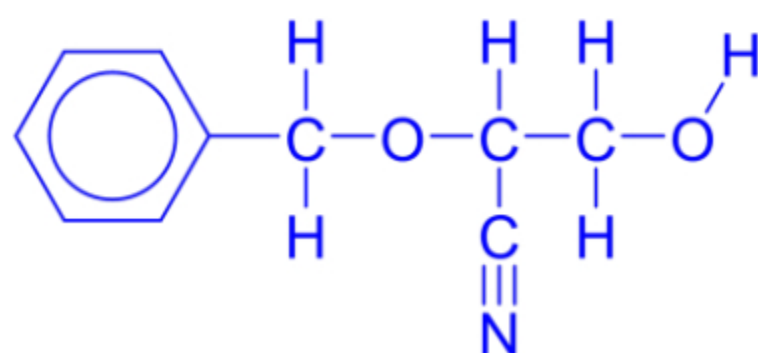
skeletal formula



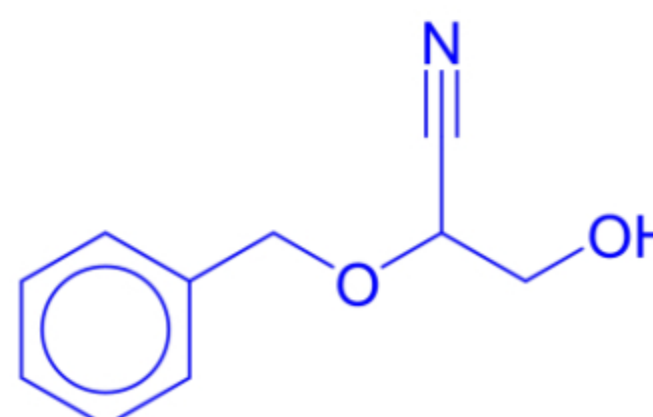
full structural formula



skeletal formula



full structural formula



skeletal formula

3 Classification of Organic Compounds

LO (b) interpret, and use the following terminology associated with organic reactions:
 (i) functional group
 (ii) degree of substitution: primary, secondary, tertiary, quaternary

Organic compounds are thought of as consisting of a relatively **unreactive backbone**, e.g., a chain of sp^3 hybridised carbon atoms, and one or several **functional groups**. Names of organic compounds are derived from the functional group(s) and main carbon chain.

3.1 Nature of structure

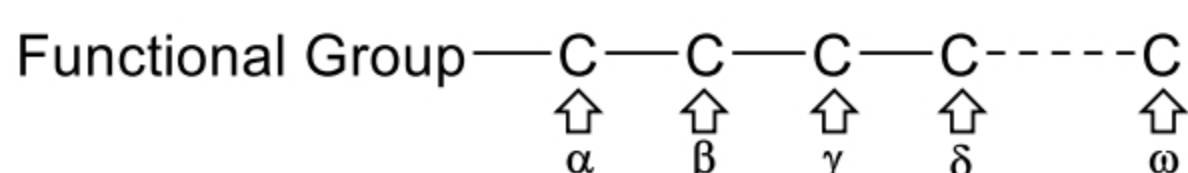
We can categorise organic compounds based on the nature of their carbon skeletons:

- **saturated:** compounds such as alkanes, whose molecules contain only *single bonds*, are referred to as saturated compounds **because these compounds contain the maximum number of hydrogen atoms that the carbon compound can possess**
- **unsaturated:** compounds with *multiple bonds*, such as alkenes, alkynes, and aromatic hydrocarbons, are said to be unsaturated because they possess **fewer than the maximum number of hydrogen atoms**, and are capable of reacting with hydrogen under the proper conditions
- **aliphatic:** acyclic (compounds with no ring of atoms) or cyclic (compounds containing ring of atoms), saturated or unsaturated carbon compounds, excluding aromatic compounds
- **aromatic:** a cyclically conjugated molecular entity with a stability (due to delocalisation) significantly greater than that of a hypothetical localised structure is said to possess aromatic character; In the traditional sense, 'having a chemistry typified by benzene'

3.2 Functional groups

The **functional group** is an atom, or a group of atoms that has similar chemical properties whenever it occurs in different compounds. It defines the characteristic **physical and chemical properties** of families of organic compounds.

The carbon atom on which the functional group is attached to is known as the **alpha (α) carbon**. The naming continues as beta (β), gamma (γ), delta (δ), ..., until the last carbon in the chain, which is termed the omega (ω) carbon.



A series of compounds with the **same functional group**, where each member differs from the next member by a **constant CH_2 unit** is called a **homologous series**. Members of a homologous series are called homologs.

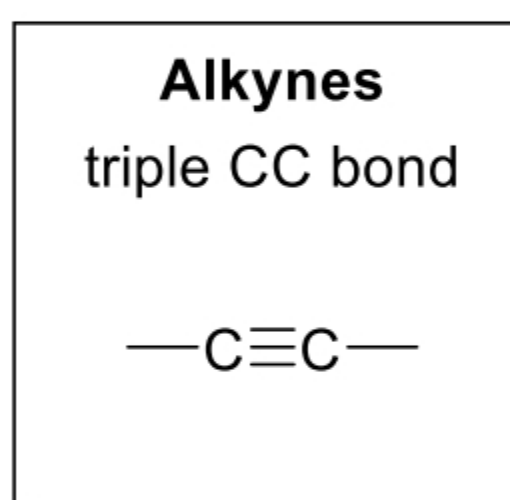
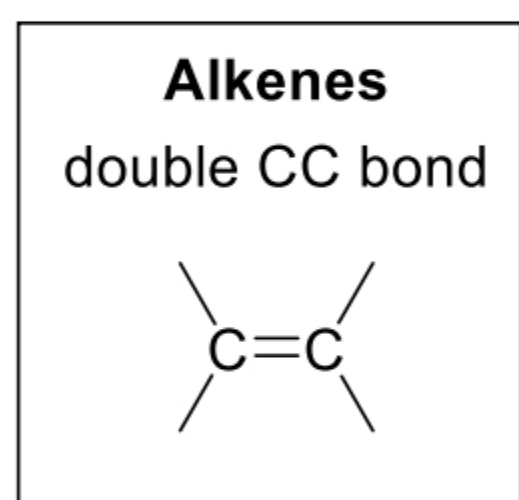
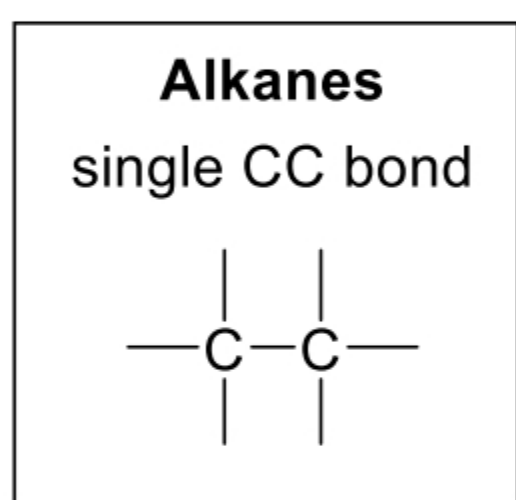
All compounds in any one homologous series

- can be represented by a general formula
- have a relative molecular mass 14 (corresponding to one CH_2 unit) greater than the preceding compound in the series
- can be prepared by similar methods
- have similar chemical properties
- exhibit a regular gradation of physical properties (due to the increasing size of hydrocarbon chain)

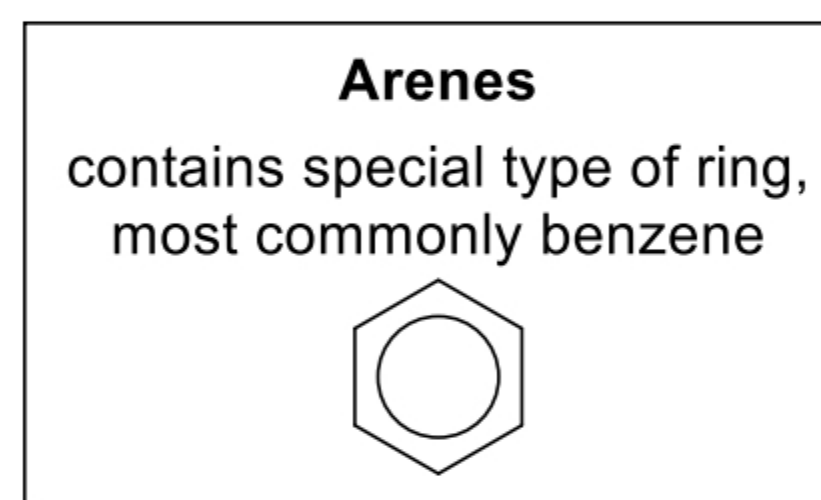
Here are the common functional groups you will encounter:

Hydrocarbons (compounds that contain only carbon and hydrogen atoms)

Aliphatic

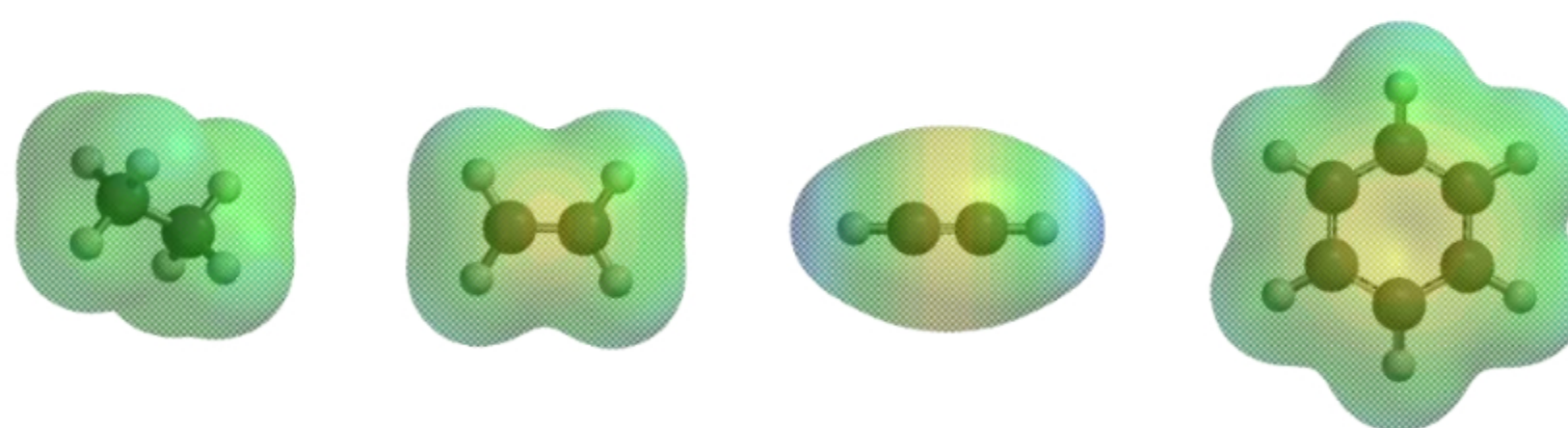


Aromatic



Technically, alkanes do not have any functional group.

From the electrostatic potential maps for ethane, ethene, ethyne and benzene, it can be seen that ethane is **non-polar** (generally green), while there are regions of **higher electron density** (yellow→red) in the other three due to the π **bond/system**.



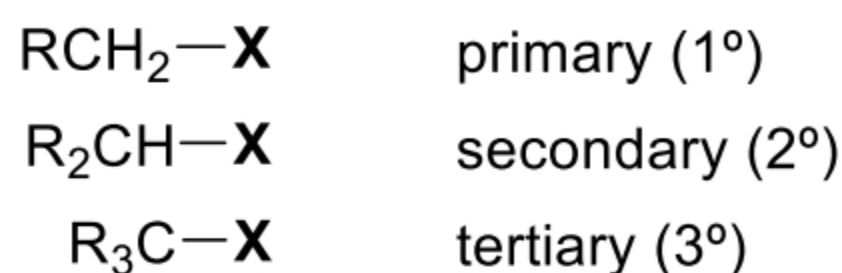
This is generally true for alkanes in that the C—C and C—H bonds are **essentially** non-polar and hence they are unreactive towards polar (charged) reagents, and forms the **unreactive skeleton** of most organic compounds.

Carbon bonded to electronegative atoms

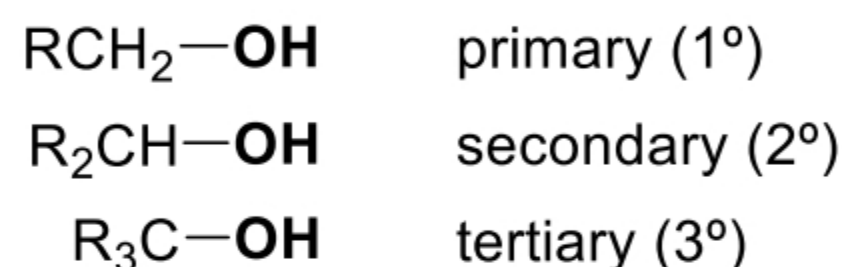
- **Single bond** (R is the carbon framework, typically an alkyl group; see 3.3)

Aliphatic

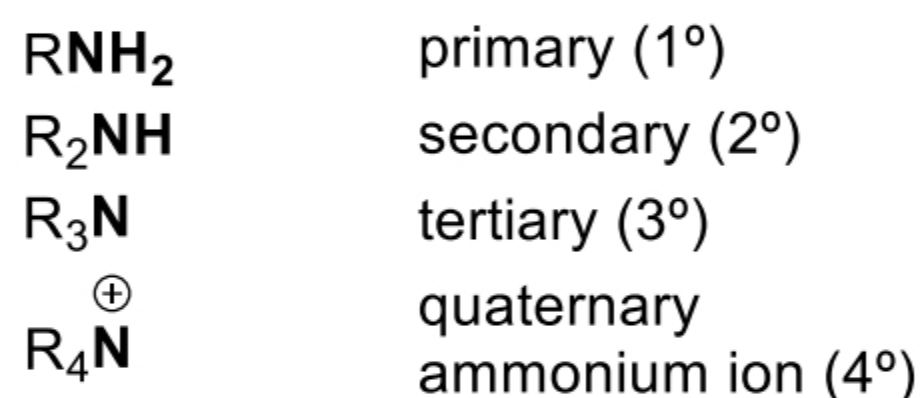
Halogenoalkanes (X = F, Cl, Br, I)



Alcohols

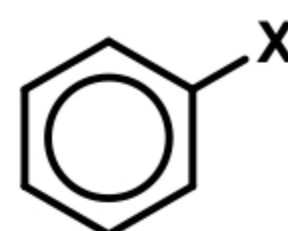


Amines

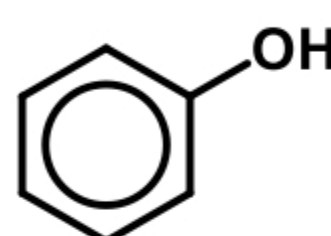


Aromatic

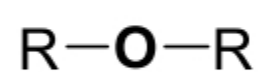
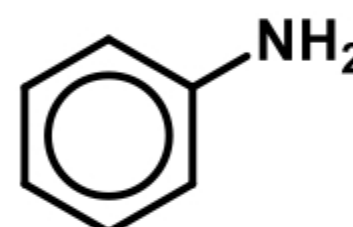
Halogenoarenes (X = F, Cl, Br, I)



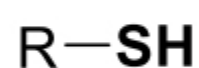
Phenol



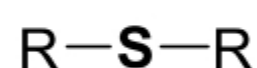
Phenylamine (Aniline)



Ether



Thiol

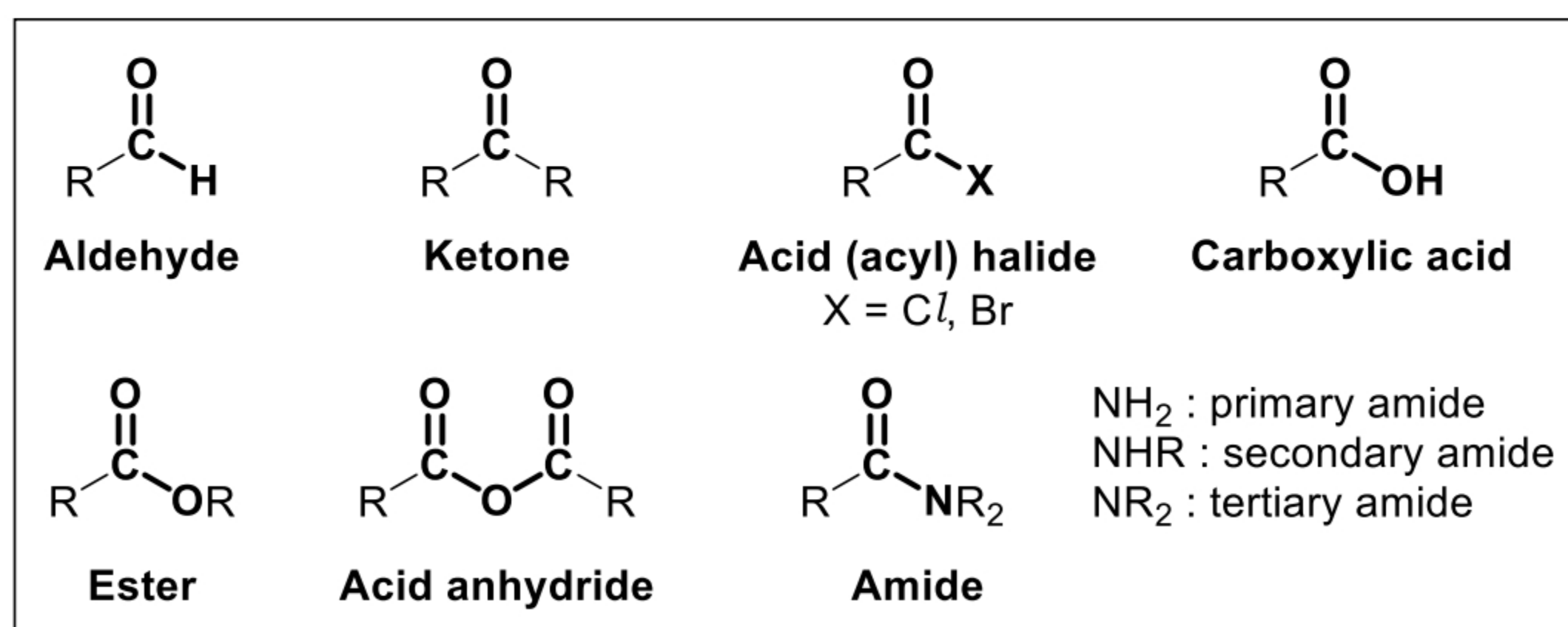


Sulfide (Thioether)



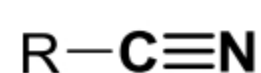
Nitro compound

- **Double bond to oxygen**



(Note: Both the R-groups for ketone, ester and acid anhydride may not be the same.)

- **Triple bond to nitrogen**

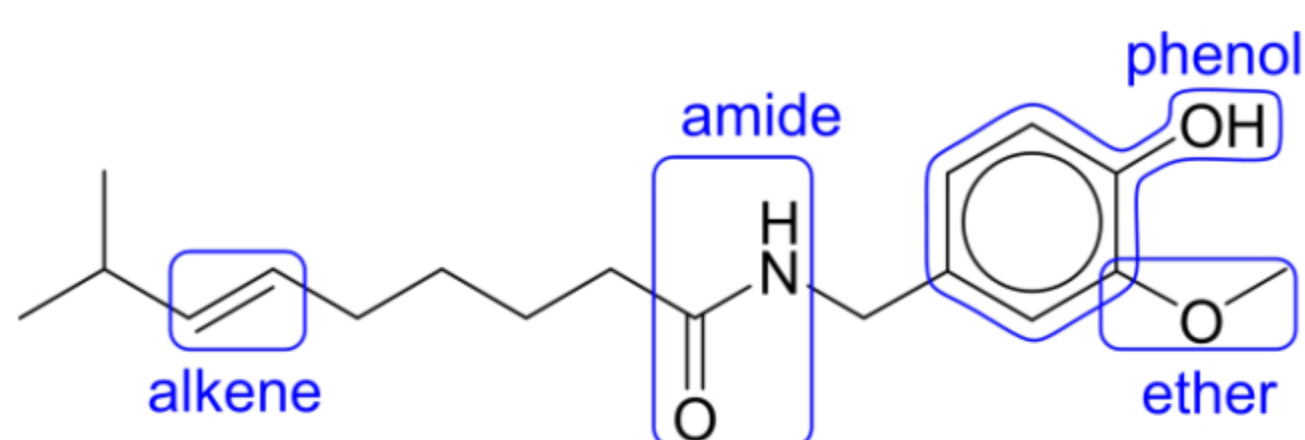


Nitrile

Example 3A

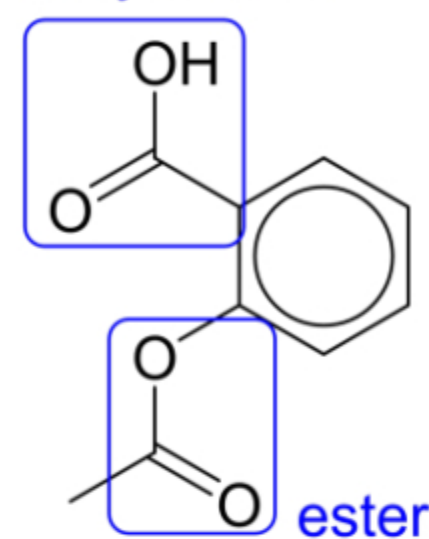
Name and circle the functional groups present in each of the compounds shown below.

(i)

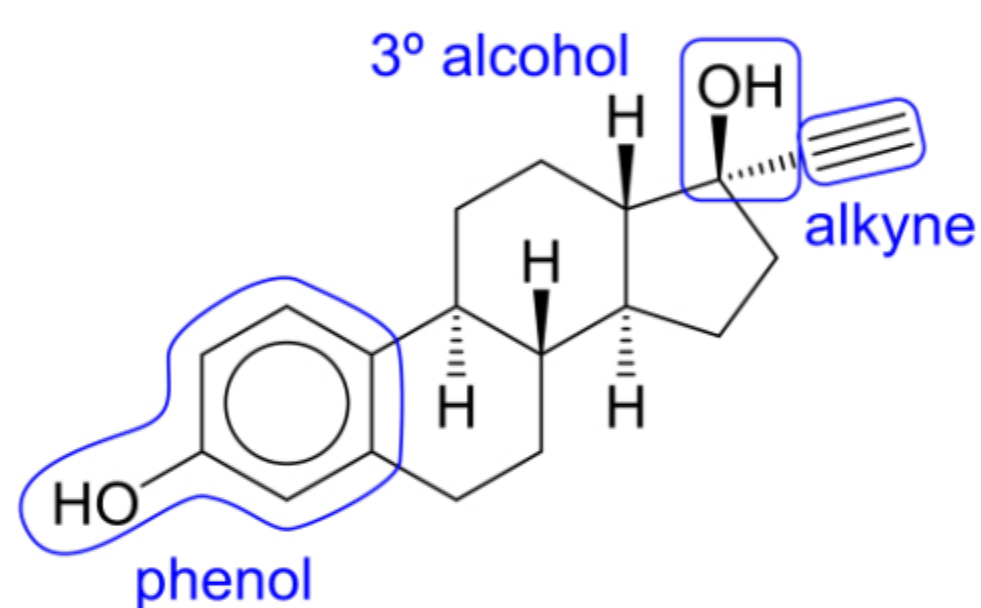
**capsaicin**

(ii)

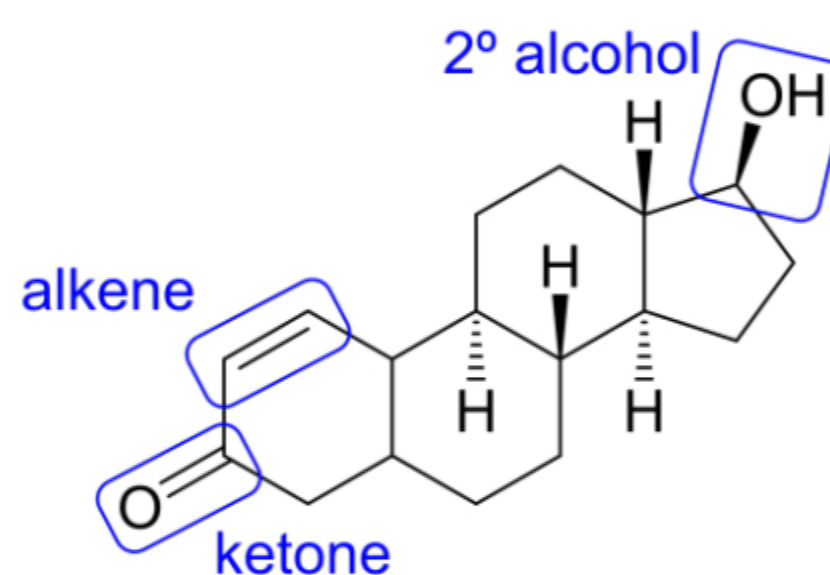
carboxylic acid

**aspirin**

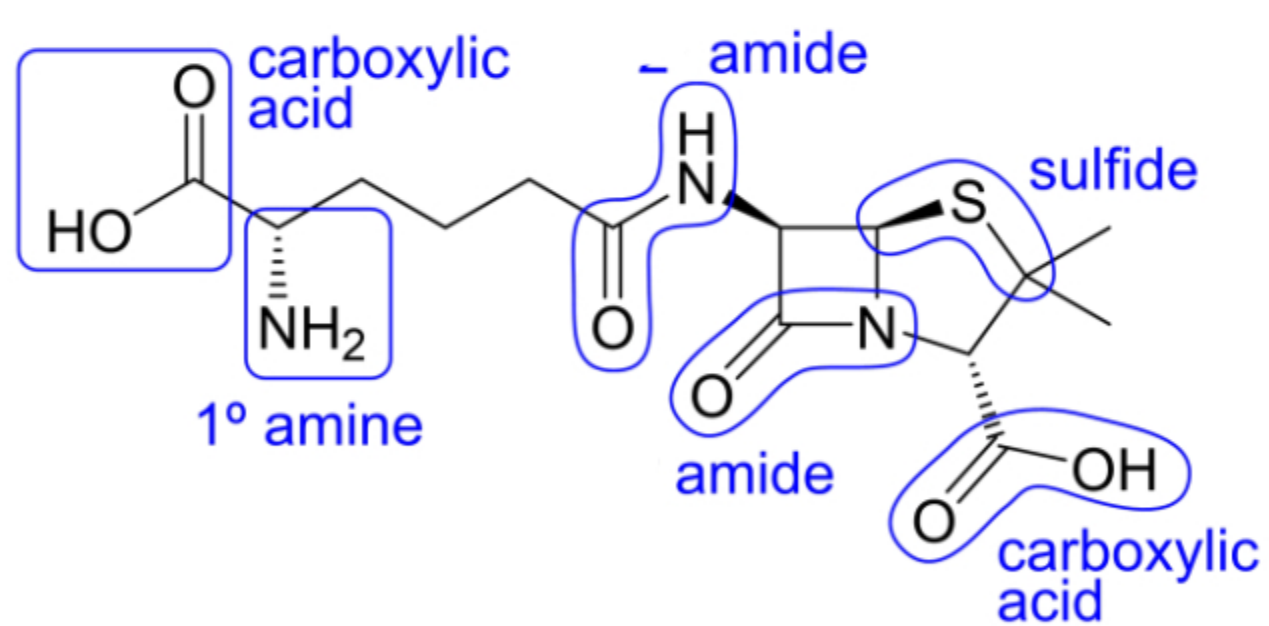
(iii)

**estrogen**

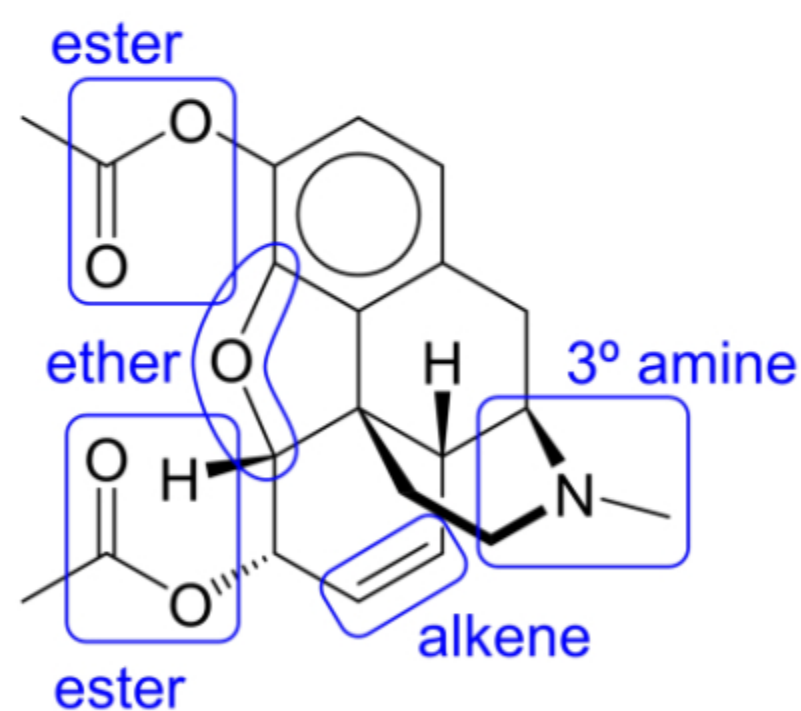
(iv)

**testosterone**

(v)

**isopenicillin N**

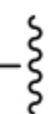
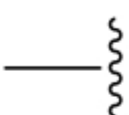
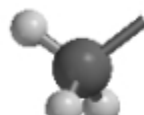
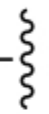
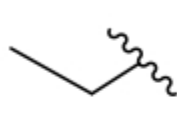
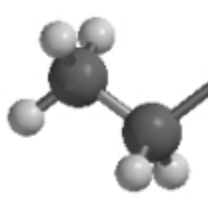
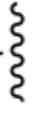
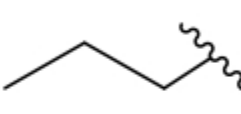
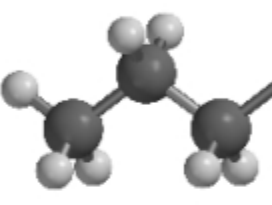
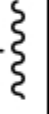
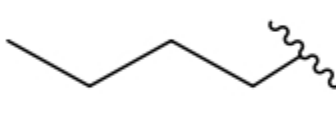
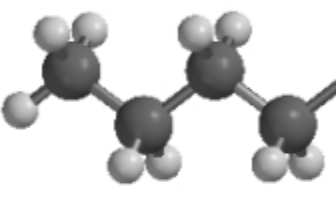
(vi)

**heroin**

3.3 Alkyl and Aryl Groups

When a hydrogen atom is removed from an alkane, this gives an **alkyl group**. The symbol **R** is used to represent a general alkyl group (*i.e.*, a methyl, ethyl, etc. group).

Alkanes have the general formula, C_nH_{2n+2} . So the **general formula for alkyl chains is $C_nH_{2n+1}-$** .

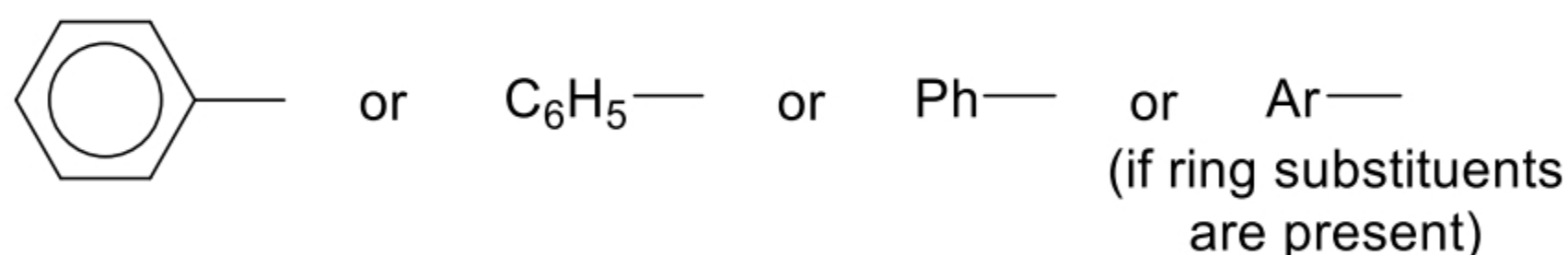
alkane	alkyl group	abbreviation	bond-line	ball-and-stick model
CH ₃ —H methane	H ₃ C—  methyl	Me—		
CH ₃ CH ₂ —H ethane	CH ₃ CH ₂ —  ethyl	Et—		
CH ₃ CH ₂ CH ₂ —H propane	CH ₃ CH ₂ CH ₂ —  propyl	Pr—		
CH ₃ CH ₂ CH ₂ CH ₂ —H butane	CH ₃ CH ₂ CH ₂ CH ₂ —  butyl	Bu—		

FYI: Ball-and-Stick Model

- Displays both the three-dimensional position of the atoms and the bonds between them
- Atoms are typically represented by spheres, bonds are represented by rods

Similarly, groups derived from arenes by removal of a hydrogen atom from an aromatic ring carbon atom are known as **aryl groups**. The symbol **Ar** is used to represent a general aryl group.

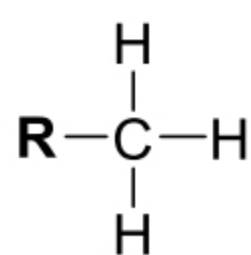
When a benzene ring is attached to some other group of atoms in a molecule, it is called a **phenyl group**, and it is represented in several ways:



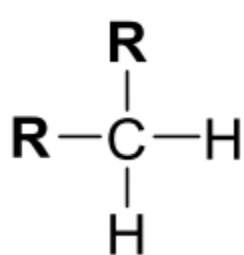
3.4 Degree of Substitution

Degree of substitution in an organic molecule is based on the **number of carbon atom(s)** (generally also the **number of alkyl group(s)**) bonded to the atom of interest.

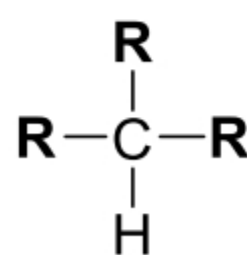
In the case of alkanes:



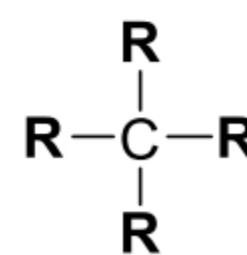
A primary (or 1°) carbon is bonded to one other carbon



A secondary (or 2°) carbon is bonded to two other carbons



A tertiary (or 3°) carbon is bonded to three other carbons



A quaternary (or 4°) carbon is bonded to four other carbons

For **alcohols and halogenoalkanes**, this is based on the number of carbon atom(s) attached to the α -carbon; while for **amines and amides**, it is based on the number of carbon atom(s) attached to the **nitrogen atom**.

	Halogenoalkanes	Alcohols		Amines
primary (1°)	RCH_2X	RCH_2OH	primary (1°)	RNH_2
secondary (2°)	R_2CHX	R_2CHOH	secondary (2°)	R_2NH
tertiary (3°)	R_3CX	R_3COH	tertiary (3°)	R_3N
			quaternary ammonium ion (4°)	R_4N^+

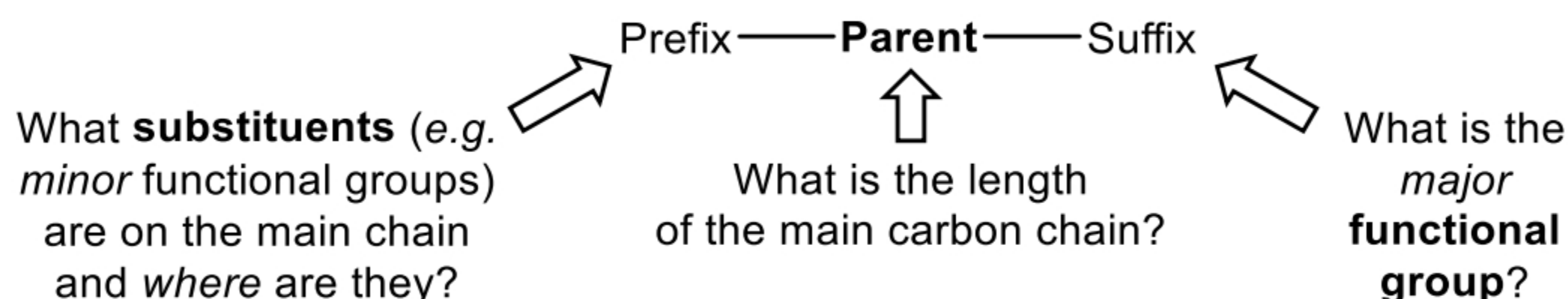
Checkpoint

- ☐ I am able to differentiate the categories of organic compounds based on the nature of their carbon skeletons: **saturated, unsaturated, aliphatic and aromatic**. For e.g., an organic molecule that contain double ($\text{C}=\text{C}$, $\text{C}=\text{O}$, etc) and/or triple ($\text{C}\equiv\text{C}$, $\text{C}\equiv\text{N}$, etc) bond(s) is considered unsaturated.
- ☐ I know that compounds with same functional groups have similar chemical properties BUT different physical properties (e.g., melting and boiling points).
- ☐ I am able to differentiate the different functional groups as characterised by their different structures. For e.g., alkenes contain $\text{C}=\text{C}$, alcohols consist of $-\text{OH}$ group, and esters consist of $-\text{COO}$ group.
- ☐ I am able to differentiate **primary (1°), secondary (2°) and tertiary (3°) carbons** by looking at the degree of substitution in an organic molecule based on the number of carbon atom(s) (generally also the **number of alkyl group(s)**) bonded to the atom of interest.

4 Organic Nomenclature

LO (a) interpret, and use the nomenclature, general formulae and displayed formulae of hydrocarbons, halogen derivatives, hydroxyl compounds, carbonyl compounds, carboxylic acids and derivatives, nitrogen compounds

The **IUPAC** (International Union of Pure and Applied Chemistry) name of an organic compound is composed of **three** parts.



There are **four** key steps in naming organic compounds.

- Find the longest carbon chain and name this as an **alkane**. This is the **parent** name.

no. of carbons	alkane name
1	methane
2	ethane
3	propane
4	butane
5	pentane
6	hexane

no. of carbons	alkane name
7	heptane
8	octane
9	nonane
10	decane
11	undecane
12	dodecane

- Identify the major functional group. Replace *-ane* (in the alkane) with a **suffix** (see Table 4.1).

If there is **more than one functional group** present in the molecule, the one of **highest priority** as stated below is the **principal functional group**, and is named by the **suffix**. All other function group(s) are substituents, and will be named using the prefix(es).

Refer to this list for the functional group priorities:

carboxylic acid (RCO_2H) > ester (RCO_2R) > acid (acyl) chloride (RCOCl) > amide (RCONH_2) > nitrile (RCN) > aldehyde (RCHO) > ketone (RCOR) > alcohol (ROH) > phenol ($\text{C}_6\text{H}_5\text{OH}$) > amine (RNH_2) > benzene (C_6H_6) > alkene (RCH=CHR) > alkyne ($\text{RC}\equiv\text{CR}$) > alkane (RH) > ether (ROR) > sulfide (RSR) > halogenoalkane (RX) > nitro compound (RNO_2)

- Number the atoms in the main chain. Begin at the end nearer the **major** functional group and give this the **lowest** number. For alkanes, begin at the end nearer the first branch point.
- Identify the substituents (e.g. minor functional groups) on the main chain and their number. The substituent name and position is the **prefix** (see Table 4.1).

The names of two or more different substituents should be included in **alphabetical order** in the prefix (e.g. hydroxy before methyl). If two substituents happen to be on the **same carbon**, they are given the **same number**.

A **multiplier** is used in the prefix or suffix to indicate the presence of two or more of the minor or major functional groups (or substituents).

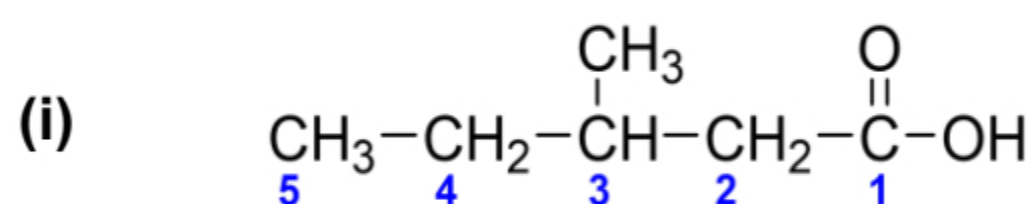
number	multiplier
1*	mono-
2	di-
3	tri-
4	tetra-
5	penta-

number	multiplier
6	hexa-
7	hepta-
8	octa-
9	nona-
10	deca-

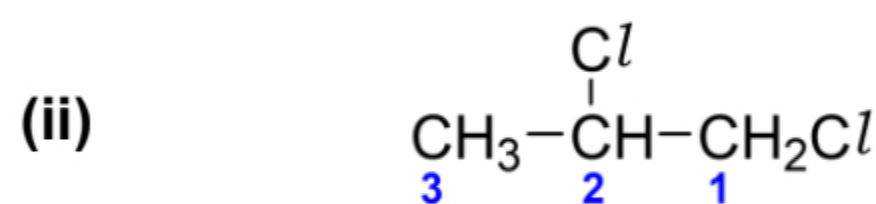
* The multiplier 'mono-' for one substituent is seldom used in the actual naming, but rather, is used in comparison to molecules with more than one substituent.

Example 4A

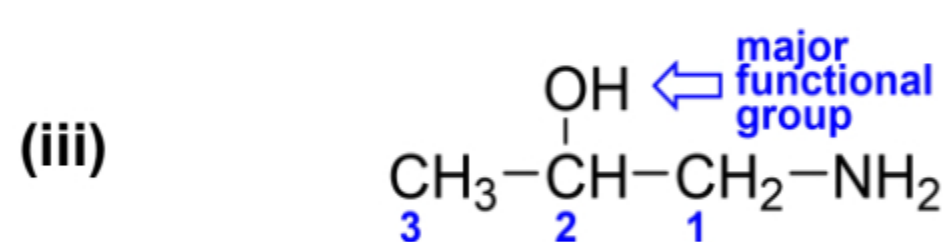
Write the IUPAC name of the following compounds.



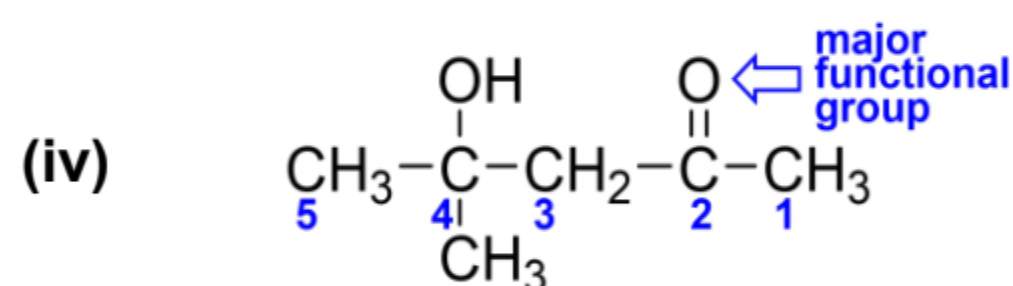
3-methylpentanoic acid



1,2-dichloropropane



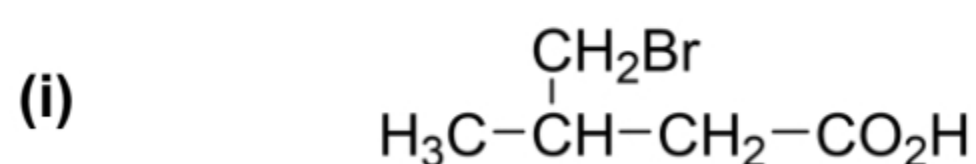
1-aminopropan-2-ol



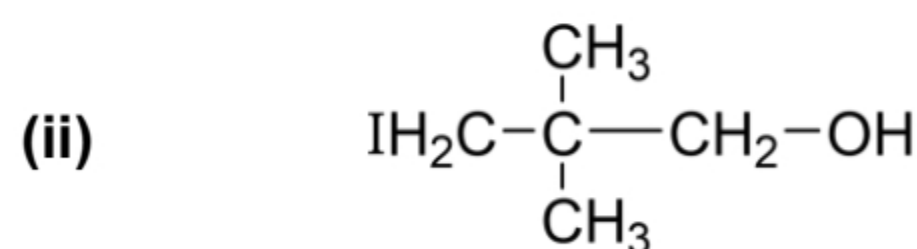
4-hydroxy-4-methylpentan-2-one

Self-Check 4A

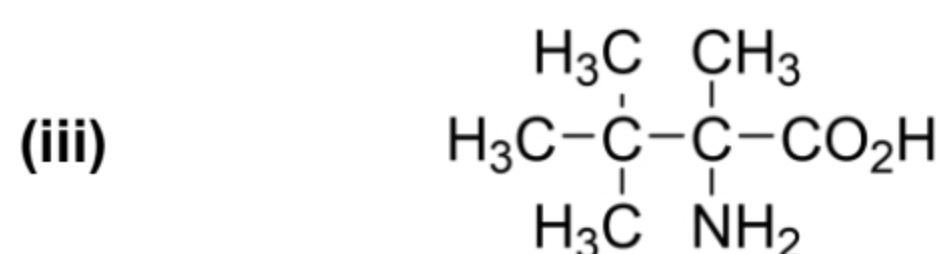
Write the IUPAC name of the following compounds.



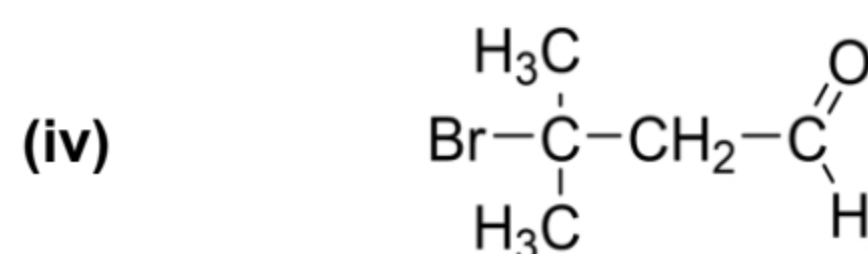
4-bromo-3-methylbutanoic acid



3-iodo-2,2-dimethylpropan-1-ol

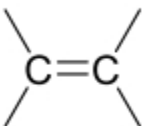
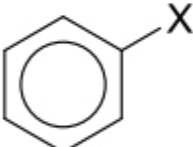
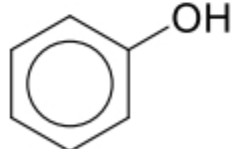
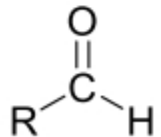


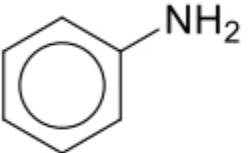
2-amino-2,3,3-trimethylbutanoic acid



3-bromo-3-methylbutanal

Table 4.1: Prefixes and suffixes of functional groups

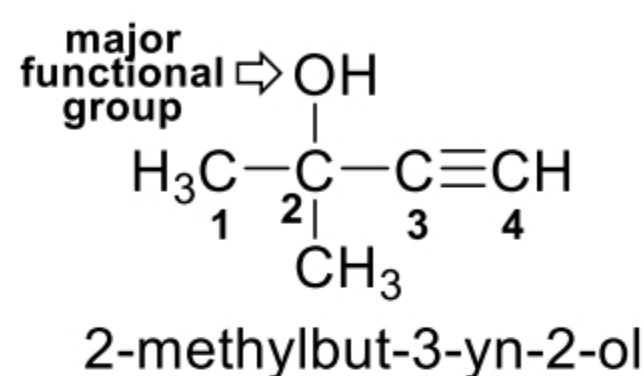
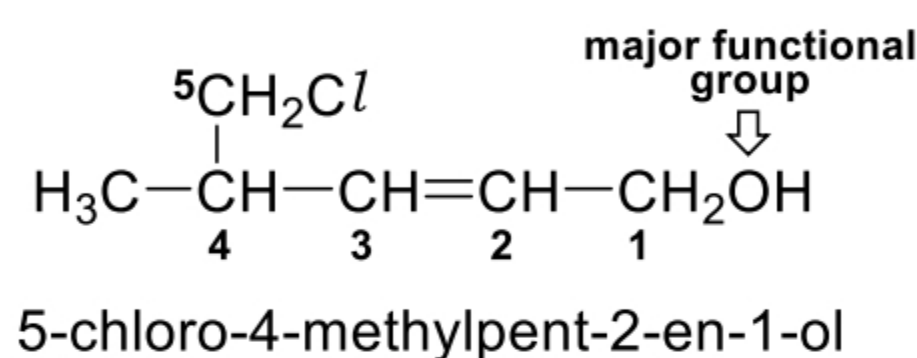
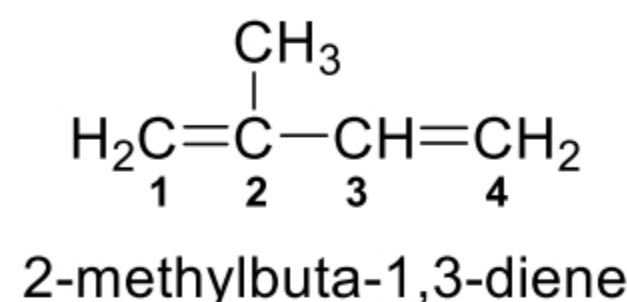
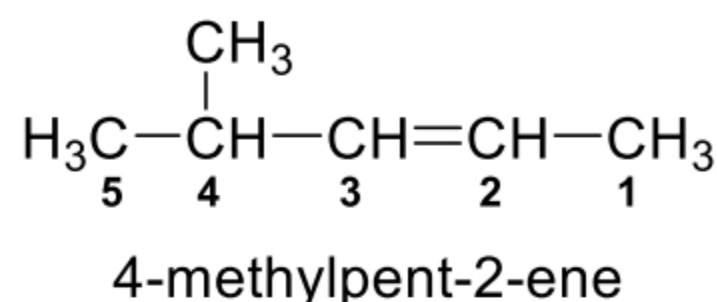
class of compound	structure of functional group	prefix (minor functional group)	suffix (major functional group)
alkane	—	alkyl- (see 3.3 for more details)	-ane
alkene		alkenyl-	-ene
alkyne	—C≡C—	alkynyl-	-yne
arene		phenyl- (see 3.3 for more details)	-benzene
halogenoalkane	$\text{RCH}_2\text{-X}$ primary (1°) $\text{R}_2\text{CH-X}$ secondary (2°) $\text{R}_3\text{C-X}$ tertiary (3°) where X = F, Cl, Br, I	fluoro- chloro- bromo- iodo-	alkyl fluoride alkyl chloride alkyl bromide alkyl iodide
halogenoarene	 where X = F, Cl, Br, I	fluoro- chloro- bromo- iodo-	aryl fluoride aryl chloride aryl bromide aryl iodide
alcohol	$\text{RCH}_2\text{-OH}$ primary (1°) $\text{R}_2\text{CH-OH}$ secondary (2°) $\text{R}_3\text{C-OH}$ tertiary (3°)	hydroxy-	-ol
phenol		(hydroxyphenyl)-	-phenol
aldehyde		formyl-	-al

class of compound	structure of functional group	prefix (minor functional group)	suffix (major functional group)
ketone	$\begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C}-\text{R} \end{array}$	oxo- (=O) or alkanoyl ($-\text{C}(=\text{O})\text{R}$)	-one
amine	RNH_2 primary (1°) R_2NH secondary (2°) R_3N tertiary (3°) R_4N^+ quaternary (4°)	amino-	-amine
phenylamine		<i>N</i> -phenylamino-	-phenylamine
amide	$\begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C}-\text{NR}_2 \end{array}$ NH_2 : primary amide NHR : secondary amide NR_2 : tertiary amide	carboxamido- or carbamoyl-	-amide
nitro compound	$\text{R}-\text{NO}_2$	nitro-	—
nitrile	$\text{R}-\text{C}\equiv\text{N}$	cyano-	-nitrile
carboxylic acid	$\begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C}-\text{OH} \end{array}$	carboxy-	-oic acid
acid(acyl) halide	$\begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C}-\text{X} \end{array}$ where X = Cl, Br	carbonohalidoyl-	-oyl chloride -oyl bromide
ester	$\begin{array}{c} \text{O} \\ \parallel \\ \text{R}-\text{C}-\text{OR} \end{array}$	alkanoyloxy ($\text{RCOO}-$) or alkoxycarbonyl ($\text{ROCO}-$)	alkyl alkanoate
ether	$\text{R}-\text{O}-\text{R}$	alkoxy-	alkyl ether

4.1 Special cases

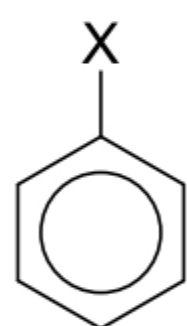
Alkenes and alkynes

The position of the double or triple bond is indicated by the number of the **lowest** carbon atom in the alkene or alkyne.



Aromatics

Monosubstituted benzene derivatives are usually named after benzene (C₆H₆), although some non-systematic or common names (in brackets) are still used.



X	name
H	benzene
Br	bromobenzene
Cl	chlorobenzene
NO ₂	nitrobenzene

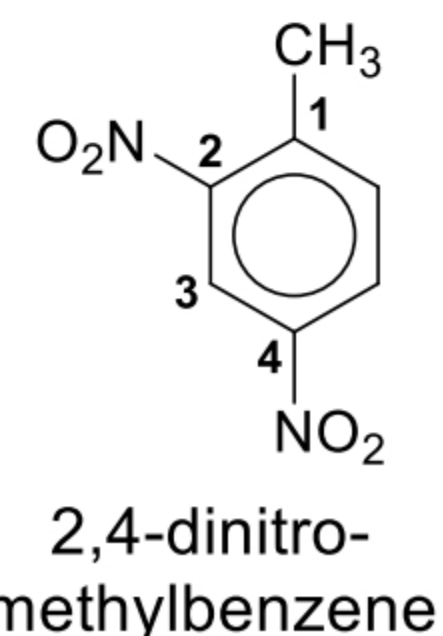
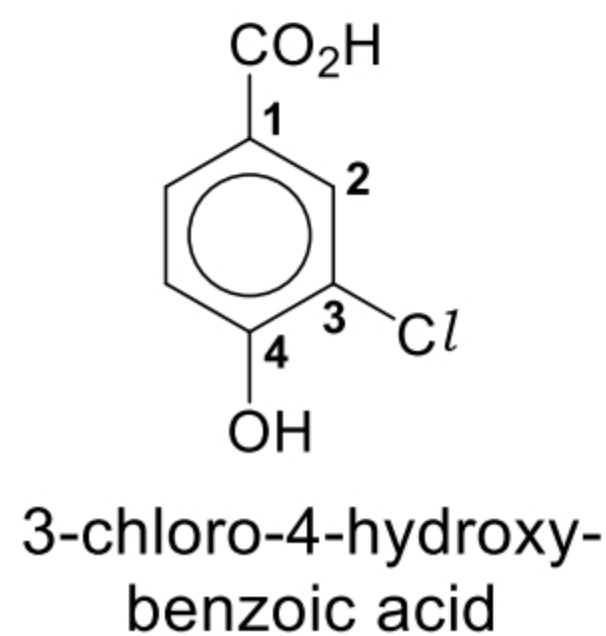
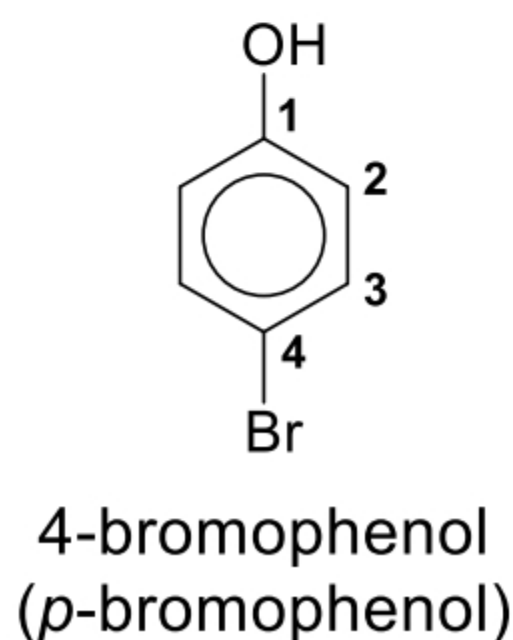
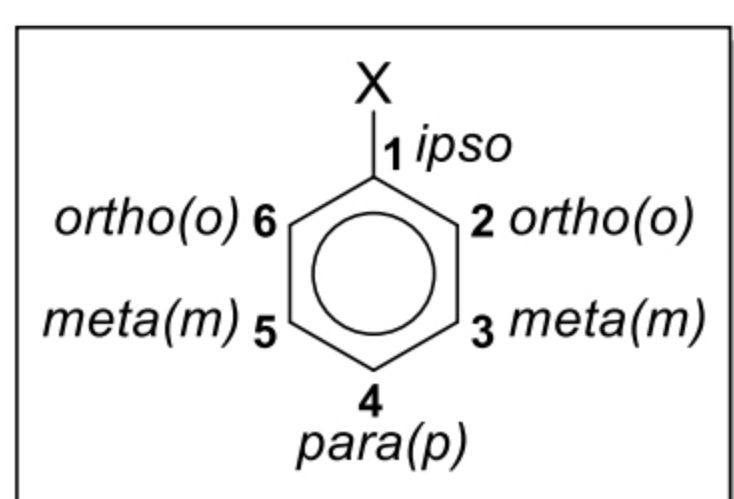
X	name
CH ₃	methylbenzene (toluene)
CH=CH ₂	ethenylbenzene (styrene)
OH	hydroxybenzene (phenol)
NH ₂	aminobenzene (aniline)
CN	cyanobenzene (benzonitrile)

The word benzene comes first when functional groups of higher priority (than benzene) are on the ring

X	name
CHO	benzenecarboxaldehyde (benzaldehyde)
CO ₂ H	benzenecarboxylic acid (benzoic acid)

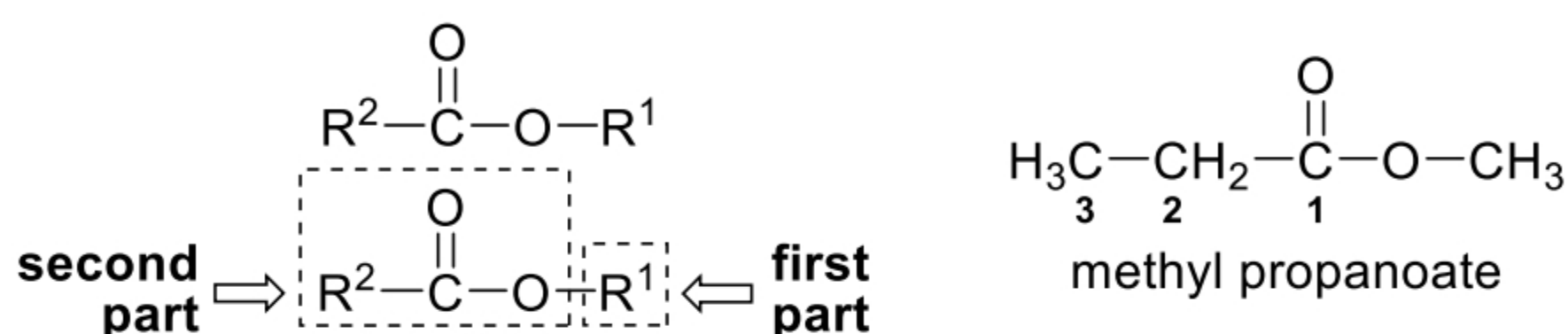
Disubstituted derivatives are sometimes named using the prefixes ortho- (or positions 2- and 6-), meta- (or positions 3- and 5-) and para- (or position 4-).

For trisubstituted derivatives, the **lowest** possible numbers are used and the prefixes are arranged alphabetically.



Esters

These are named in two parts. The first part represents the **R¹ group attached to oxygen** (Note: **This R¹ group comes from the alcohol**). The second represent the **R²CO₂** (Note: **R² group comes from the carboxylic acid**) portion which is named as an alkanoate (*i.e.* the suffix is -oate). A space separates the two parts of the name.

**Checkpoint**

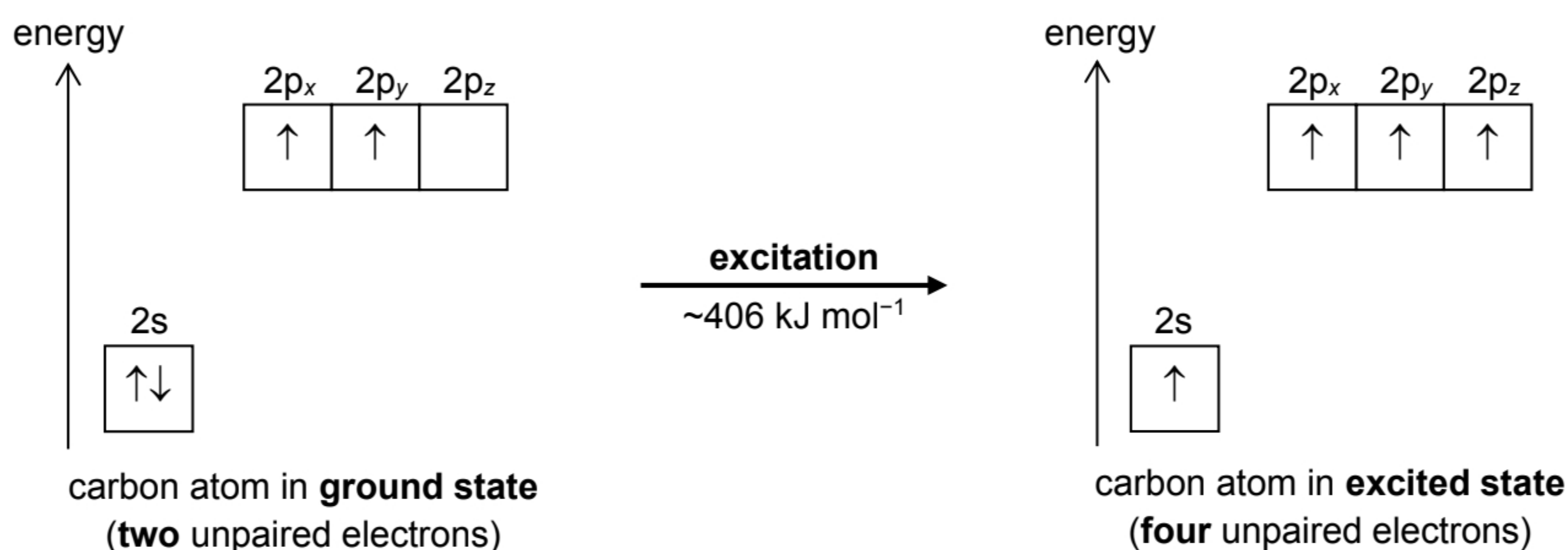
- ☐ I know how to name organic molecules using the following steps:
- Identify the longest carbon chain that contains the functional group with the highest priority.
 - The “parent” will carry the suffix of the functional group with the highest priority.
 - The suffix will be numbered with the smallest number.
 - The substituents will then be the prefix with the lowest numbering, arranging in alphabetical order.

5 Bonding in Carbon Compounds

- LO (d) describe sp^3 hybridisation, as in ethane molecule, sp^2 hybridisation, as in ethene and benzene molecules, and sp hybridisation, as in ethyne molecule
- (e) explain the shapes of, and bond angles in, the ethane, ethene, benzene, and ethyne molecules in relation to σ and π carbon-carbon bonds
- (f) predict the shapes of, and bond angles in, molecules analogous to those specified in (e)

The electronic configuration of carbon is $1s^2 2s^2 2p^2$. Carbon has four valence electrons and can form **four bonds** to neighbouring atoms (*i.e.* **tetravalent**).

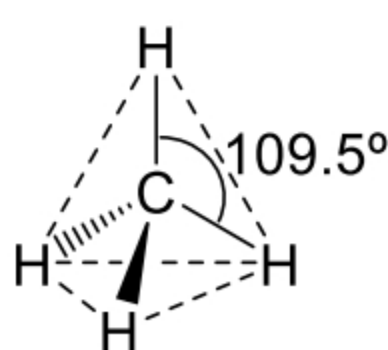
The **formation of covalent bonds** with other atoms require **unpaired electrons**. In its ground state, a carbon atom only has two unpaired electrons in its 2p orbitals, making it seem as if it can only form two bonds. However, it is possible to excite the carbon atom such that one of the paired electrons in the 2s orbital is **promoted** to the vacant 2p orbital:



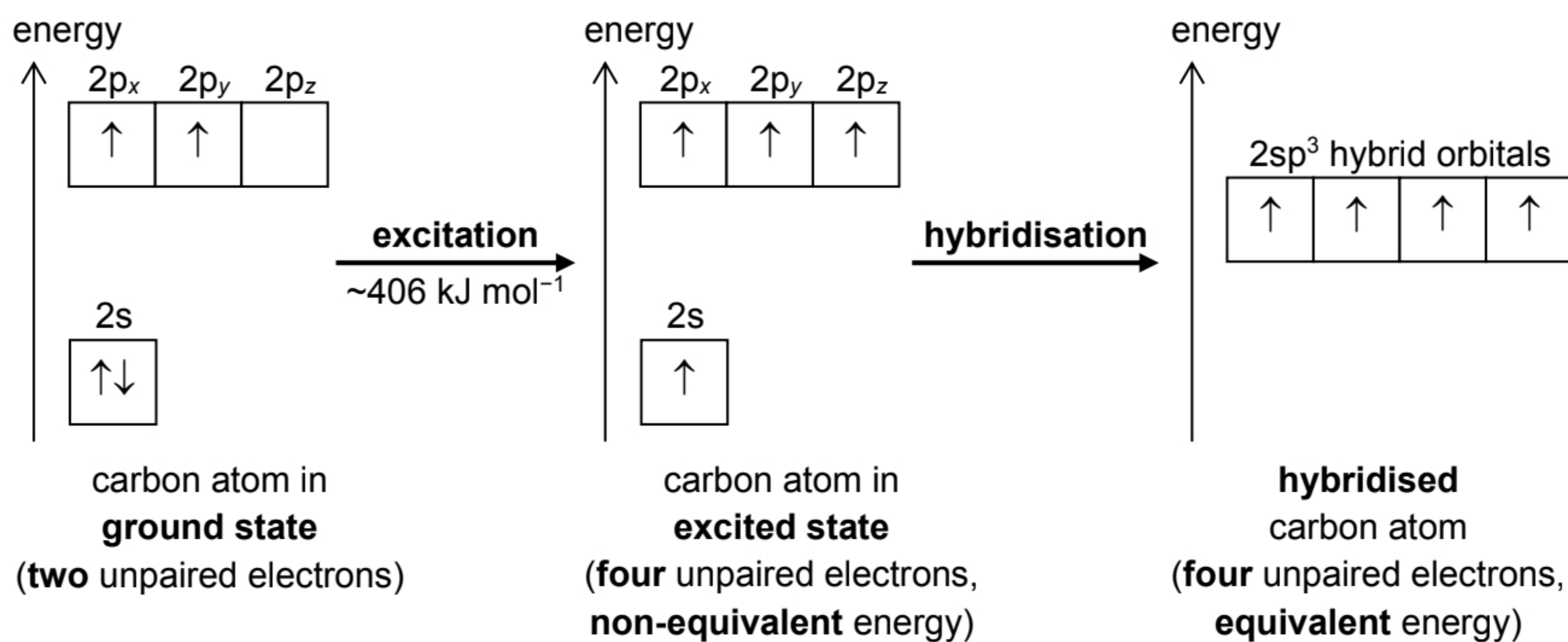
In this way, the carbon atom now has **four unpaired electrons**, which makes it possible for it to form four bonds with other atoms or groups. The large amount of energy produced by forming these two extra bonds considerably outweighs that required ($\approx 406 \text{ kJ mol}^{-1}$) for the uncoupling of the $2s^2$ electrons, followed by the $2s \rightarrow 2p$ promotion.

5.1 Hybridisation

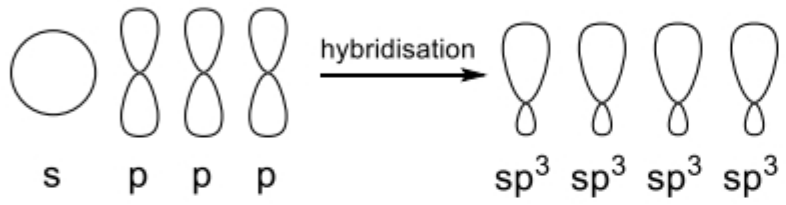
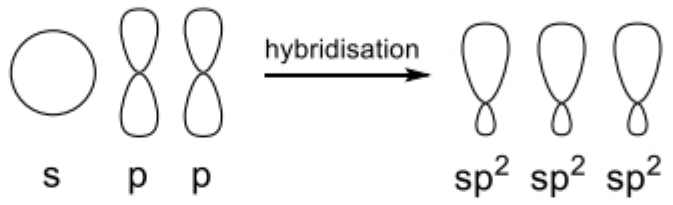
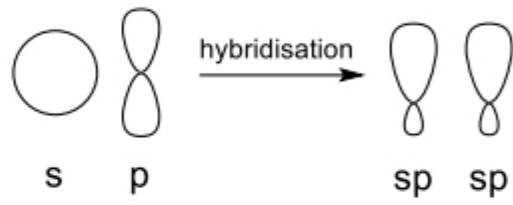
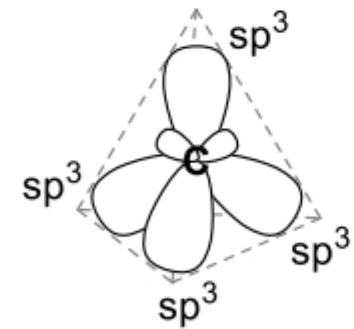
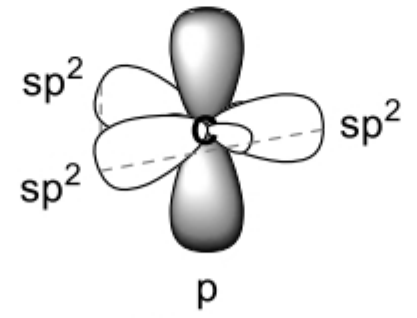
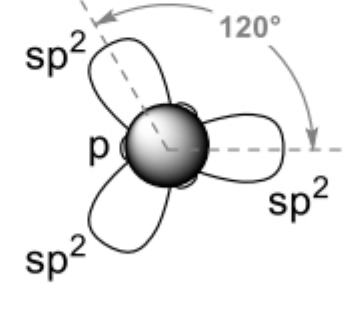
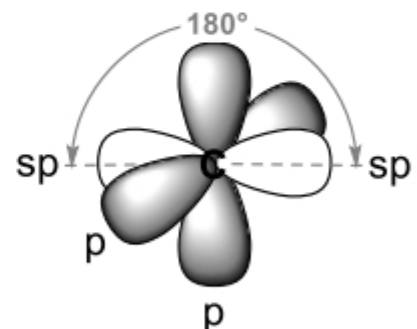
The unpaired electrons available in a carbon atom for bonding are in **one 2s** and **three 2p** orbitals. If these orbitals are used for bonding, we will expect two kinds of bonds to be formed – one non-directed bond (due to the spherical 2s orbital), and three directed bonds at right angles to one another (due to the three 2p orbitals). However, we know that this is not the case. For example, the four C–H bonds in methane are known to be **identical** and **arranged symmetrically** (tetrahedrally) at an angle of 109.5° .

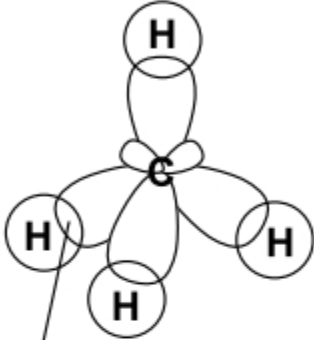
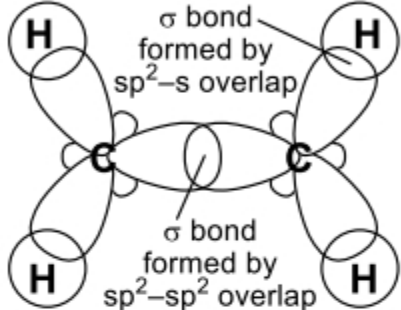
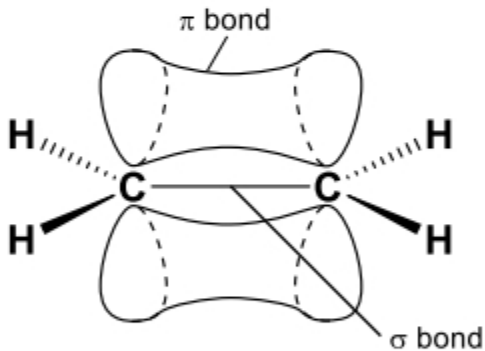
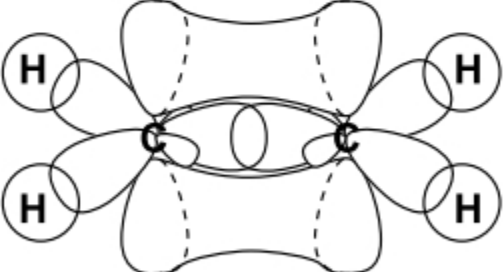
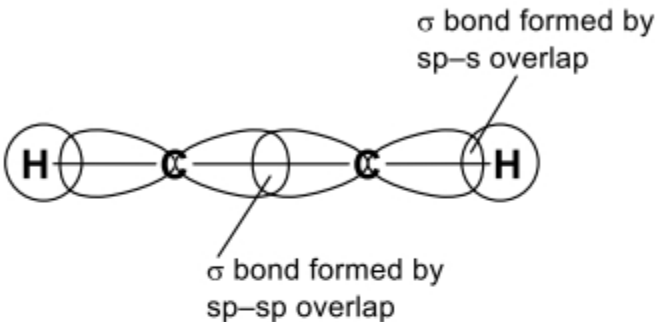
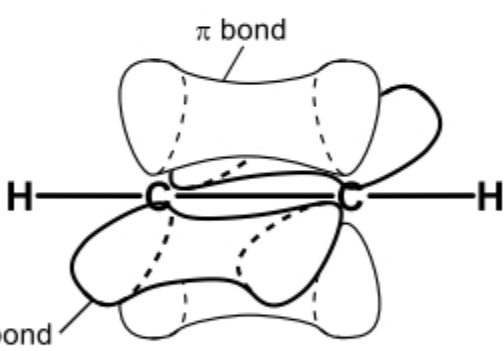
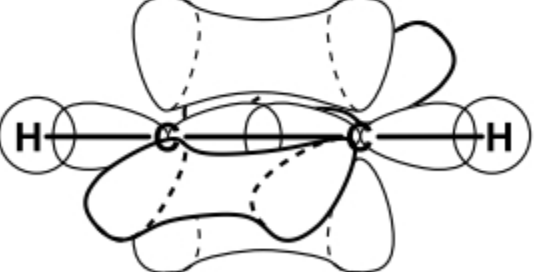


In 1931, Linus Pauling explained this by showing mathematically that the 2s and three 2p atomic orbitals combine or **hybridise** to form four new identical atomic orbitals capable of forming stronger bonds. This is the concept of **hybridisation**.



In organic chemistry, the most common types of hybridisation for carbon are sp^3 (as in ethane), sp^2 (as in ethene and benzene) and sp (as in ethyne).

	sp^3 hybridisation	sp^2 hybridisation	sp hybridisation
when does it occur	when carbon forms <u>four σ bonds</u>	when carbon forms <u>three σ bonds and one π bond</u>	when carbon forms <u>two σ bonds and two π bonds</u>
orbitals hybridised	<u>one</u> s orbital <u>three</u> p orbitals	<u>one</u> s orbital <u>two</u> p orbitals	<u>one</u> s orbital <u>one</u> p orbital
number of hybrid orbitals formed	<u>four</u> sp^3 hybrid orbitals 	<u>three</u> sp^2 hybrid orbitals 	<u>two</u> sp hybrid orbitals 
orientation of orbitals	the four sp^3 hybrid orbitals point to the corners of a tetrahedron (bond angle of 109.5°).	- the three sp^2 hybrid orbitals point to the corners of a triangle (bond angle of 120°). - the remaining unhybridised p orbital is perpendicular to the sp^2 plane.	- the two sp hybrid orbitals point in the opposite directions (bond angle of 180°). - the two remaining unhybridised p orbitals are perpendicular to the sp plane, and to each other.
		 side view  top view	

	sp^3 hybridisation	sp^2 hybridisation	sp hybridisation
example	CH₄, methane: each of the singly occupied sp^3 hybrid orbital overlaps with the singly occupied 1s orbital on hydrogen to form 4 identical C–H bonds.  σ bond formed by sp^3-s overlap (Note: You need to know how to draw this.)	C₂H₄, ethene: - each carbon utilises two sp^2 hybrid orbitals to form two C–H bonds with two hydrogen 1s orbitals.  - the C=C double bond consist of a σ bond formed by head-on overlap between two sp^2 hybrid orbitals, one from each C, and a π bond formed by side-way overlap between the two perpendicular p orbitals.  Combining all orbitals:  (Note: You need to know how to draw this.)	C₂H₂, ethyne: - each carbon utilises one sp hybrid orbital to form one C–H bond with the 1s orbital of a hydrogen.  - the C≡C triple bond consist of a σ bond formed by head-on overlap between two sp hybrid orbitals, one from each C, and two π bonds formed by side-way overlap between the two perpendicular sets of two p orbitals.  Combining all orbitals: 

Think about this...

The C—H bonds in ethane, ethene and ethyne are of different strengths (and thus length). Why is this so?

compound	$\text{H}_3\text{C}-\text{CH}_2-\text{H}$	$\text{H}_2\text{C}=\text{CH}-\text{H}$	$\text{HC}\equiv\text{C}-\text{H}$
C—H bond length / nm	0.109	0.1076	0.106
C—H bond strength / kJ mol^{-1}	420	444	552

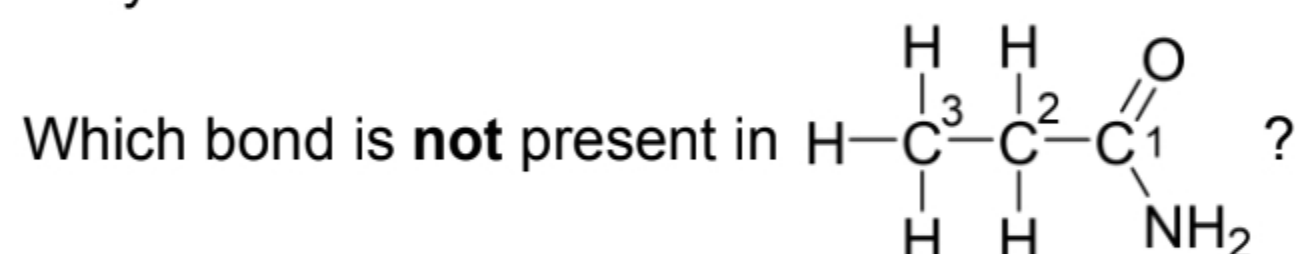
Each type of hybrid orbital has different characteristics depending on its original atomic orbitals.

hybrid orbital	s character	p character
sp^3	25%	75%
sp^2	33.3%	66.7%
sp	50%	50%

The greater the 's' character of the carbon hybrid orbitals, the stronger the bond and shorter is the bond. This is because the electrons are held closer to the nucleus.

Example 5A

Covalent bonds are formed by orbital overlap. The shape of molecules can be explained in terms of hybridisation of orbitals.



		present?	which bond in molecule?
A	a π bond formed by 2p–2p overlap	Yes	C=O π bond
B	a σ bond formed by 1s–2sp overlap	No	N.A.
C	a σ bond formed by 1s–2sp ³ overlap	Yes	C–H σ bond
D	a σ bond formed by 2sp ² –2sp ³ overlap	Yes	C ₁ –C ₂ σ bond

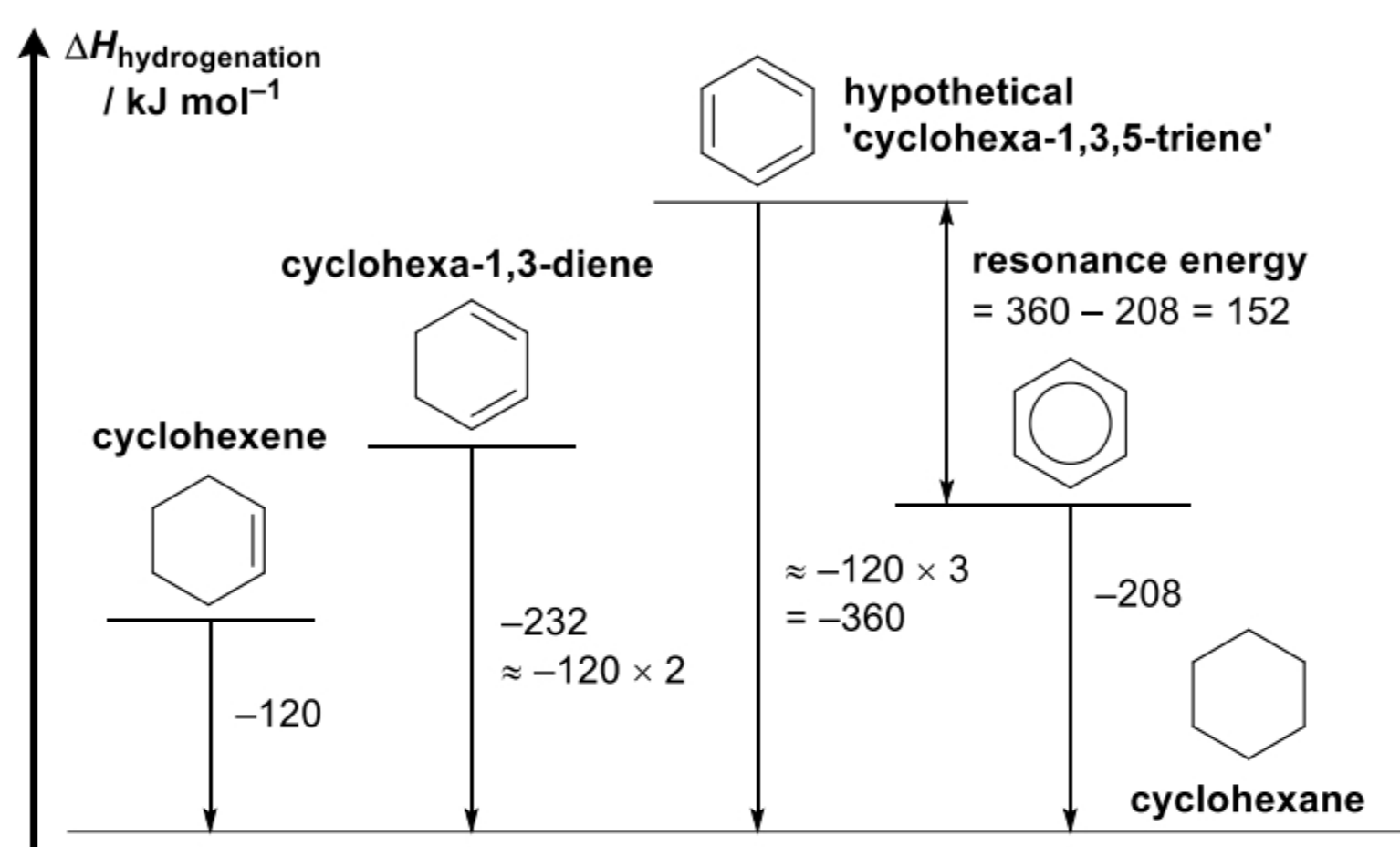
Hybridisation in benzene

LO (c) interpret, and use the following terminology associated with organic reactivities:
(i) delocalisation

One of the major problems of elementary organic chemistry is the detailed structure of **benzene**, C_6H_6 . Although it is clearly unsaturated, it is much more stable than typical alkenes (see box below for details) and does not undergo the usual alkene reactions. Hence, the structure of benzene should be quite different from that of an alkene.

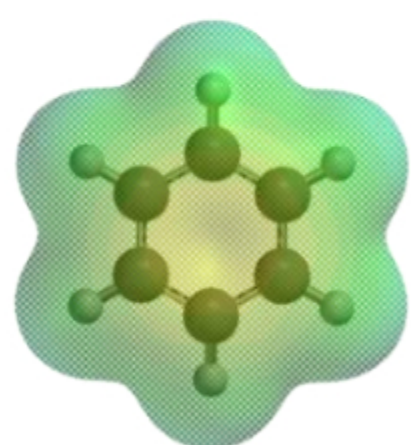
FYI: Comparison of Stabilities of Benzene and Related Alkenes

- A rough estimate of the stabilisation of benzene compared with simple cyclic unsaturated structures, termed the **delocalisation energy**, can be obtained by comparing its heat of hydrogenation with those of cyclohexene and cyclohexa-1,3-diene:



- 'Real' benzene is thus thermodynamically more stable than the hypothetical 'cyclohexa-1,3,5-triene' by about 152 kJ mol⁻¹; this compares with only approximately 8 kJ mol⁻¹ by which the conjugated cyclohexa-1,3-diene is stabilised, with respect to cyclohexene.

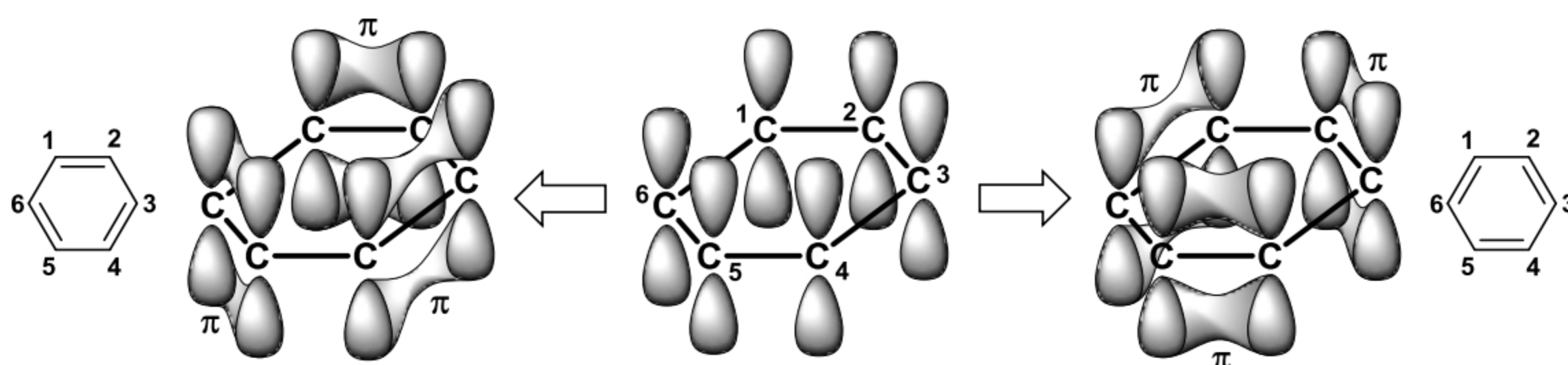
The **carbon-carbon bond lengths** in benzene are found to be **exactly the same**, 0.140 nm. This means that benzene is a regular hexagon with bond lengths somewhere in between the normal values of a single (0.154 nm) and a double (0.133 nm) bond. In addition, an electrostatic potential map shows that the **electron density** in all six carbon-carbon bonds is **identical**.

**FYI: Electrostatic Potential Map**

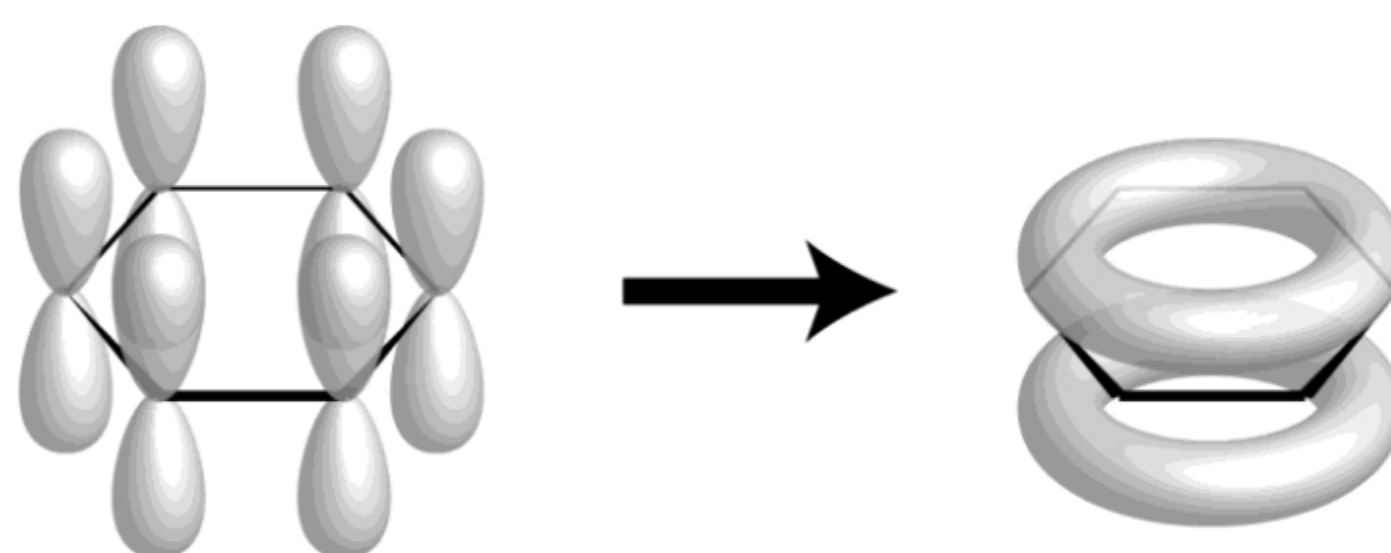
- Illustrates charge distributions of molecules three dimensionally
 - Low potential *i.e.* abundance of electrons: red
 - High potential *i.e.* absence of electrons: blue
- Allows us to visualise variably charged regions of a molecule, which can help us determine how molecules interact with one another

Hence, we know that benzene is a **planar** molecule with the shape of a regular hexagon, which in turn implies that all six carbon atoms in the ring are **sp² hybridised**, with a (singly occupied) 2p atomic orbital each perpendicular to the plane of the ring. Each carbon atom uses its sp² hybrid orbitals to form σ bonds with two other carbons and one hydrogen atom, and the unhybridised 2p orbital to form π bonds.

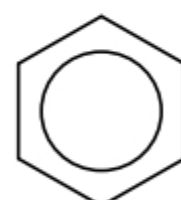
Overlapping of the 2p orbitals can take place either between (i) C₁ and C₂, C₃ and C₄, C₅ and C₆; or between (ii) C₁ and C₆, C₂ and C₃, C₄ and C₅, leading to the two Kekulé structures for benzene that involve alternating double and single bonds.



However, such a structure does not support the differences benzene displays compared to alkenes. Rather, a more probable structure of benzene is one in which **all** six adjacent 2p orbitals could overlap, resulting in the formation of an annular π electron cloud, above and below the plane of the ring:



As the 2p electrons are no longer held between just two carbon atoms but are spread over the entire ring, the electrons are said to be **delocalised**. To represent the unique structure of benzene, we use the following symbol:

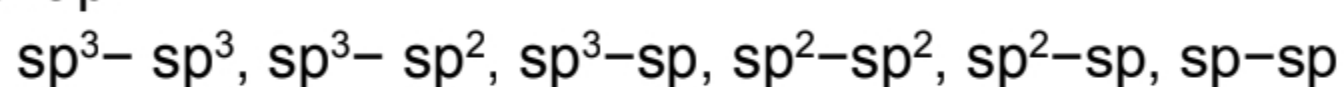


Checkpoint

- ☐ I am able to differentiate the different types of hybridisation states of an atom:

hybridisation	no. of bonds	shape	bond angle
sp^3	4 σ bond (4 regions of electron densities)	tetrahedral	109.5°
sp^2	3 σ bond, 1 π bond (3 regions of electron densities)	trigonal planar	120°
sp	2 σ bond, 2 π bond (2 regions of electron densities)	linear	180°

- ☐ I know different ways to form a carbon-carbon bond in an organic molecule through the following orbitals overlap:



The greater the percentage of s-character in the hybrid orbital, the stronger the bond formed

- ☐ I know that each of the six carbon atoms in benzene is sp^2 hybridised. Hence, a benzene (C_6H_6) molecule is planar in shape.
- ☐ I am able to appreciate that the carbon-carbon bond in benzene has a bond order of 1.5 due to the delocalisation of electrons around the six carbon atoms in the benzene.

6 Organic Reactions

LO (b) interpret, and use the following terminology associated with organic reactions:

- (iii) homolytic and heterolytic fission
- (vi) electrophile (Lewis acid), nucleophile (Lewis base)
- (vii) addition, substitution, elimination, condensation, hydrolysis
- (viii) oxidation and reduction

In organic chemistry, we are interested in **what kinds** of reactions occur and **how** they occur.

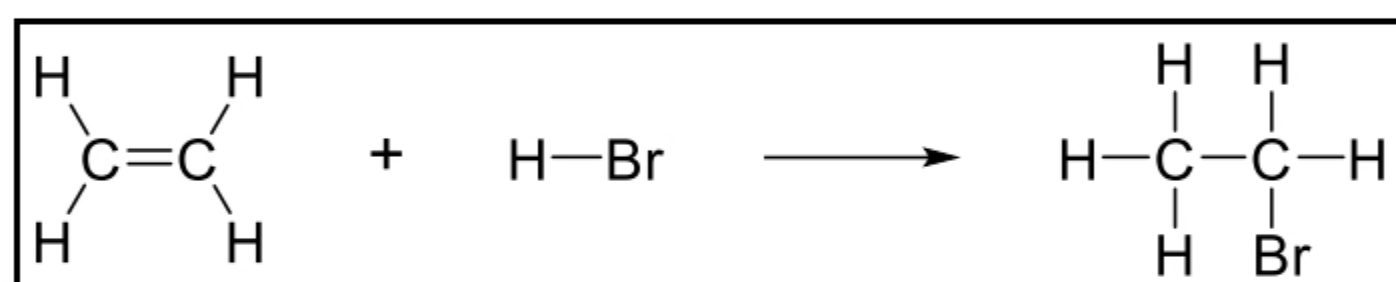
6.1 Types of Reactions

(a) Addition reactions

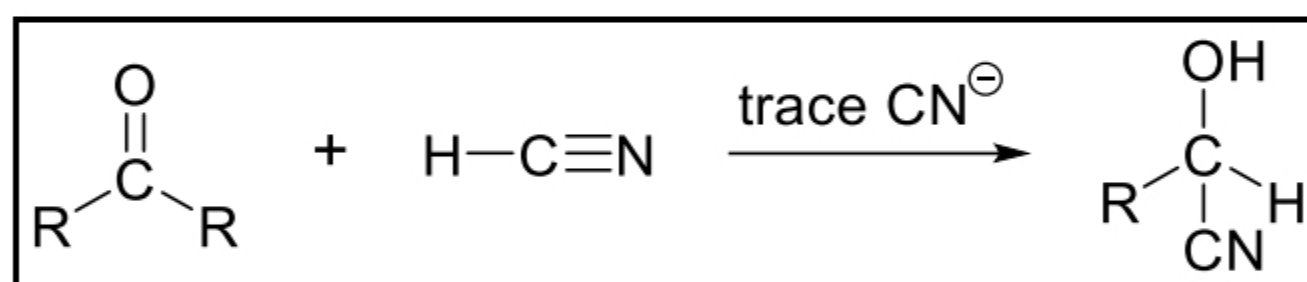
Addition reactions occur when two starting materials add together to form only one product, *i.e.*, “1+1 = 1”.



- Electrophilic addition to alkenes

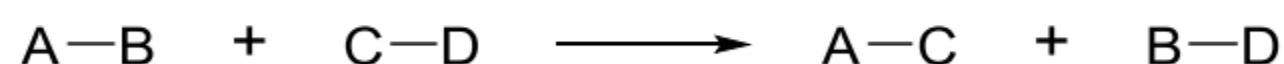


- Nucleophilic addition to aldehydes and ketones

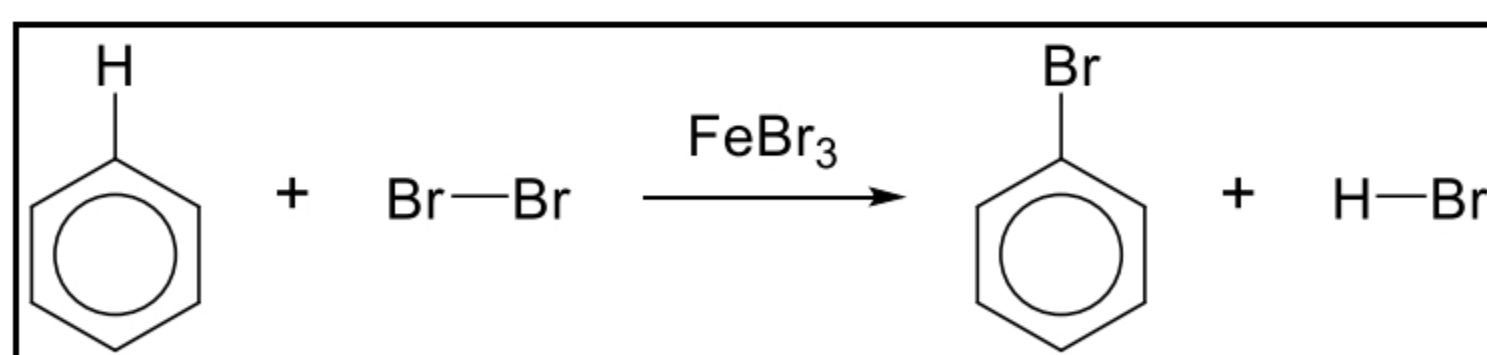


(b) Substitution reactions

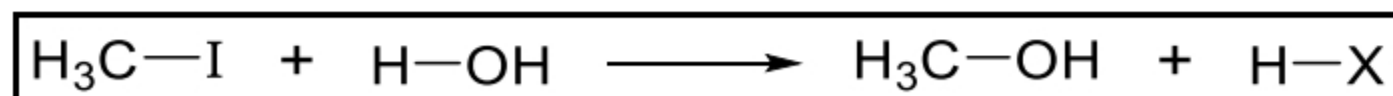
Substitution reactions occur when two starting materials exchange groups to form two new products, *i.e.*, “1+1 = 1+1”.



- Electrophilic substitution of benzene

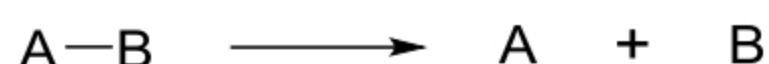


- Nucleophilic substitution of halogenoalkanes

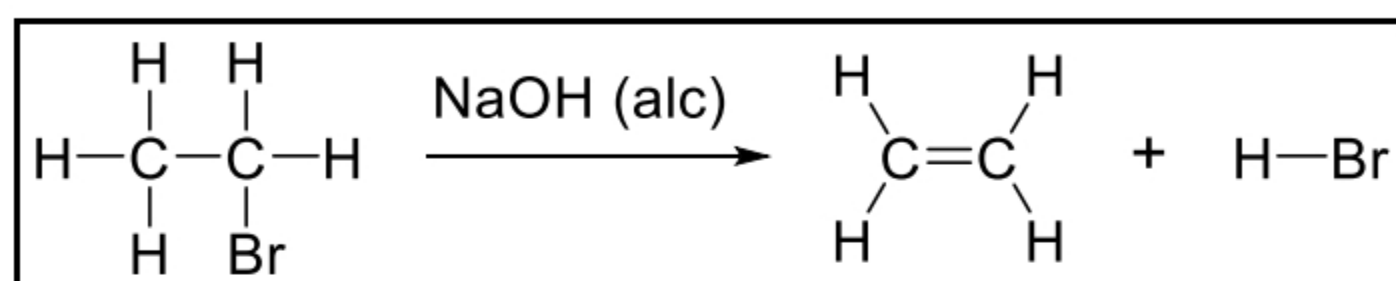


(c) Elimination reactions

Elimination reactions are the opposite of addition reactions. One starting material is converted into two products, *i.e.*, “1 = 1+1”.

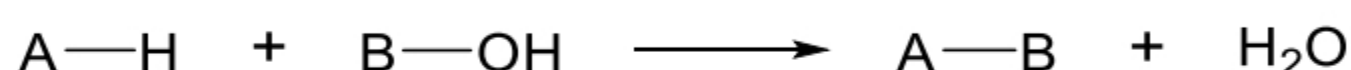


- Elimination of halogenoalkanes

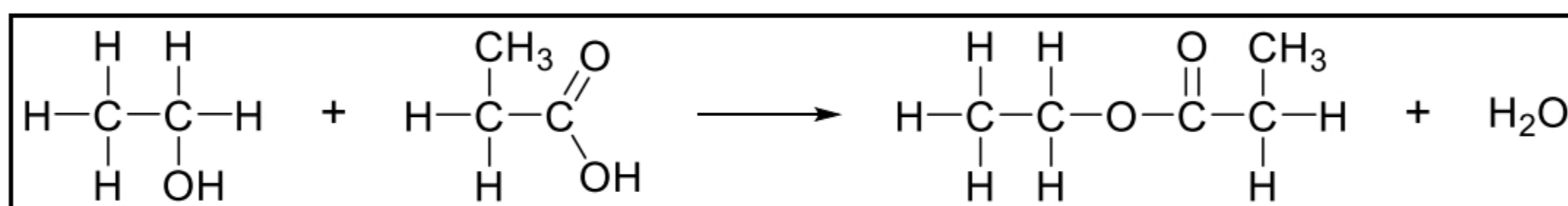


(d) Condensation reactions

Condensation reactions occur when two reactants are added together to form a single product with the elimination of a small molecule, *e.g.*, H_2O , HCl , NH_3 , etc.

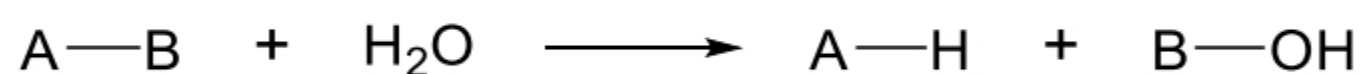


- Esterification (a type of condensation reaction)

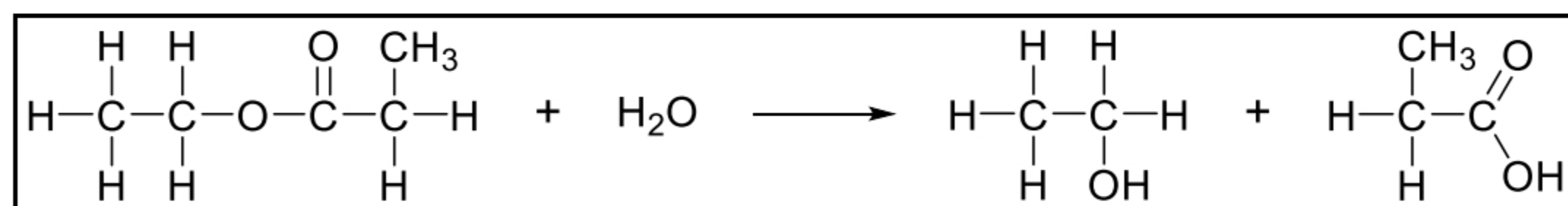


(e) Hydrolysis reactions

Hydrolysis reactions occur when a single reactant is split into two by the action of **water**.



- Hydrolysis of esters

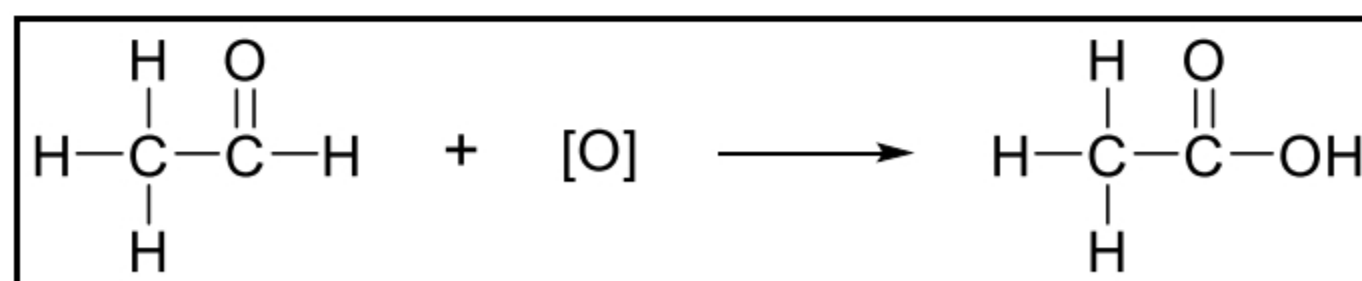


(Note: Hydro- means ‘water’, -lysis means to ‘break up’.)

(f) Oxidation reactions

Oxidation reactions occur when there is an increase in oxygen and/or decrease in hydrogen.

- Oxidation of aldehydes

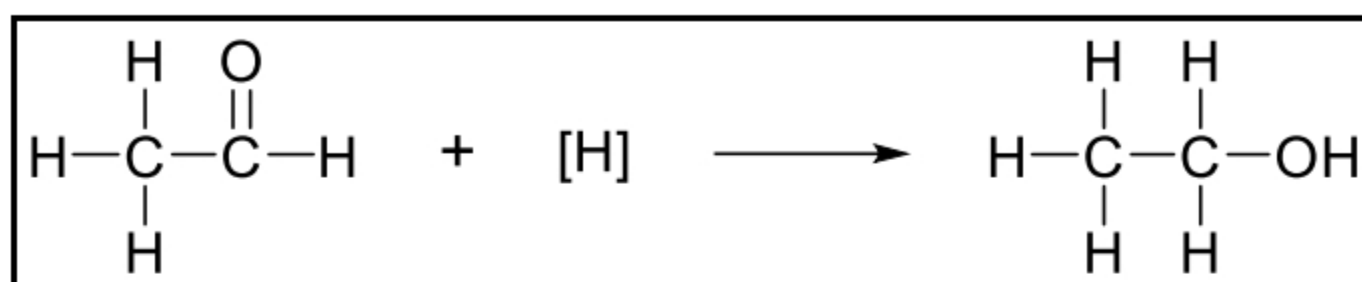


(Note: [O] symbol is used to balance the equation.)

(g) Reduction reactions

Reduction reactions occur when there is a decrease in oxygen and/or increase in hydrogen.

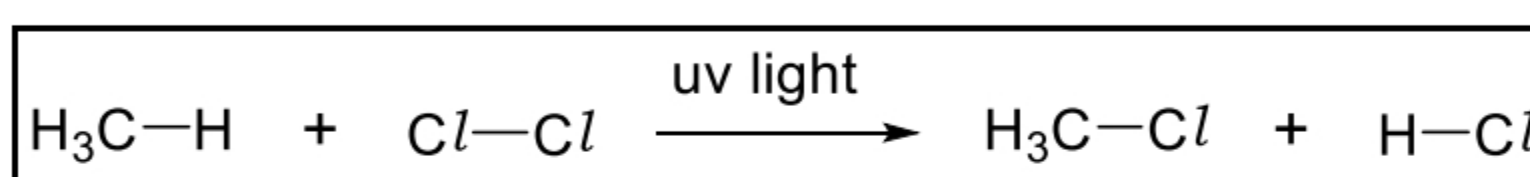
- Reduction of aldehydes



(Note: [H] symbol is used to balance the equation.)

(h) Radical reactions

- Free-radical substitution of alkanes

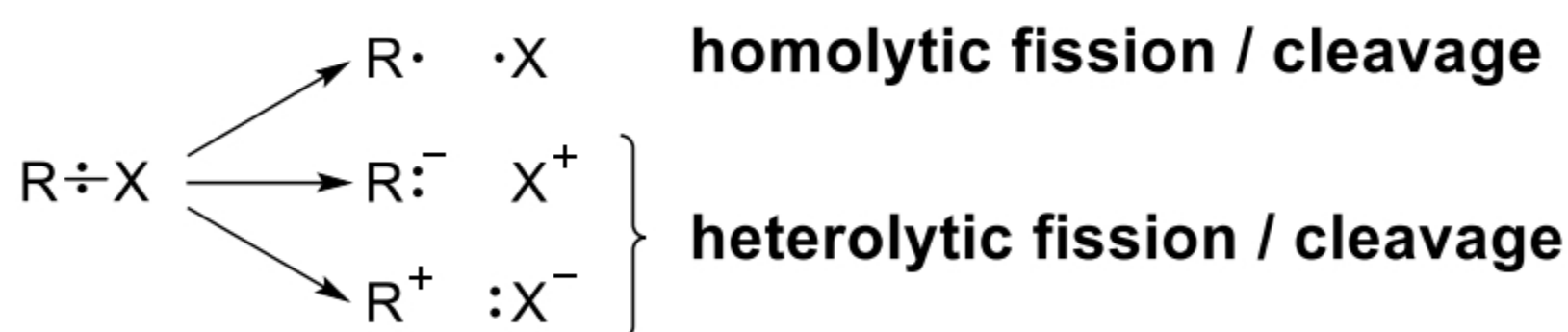
**6.2 Reaction Mechanisms**

LO (h) recognise that the mechanism of polar reactions involve the flow of electrons from electron-rich to electron-poor sites

Reaction mechanisms provides a description of how a reaction occurs. It details what takes place at each stage of a chemical transformation – which bonds are broken/formed and the order in which they do so, as well as the relative rates of the different steps within the reaction (recall what you have learnt in the topic of Reaction Kinetics).

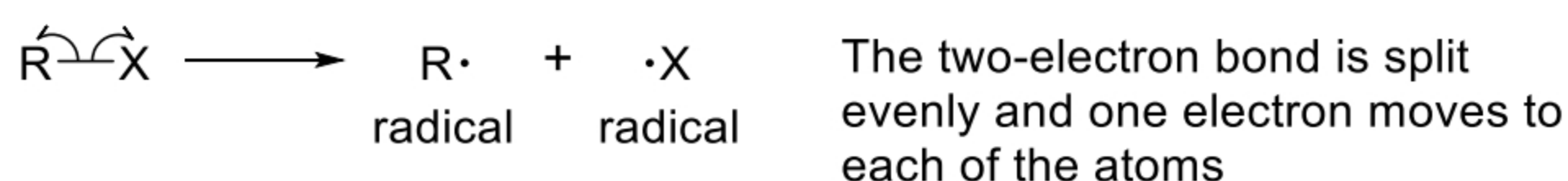
6.2.1 The Breaking and Forming of Bonds

All chemical reactions involve the bond breaking and bond formation. A covalent bond between two atoms can be broken in essentially the following ways:



In homolytic fission, each atom separates with one electron, leading to the formation of highly reactive entities called (free) radicals, owing their reactivity to their unpaired electron; this is referred to as homolytic fission or cleavage of the bond.

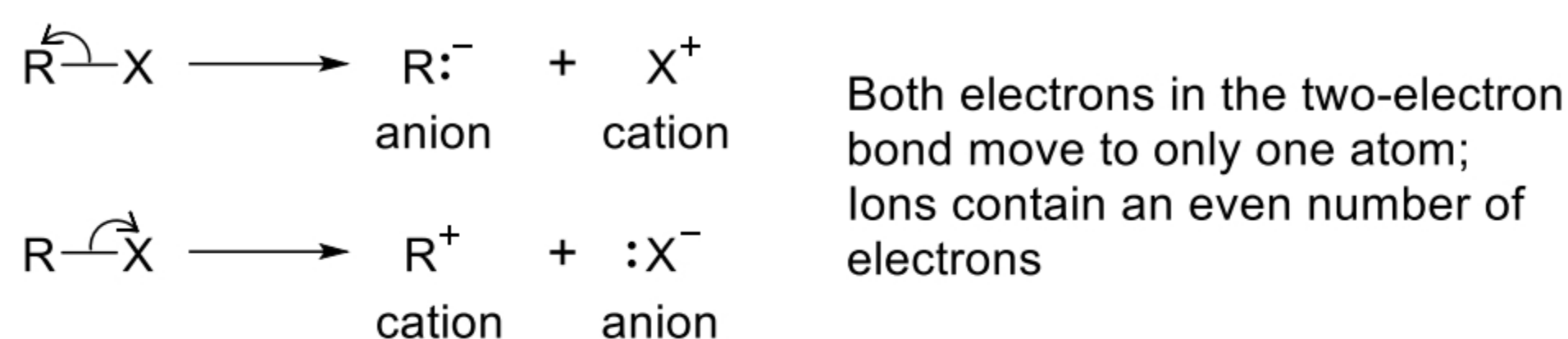
To show the movement of a single, unpaired electron, a half-arrow or fish hook is used.



Alternatively, one atom may hold on to **both electrons**, leaving none for the other, resulting in the formation of an **ion pair**, consisting of a negative and a positive ion; this is referred to as heterolytic fission or cleavage of the bond.

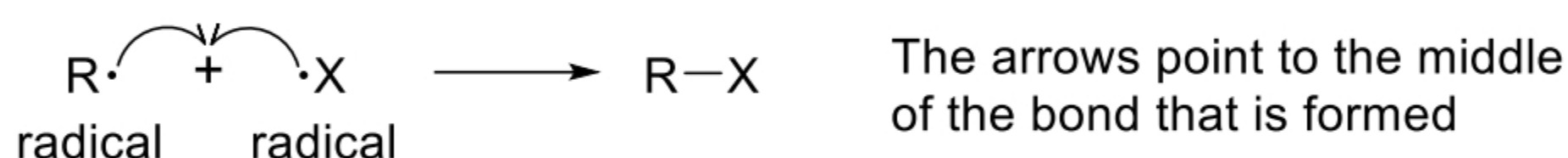
When R and X are not identical, the fission can take place in either of two ways, depending on whether R or X retains the electron pair.

To show the movement of a pair of electrons, a **full arrow** is used.

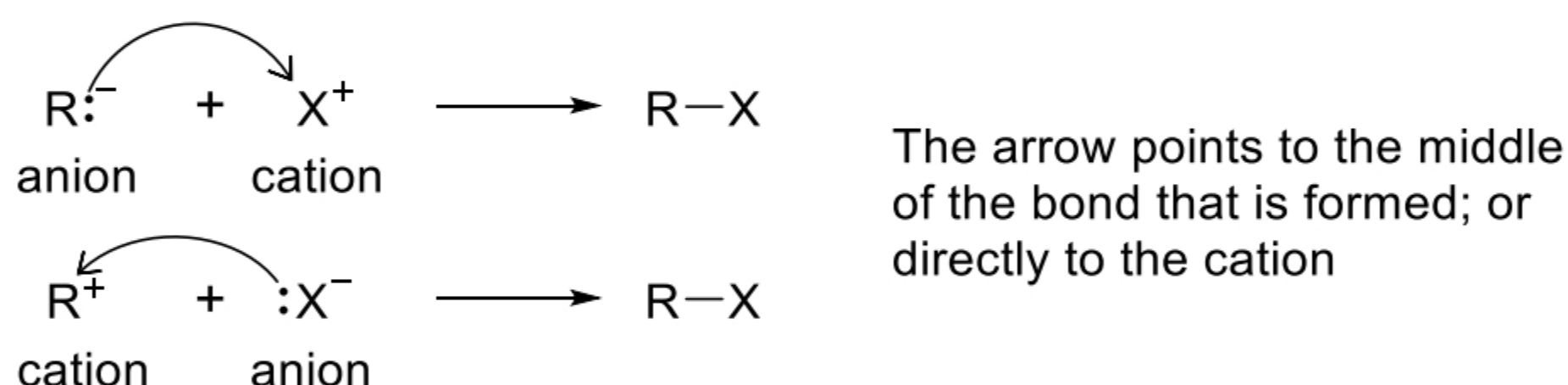


Formation of a covalent bond can take place by the **reversal** of any of the bond breaking processes:

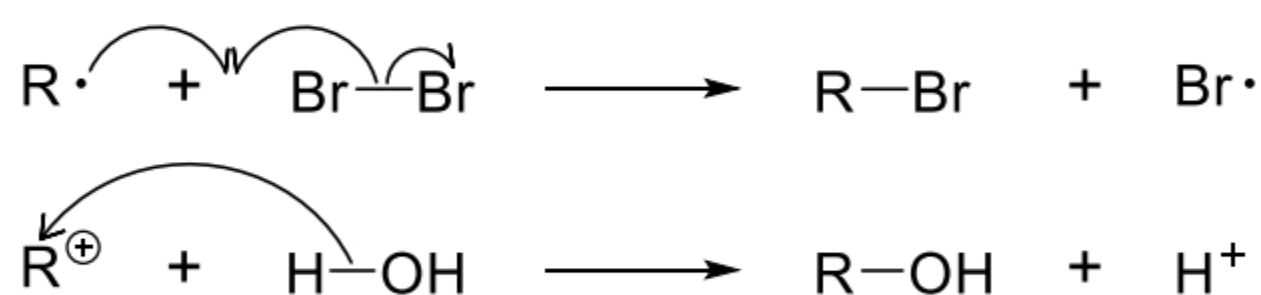
Homolytic bond formation



Heterolytic bond formation



and also, by the attack of first-formed radicals or ions on other species:



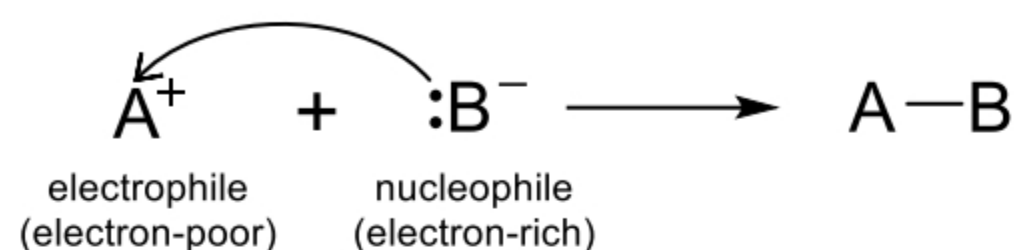
In general, regardless of whether we are looking at bond breaking or bond formation, movement of electrons (and hence direction of arrows) always occurs from electron **rich** regions to electron **poor** regions.

Reactions that involve symmetrical homolytic bond cleavage or formation are known as **radical reactions**. These reactions tend to occur in the **gas phase** and in solution in **non-polar** solvents, and are usually catalysed by light and by the addition of other radicals.

Reactions that involve asymmetrical heterolytic bond cleavage or formation are known as **polar (or ionic) reactions**. These reactions take place more readily in solution in **polar** solvents, because the greater ease of separation of charge therein, and very often because of the stabilisation of the resultant ion pairs through solvation (ion–dipole interactions).

6.2.2 Types of Reagents in Organic Reactions

All polar reactions take place between an **electron-poor site** and an **electron-rich site**. Such reactions involve the **donation of an electron pair** from a **nucleophile** to an **electrophile**.



The types of reagents involved in polar reactions are:

- **electrophiles:** (also known as 'electron-loving') are electron-poor species that can form a covalent bond by accepting an electron pair from an electron-rich site.
- **nucleophiles:** (also known as 'nucleus-loving') are electron-rich species that can form a covalent bond by donating an electron pair to an electron-deficient site.

6.2.2.1 Relative Strength of Electrophiles and Nucleophiles

Electrophiles are *often positively charged* (cations) although they can also be sites on neutral species carrying a **partial positive charge** (δ^+).

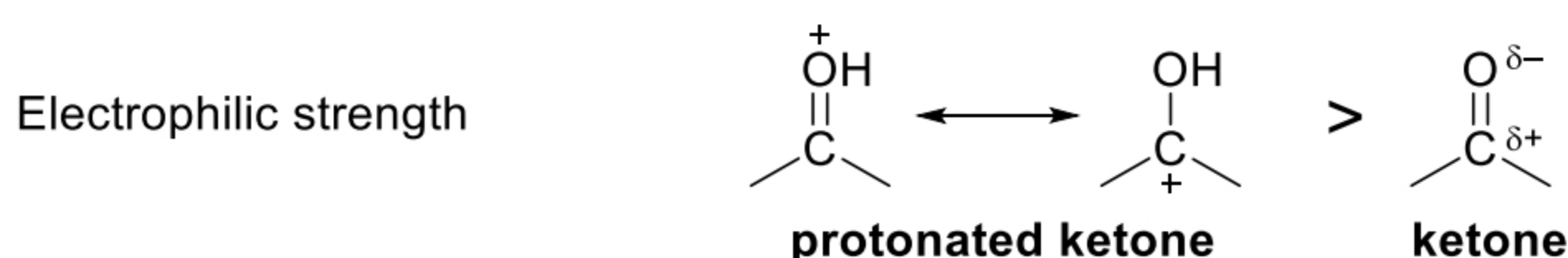
For example, electron-rich (and hence nucleophilic) phenol can be attacked by electrophiles such as the positively charged nitronium cation, NO_2^+ , and the electron-deficient nitrogen atom of nitric acid (HNO_3) or dinitrogen pentoxide (N_2O_5):



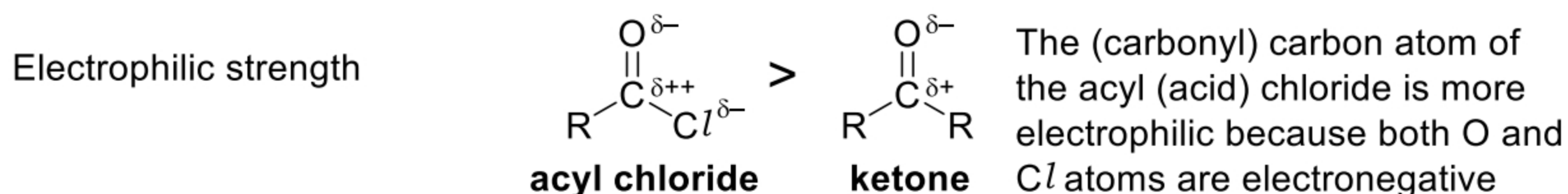
(Note: $\delta+++$ simply means three δ^+ added together. It is just to indicate that the electron deficiency arises from three electronegative oxygen atoms.)

The relative electrophilic strength (or electrophilicity) of a cation, or electrophilic site within a neutral molecule depends on the **level of electron deficiency**.

- An electrophile with a positive charge is always a **stronger** electrophile than its conjugate base (which is neutral).

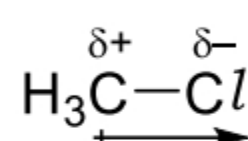


- Carbon atoms are electrophilic when attached to electronegative atoms. The more electronegative the atom(s) bonded to carbon, the more electrophilic the carbon atom.



Nucleophiles are usually **negatively charged** (anions) or neutral molecules that contain a **lone pair of electrons**.

For example, anions such as OH⁻ and CN⁻ and the electron-rich nitrogen atom in ammonia or amines, H₃N: or R₃N: can act as nucleophiles to attack the electron-deficient (and hence electrophilic) carbon atom in chloromethane.

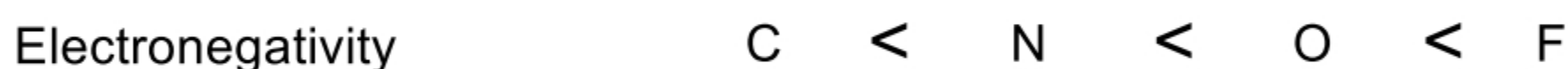
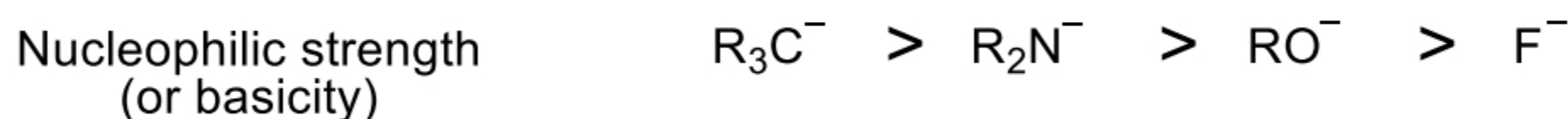


The relative nucleophilic strength (or nucleophilicity) of an anion, or nucleophilic site within a neutral molecule depends on the **availability of the pair of electrons**.

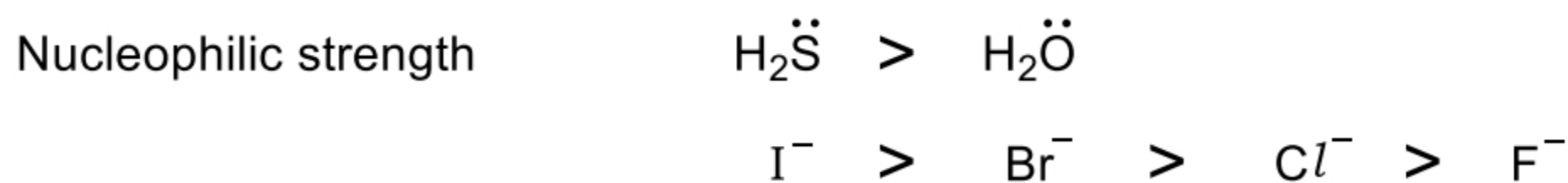
- A nucleophile with a negative charge is always a **stronger** nucleophile than its conjugate acid (which is neutral).



- The nucleophilic strength of anions, within the same period of the Periodic Table, follows the same order as basicity: **the more electronegative the atom bearing the negative charge, the tighter the electrons are held to the nucleus, the weaker the nucleophile, and the weaker the base**.



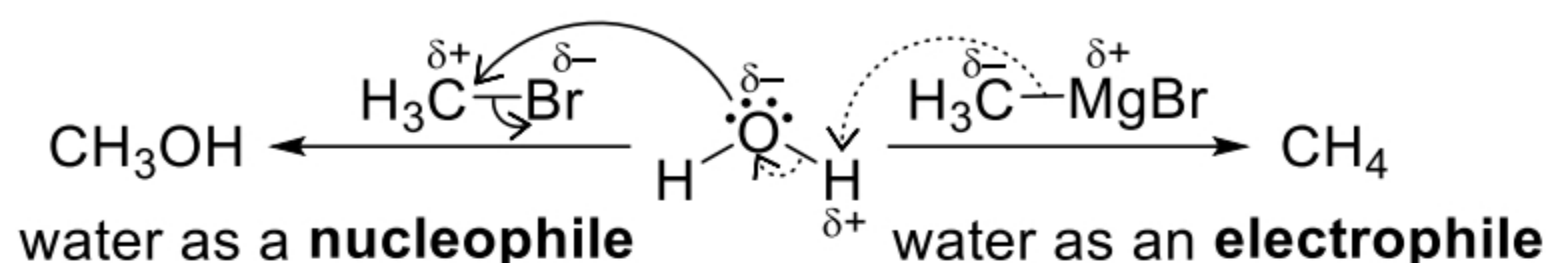
- The **nucleophilic strength of anions and neutral atoms increases on going down a group of the Periodic Table**. The electrons are held less tightly to the nucleus as the atom size increases, and hence they are more available for forming bonds.



This electrophile/nucleophile dichotomy can be looked upon as a special case of the **Lewis acid-base concept**. Electrophiles and nucleophiles in organic reactions can be looked upon essentially as electron pair acceptors (**Lewis acids**) and donors (**Lewis bases**), respectively, from and to other atoms – most frequently **carbon**.

You will learn more about the concept of conjugate acid/base and Lewis acid/base in the topic of Ionic Equilibrium.

It is possible for a species to be either a nucleophile or an electrophile, depending on the circumstances. It is said to be an **amphiphile**. For example, water can act as a nucleophile in one reaction, and as an electrophile in another:



In Radical Reactions

A **radical**, also known as a free radical, is an atom, molecule, or ion that has at least one unpaired valence electron.

Reactions involving **radicals** as the reactive entities are also known. These are much less susceptible to variations in electron density in the substrate than are reactions involving polar intermediates.

They are however greatly affected by the addition of small traces of substances that either produce or consume radicals.

Checkpoint

☐ I know how to identify and name the following organic reactions:

free-radical substitution	electrophilic addition	electrophilic substitution	nucleophilic substitution	nucleophilic addition
elimination	oxidation	reduction	hydrolysis	condensation

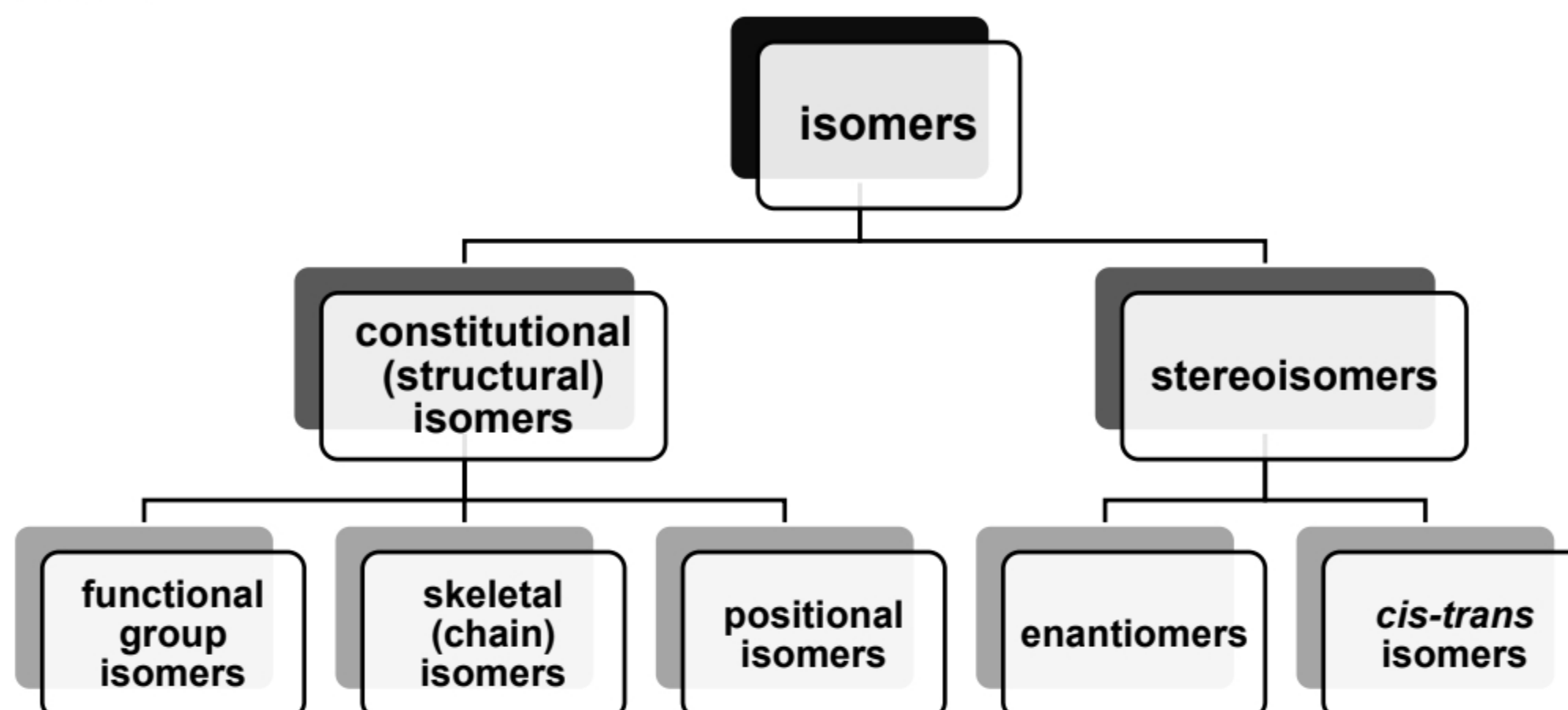
☐ I know the difference between electrophiles, nucleophiles and radicals.

☐ I know that polar reactions involve the flow of electrons from electron-rich to electron-poor sites. Such reactions involve the donation of an electron pair from a nucleophile to an electrophile.

7 Isomerism

An **isomer** is one of several species (or molecular entities) that have the **same** atomic composition (i.e., **molecular formula**) but different line formulae or different stereochemical formulae (i.e., **different molecular structures**) and hence different physical and/or chemical properties.

Isomers are subdivided into two major types, namely, (i) **constitutional (structural) isomers** and (ii) **stereoisomers**:



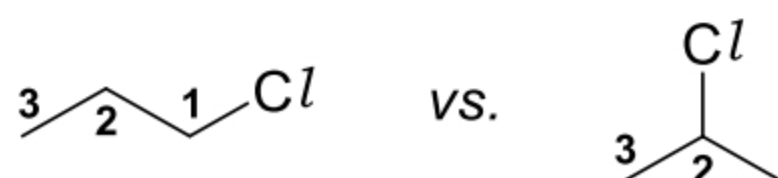
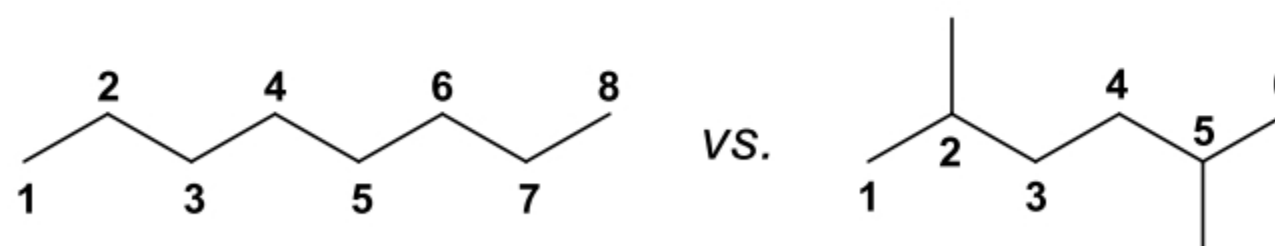
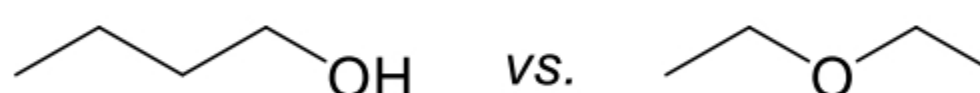
7.1 Constitutional (Structural) Isomerism

LO (a) describe constitutional (structural) isomerism
 (i) deduce the possible isomers for an organic molecule of known molecular formula

Constitutional isomers have the **same molecular formula** but **different structural formula**.

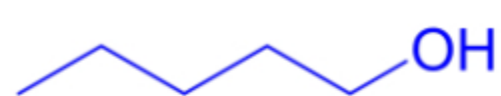
There are three types of constitutional isomers:

- **Functional group isomers:** Constitutional isomers with **different functional groups**.
E.g. butan-1-ol, $\text{CH}_3(\text{CH}_2)_3\text{OH}$, and diethyl ether, $\text{CH}_3\text{CH}_2\text{OCH}_2\text{CH}_3$
- **Skeletal/Chain isomers:** Constitutional isomers that differ with respect to **branching of the carbon skeleton**, i.e. different **chain length/skeleton** (same functional group).
E.g. octane and 2,5-dimethylhexane
- **Positional isomers:** Constitutional isomers that differ only with respect to the **point of attachment of a substituent** (on the same chain/skeleton).
E.g. 1-chloropropane ($\text{ClCH}_2\text{CH}_2\text{CH}_3$) and 2-chloropropane ($\text{CH}_3\text{CHClCH}_3$)

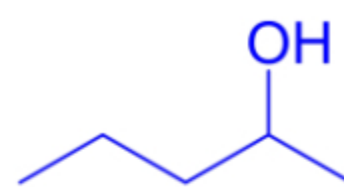


Example 7A

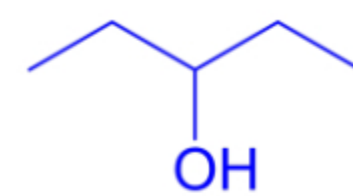
Draw all constitutional isomers with the molecular formula $C_5H_{12}O$ and write their IUPAC name.

Positional isomers

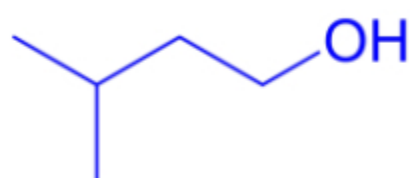
pentan-1-ol



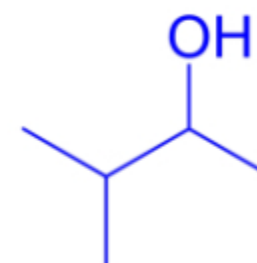
pentan-2-ol



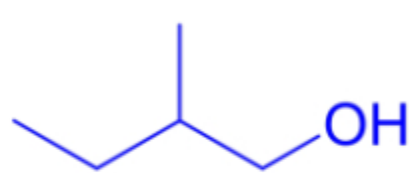
pentan-3-ol

Chain isomers

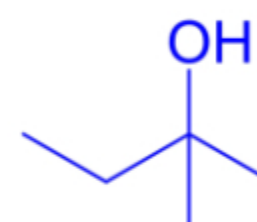
3-methylbutan-1-ol



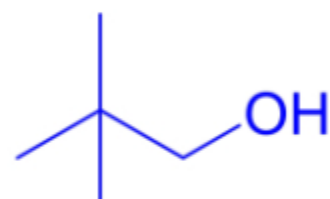
3-methylbutan-2-ol



2-methylbutan-1-ol



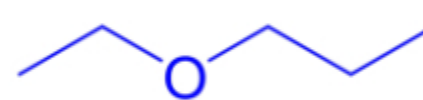
2-methylbutan-2-ol



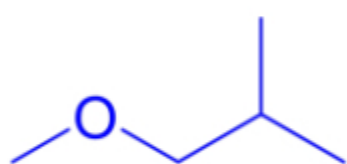
2,2-dimethylpropan-1-ol

Functional group isomers

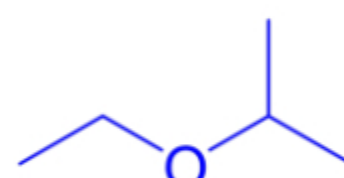
1-methoxybutane



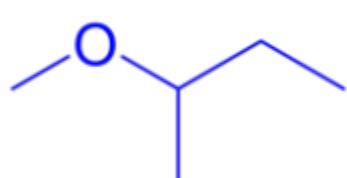
1-ethoxypropane

Chain isomers

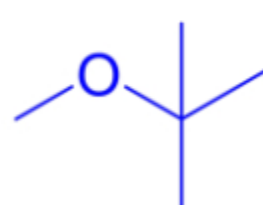
1-methoxy-2-methylpropane



2-ethoxypropane



2-methoxybutane



2-methoxy-2-methylpropane

7.2 Stereoisomerism

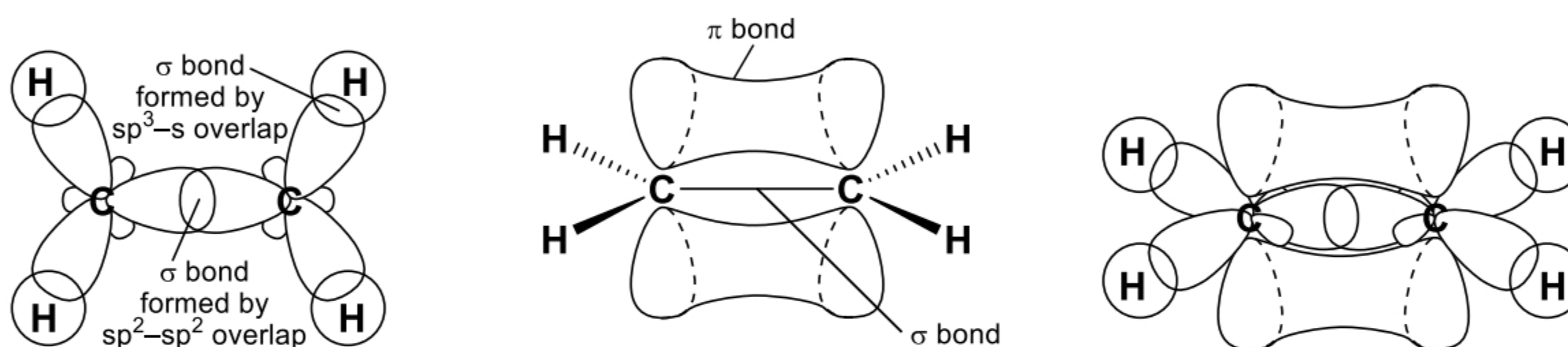
Stereoisomers are isomers that have the **same molecular and structural formulae** but differ in their **spatial arrangement** (3-dimensional orientation) of the atoms.

7.2.1 *cis-trans* Isomerism

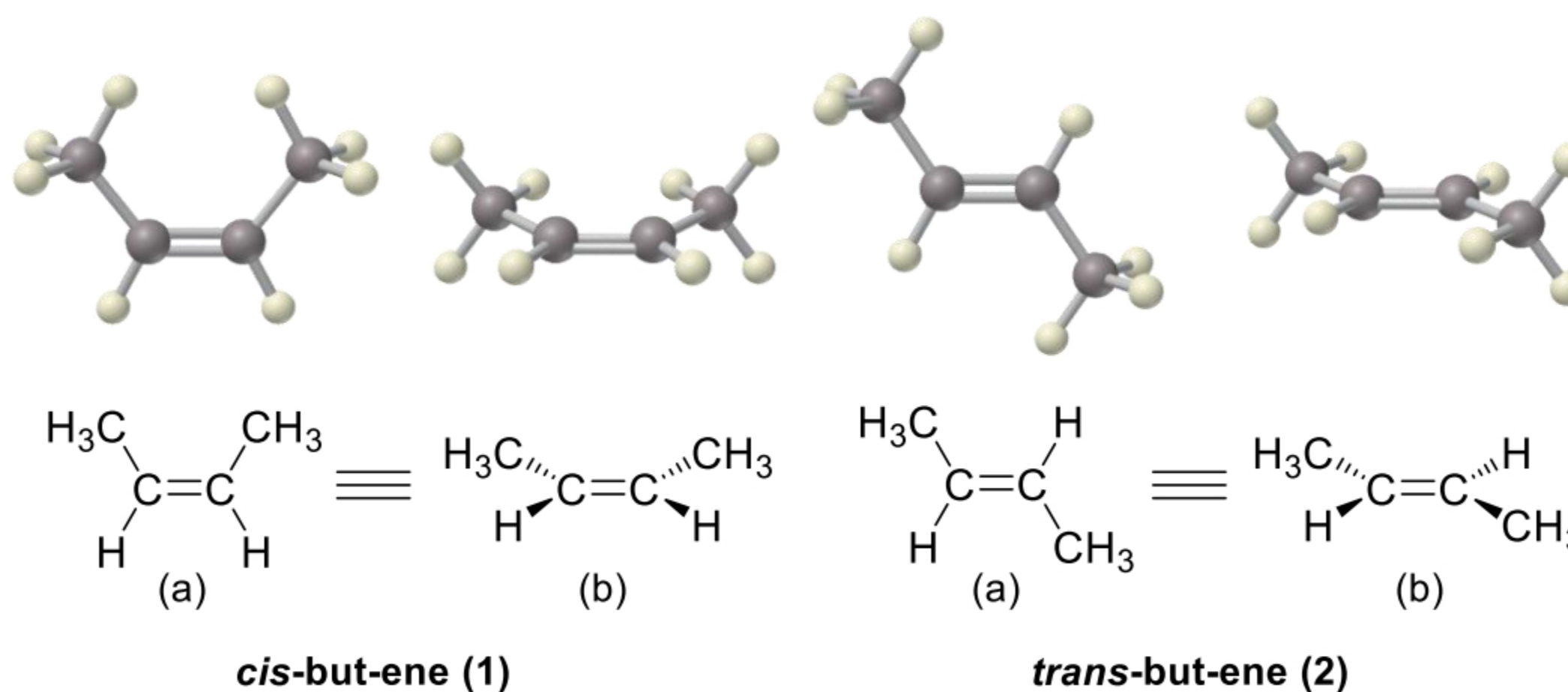
- LO (b) describe *cis-trans* isomerism in alkenes, and explain its origin in terms of restricted rotation due to the presence of π bonds
 (i) deduce the possible isomers for an organic molecule of known molecular formula
 (j) identify chiral centres and/or *cis-trans* isomerism in a molecule of given structural formula

In general, alkenes have two adjacent sp^2 hybridised carbons. These carbon atoms together with the four atoms to which they are attached are co-planar. Above and below the plane defined by these six atoms, there exists a region of electron density, the π bond, which arises from the sideways overlap of p orbitals on the adjacent alkene carbons.

We have seen this in ethene in Section 5.1:



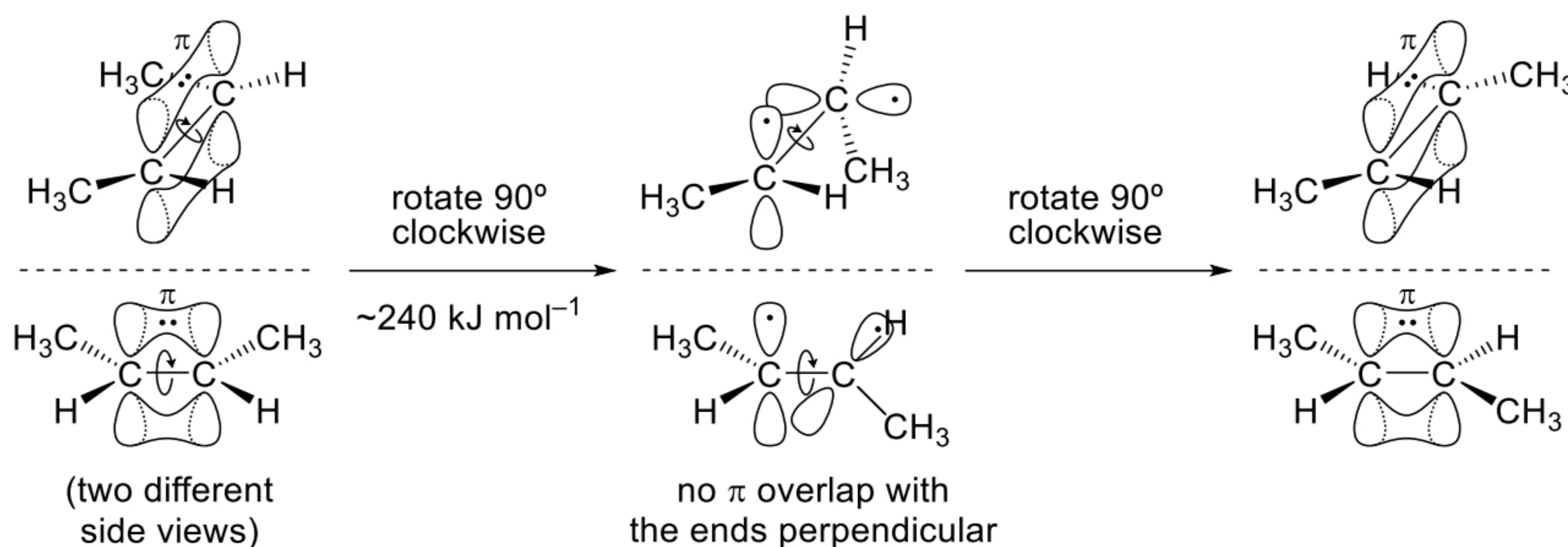
In but-2-ene, $\text{CH}_3\text{CH}=\text{CHCH}_3$, the two methyl groups can lie either on the same side or on opposite sides of the double bond.



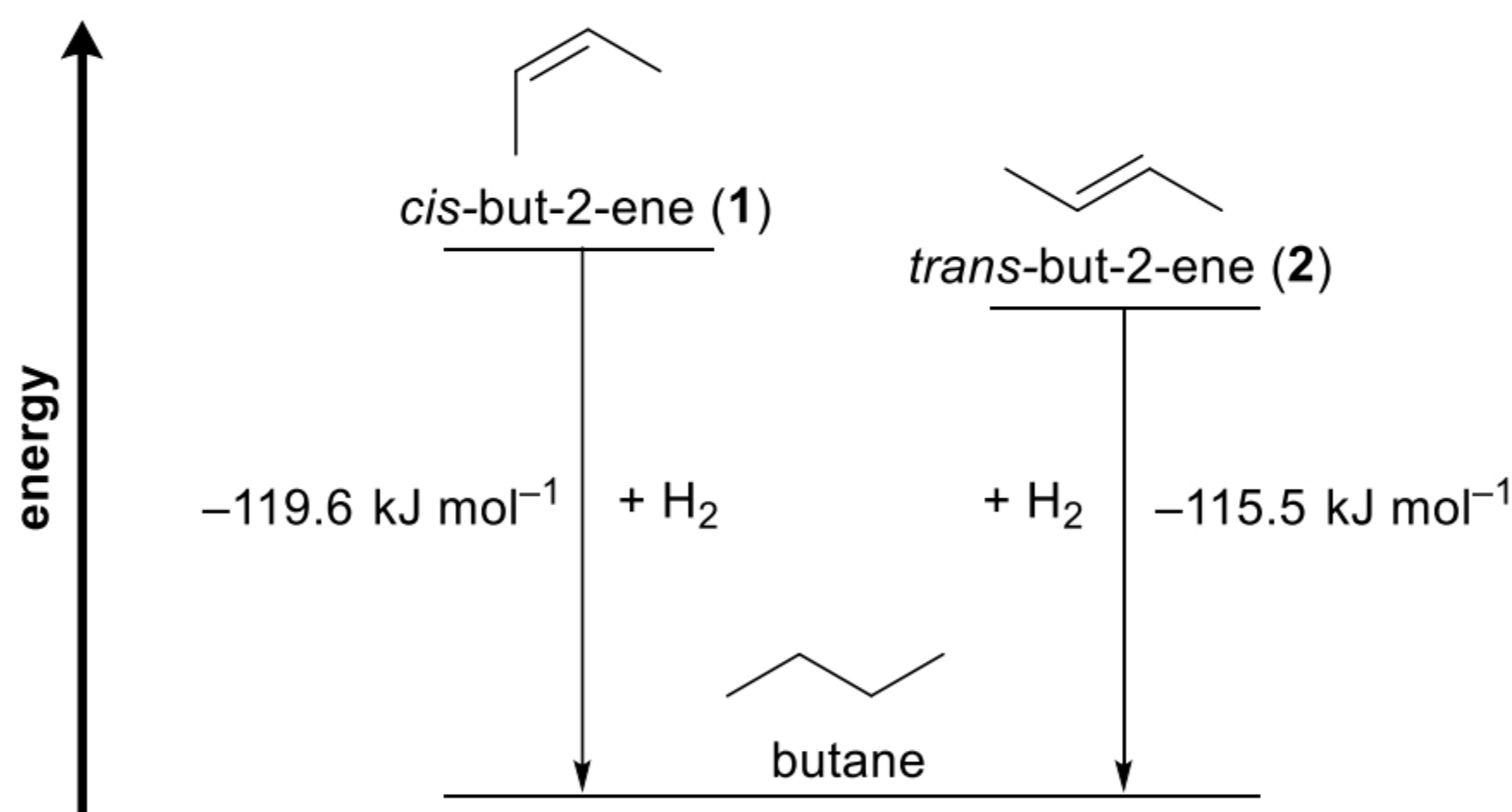
Note: Alkenes can be viewed either (a) from 'above' the plane of the molecule, in which case the wedges and dashed wedges are *not* included, or (b) from almost sideways; in this case, wedges and dashed wedges are included.

Compound **1** with the two methyl groups on the **same side** is ***cis***-but-2-ene, while compound **2** with the two methyl groups on **opposite side** is ***trans***-but-2-ene. They are called ***cis-trans* isomers** (an obsolete name still seen in some textbooks refer to them as geometric isomers).

Compounds **1** and **2** can be regarded as **non-interconvertible** as changing from one form to the other will involve **breaking the π bond** ($\sim 240 \text{ kJ mol}^{-1}$), rotation about the σ bond, followed by reforming the π bond:



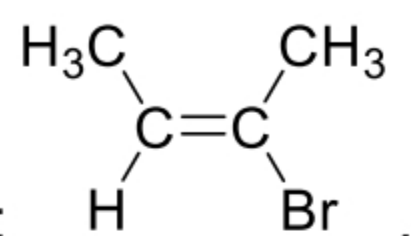
For *cis*-but-2-ene (**1**) and *trans*-but-2-ene (**2**), the enthalpy of hydrogenation is $-119.6 \text{ kJ mol}^{-1}$ and $-115.5 \text{ kJ mol}^{-1}$, respectively (both give butane upon hydrogenation).



Since the *cis*-isomer **1** releases about 4 kJ mol^{-1} more energy on hydrogenation than does **2**, it follows that *cis*-isomer **1** is more unstable because the methyl groups are closer together, resulting in greater **steric strain** (resulting in interelectronic repulsion).

With larger substituents, differences greater than 4 kJ mol^{-1} are encountered, with the *trans*-alkene being more stable than the corresponding *cis*-alkene.

The *cis* and *trans* nomenclature is unambiguous for **disubstituted** alkenes; however, the situation is not clear-cut for tri- and tetrasubstituted alkenes. With these latter compounds, problems arise in the definition of which substituent is *cis* or *trans* to which.



For example, look at the following trisubstituted alkene:

Is this considered a *cis* or *trans* isomer?

- Based on steric size, the two biggest group (CH_3 and Br) are on opposite sides, while the two identical groups (CH_3) are on the same side.
- The *cis*- and *trans*- descriptors are **not** applicable in this case.
- Scan this QR code to read more about E, Z isomerism (not required in syllabus):



Checkpoint

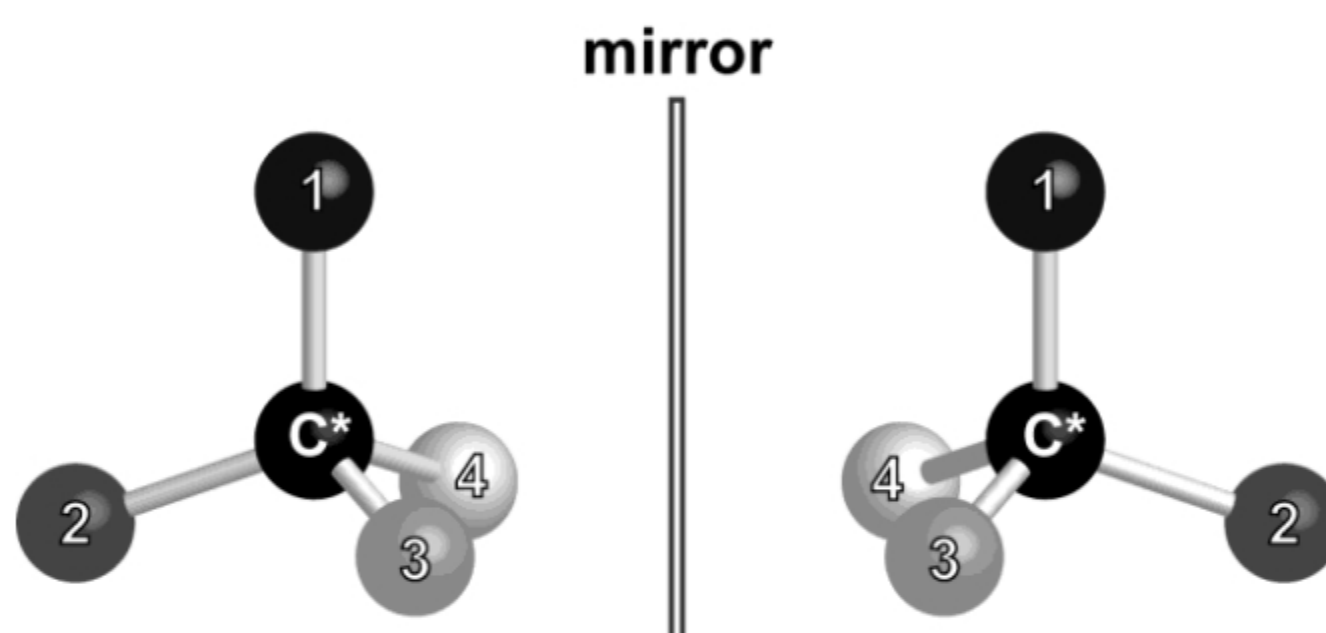
- ☐ I know that constitutional isomers (also known as structural isomers) have the **same molecular formula but different structural formulae**.
- ☐ I know that stereoisomers are isomers that have the **same molecular and structural formulae** but differ in their **spatial arrangement** (3-dimensional orientation) of the atoms
- ☐ I know the two criteria for cis-trans isomerism are as follows:
 - restricted rotation about the $\text{C}=\text{C}$ bond; and
 - two different groups of atoms bonded to each of the carbon atoms of the $\text{C}=\text{C}$ bond.

7.2.2 Enantiomerism

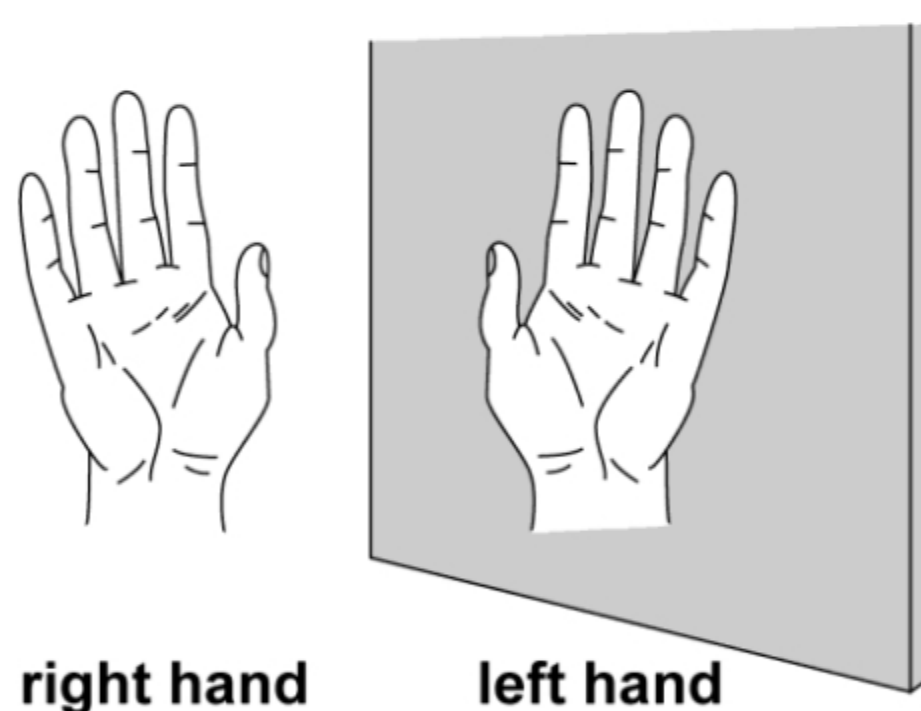
- LO (c) explain what is meant by a chiral centre
 (d) deduce whether a given molecule is chiral based on the presence or absence of chiral centres and/or a plane of symmetry
 (e) recognise that an optically active sample rotates plane-polarised light and contains chiral molecules
 (f) recognise that enantiomers have identical physical properties except in the direction in which they rotate plane-polarised light
 (g) recognise that enantiomers have identical chemical properties except in their interactions with another chiral molecule
 (i) deduce the possible isomers for an organic molecule of known molecular formula
 (j) identify chiral centres and/or *cis-trans* isomerism in a molecule of given structural formula

A sp^3 hybridised tetrahedral carbon atom that is attached to **four different entities** (atoms or groups) is known as an asymmetric carbon atom.

A molecule with an asymmetric carbon atom (denoted by an **asterisk (*)** on the C), as in the diagram below, **cannot be superposed on its mirror image**.



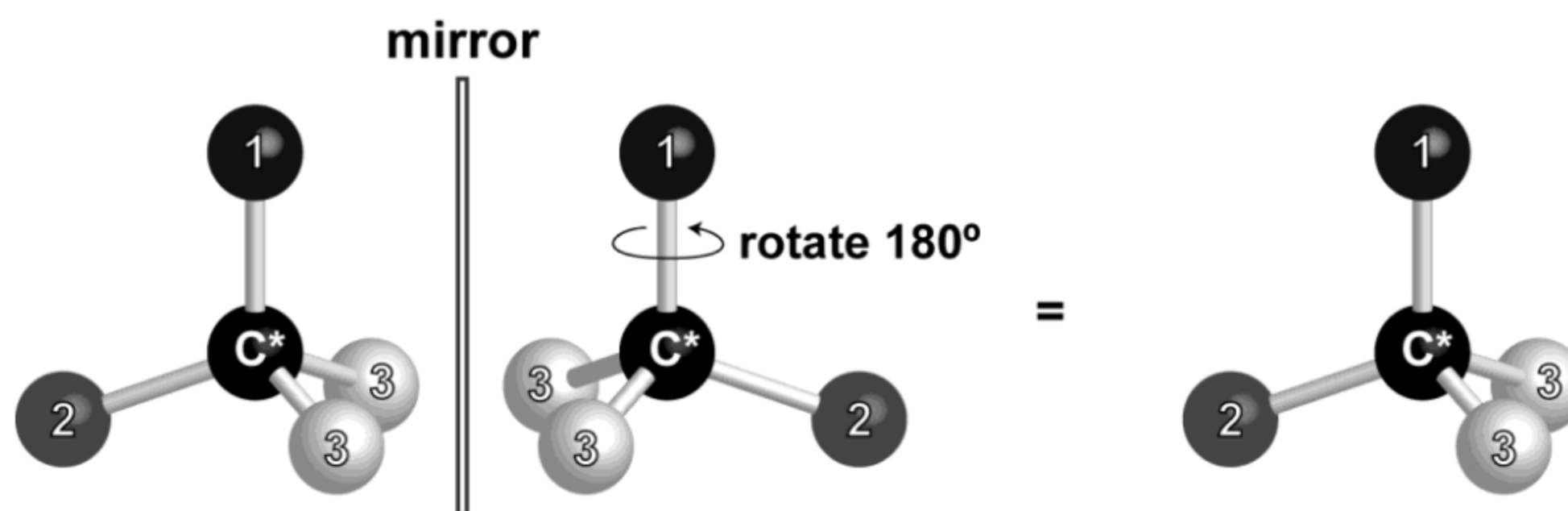
This is the same property that a right hand, say, placed in front of a plane mirror possess.



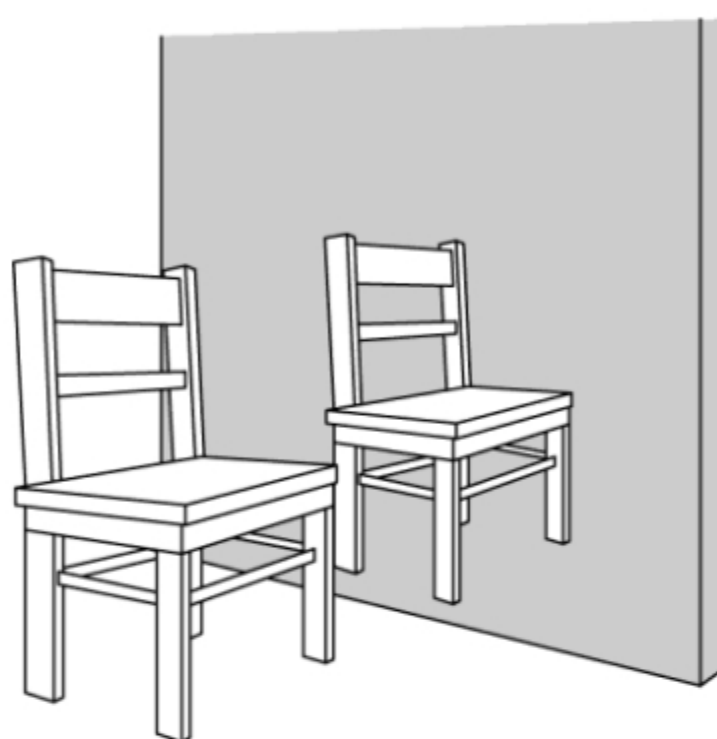
Molecules such as the one shown above and our hands are said to be **chiral** (or handed), from the Greek word 'cheir' for hand.

Chirality then is the property of handedness. It is the geometric property of a rigid object (or spatial arrangement of points or atoms) of being **non-superposable on its mirror image**. The adjective 'chiral' refers to the molecule as a whole, rather than to a particular atom.

Molecules such as CCl_4 , CH_2Cl_2 and $CHFC l_2$ that can be superposed on their mirror images are said to be '**achiral**'.

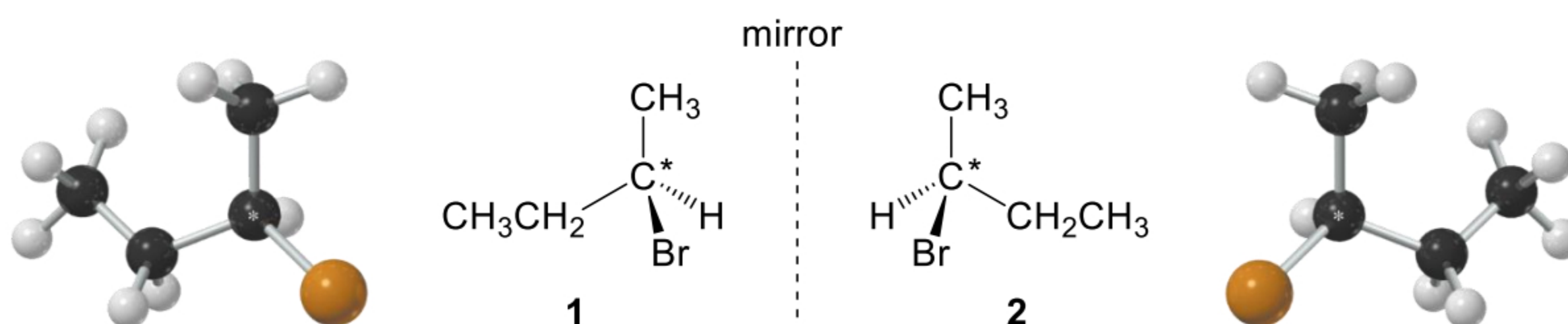


A chair for example is also achiral as it can be superposed on its mirror image.



An asymmetric carbon attached to four different substituents is said to be a chiral carbon or **chiral centre**, since the resulting molecule is chiral.

To represent three-dimensional molecules in two-dimension, the **wedge-and-dash notation** is used. In this notation, two bonds are drawn in the plane of the page (sticks: —), one bond is drawn coming toward you, out of the page (wedged: $\blacktriangleleft$), and one bond is drawn going away from you, behind the page (dashed: $\cdots$). *E.g.*, 2-bromobutane



Based on this figure above, molecules 1 and 2 are mirror images of each other and are non-superposable, hence molecules 1 and 2 are considered **enantiomers** ('enantio' in Greek means opposite).

Enantiomers are a pair of molecules which are **mirror images** of each other and **non-superposable**.

Enantiomers have **identical physical** (e.g., melting point, boiling point and solubility) and **chemical properties** under normal (achiral) conditions, with one exception – optical activity.

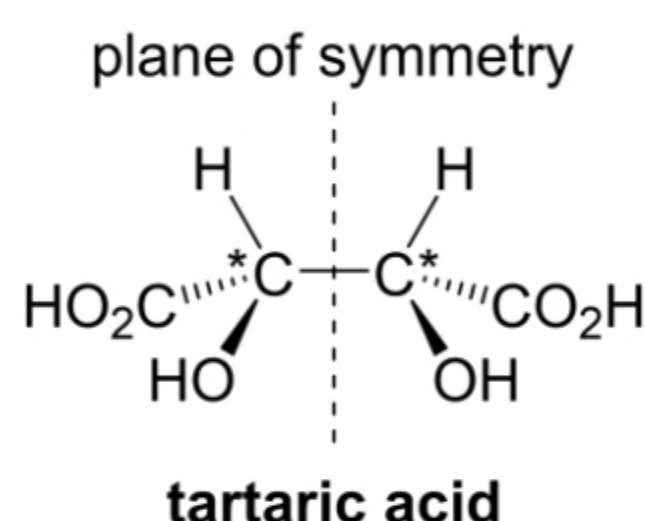
How to determine whether a molecule is chiral?

The ultimate way to test for molecular chirality is to construct models of the molecule and its mirror image and then determine whether they are superposable. We can apply this test with actual models, or by attempting to superpose them in our minds.

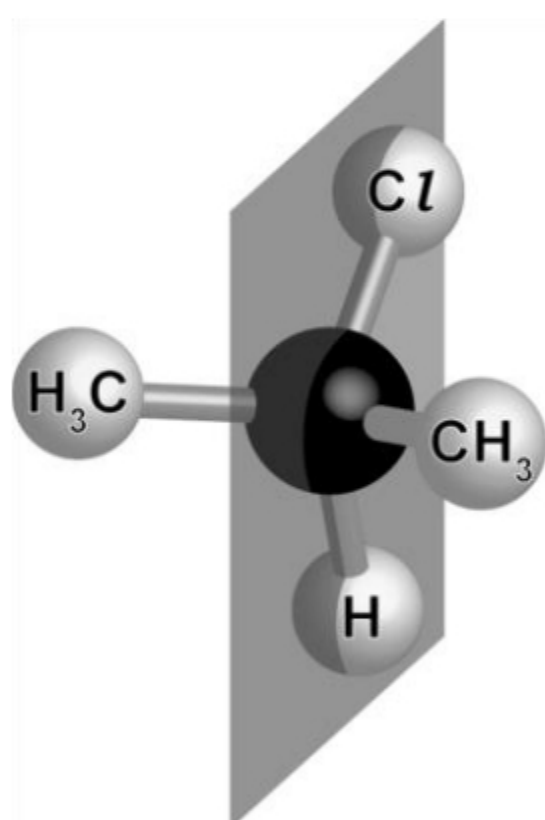
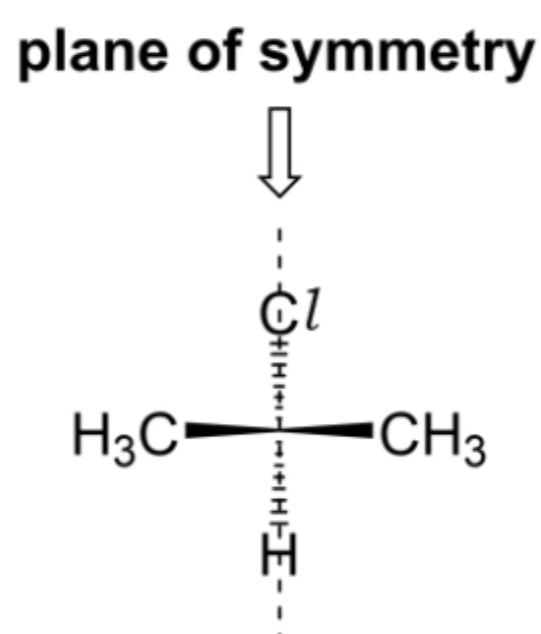
There are other aid that can assist us in recognising chiral molecules.

We have seen one already: the presence of a **single chiral centre**.

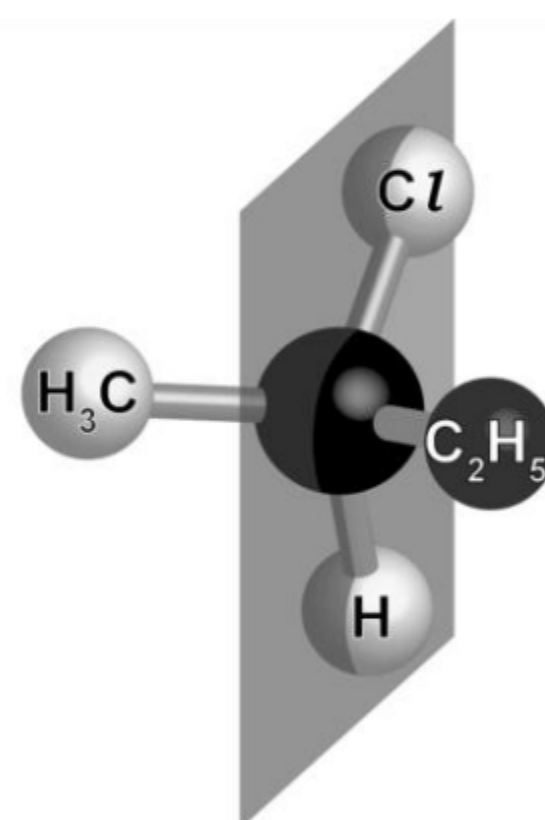
However, when there are more than one chiral centres in a molecule, it may sometimes lead to an achiral molecule due to the presence of a plane of symmetry. *Meso*-tartaric acid (see below) has two chiral centres but it possesses an internal plane of symmetry, hence it is **achiral (or not chiral)**.



A plane of symmetry (also called a mirror plane) is defined as an imaginary plane that bisects a molecule in such a way that the two halves of the molecule are mirror image of each other.



achiral



chiral

However, the absence of a plane of symmetry does not necessarily guarantee that a molecule is chiral, although it is true in many cases.

In short, to determine if a molecule is chiral, we generally consider the following factors:

- (1) Contains one or more chiral centres
- (2) Should not have internal plane of symmetry

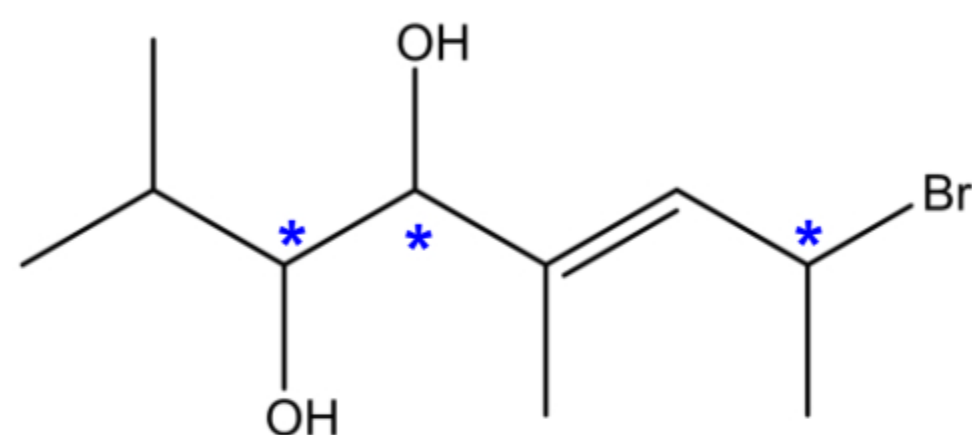
Example 7B

1. Identify all chiral centres (*) in the following molecules.

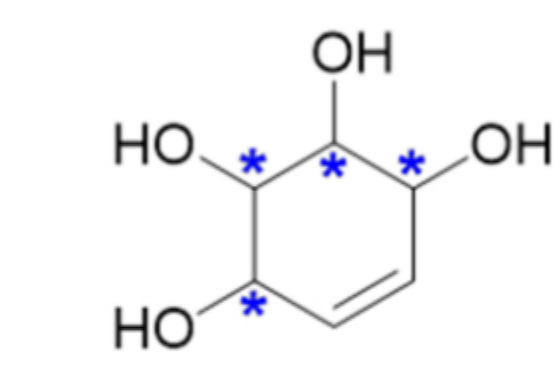
(a)



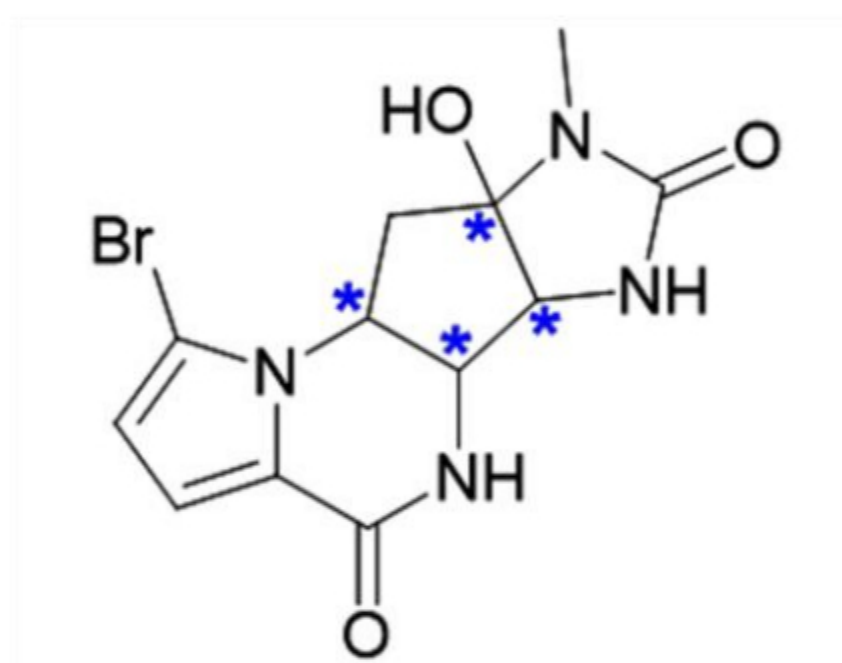
(b)



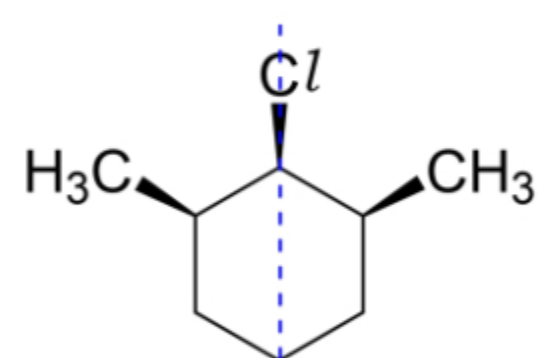
(c)



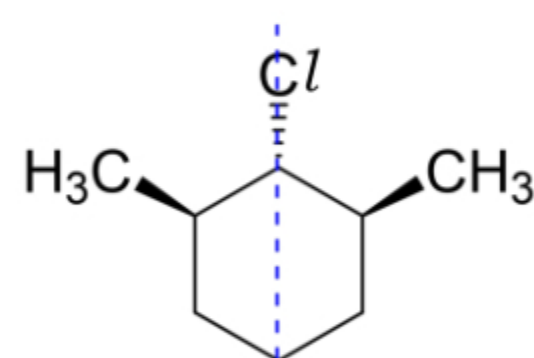
(d)



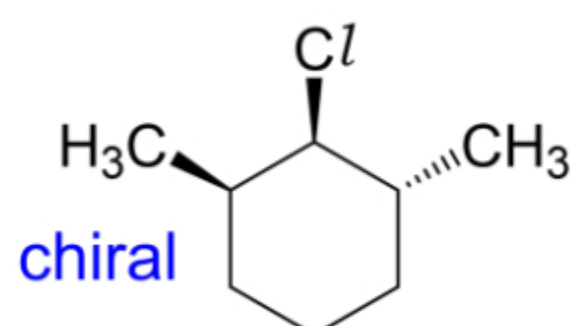
2. Determine which of the following molecules are chiral.



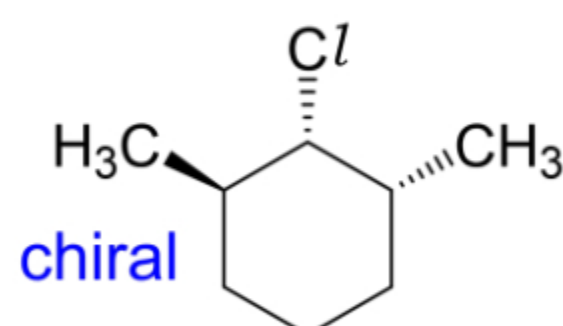
achiral mirror plane



achiral mirror plane



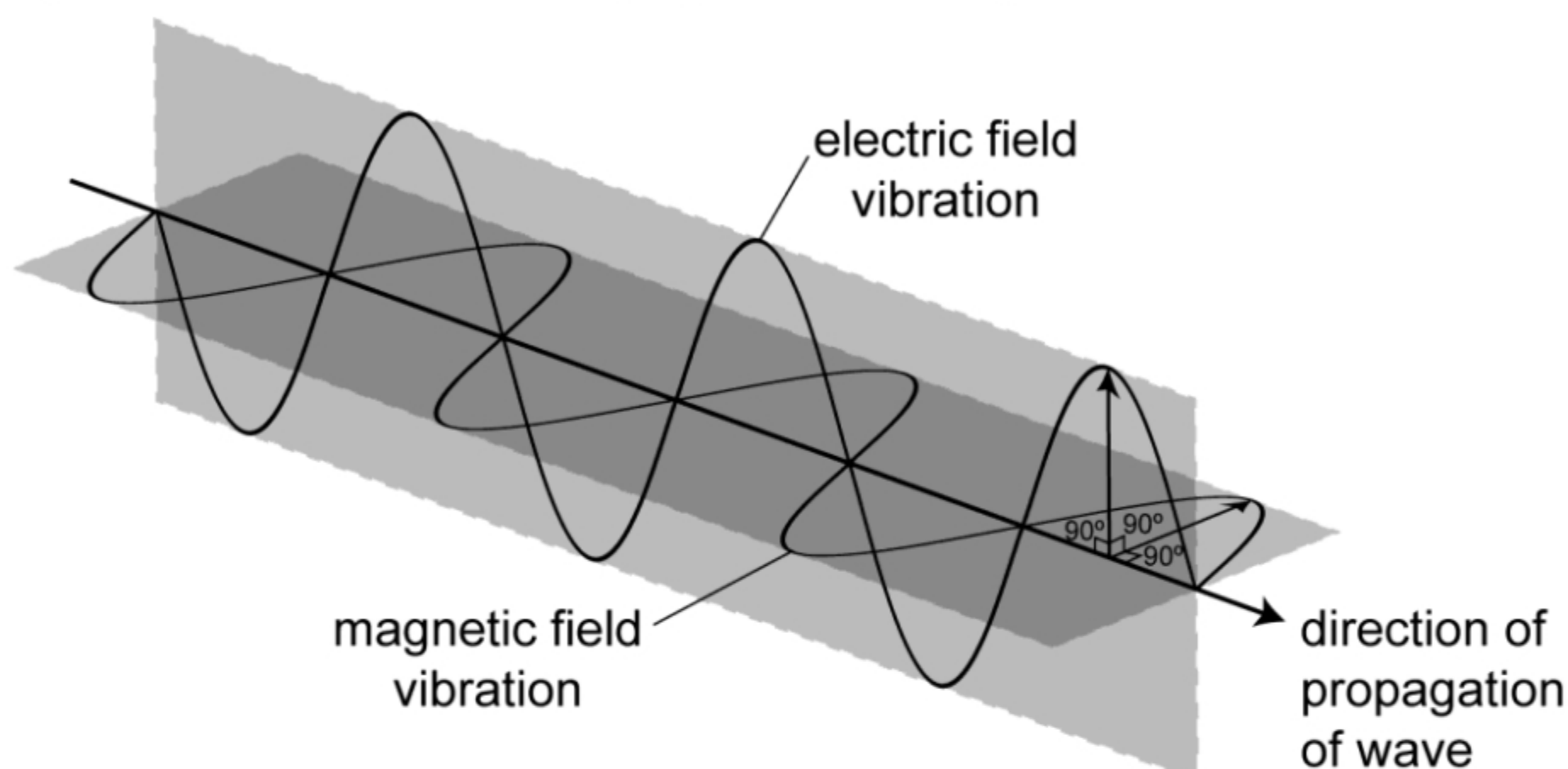
chiral



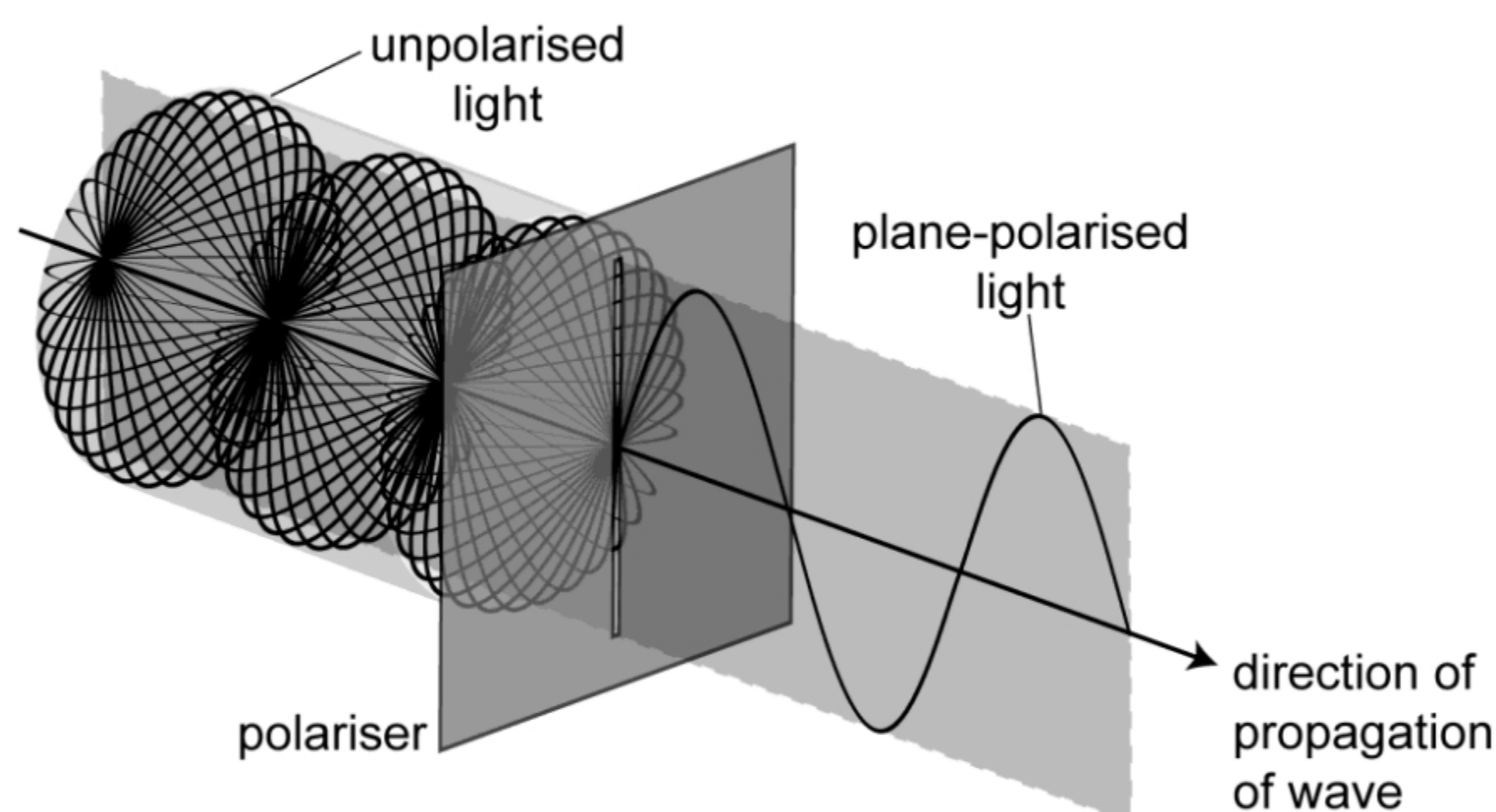
chiral

Optical Activity

Light may be regarded as a wave motion that contain oscillating perpendicular electric and magnetic fields, at right angles to the direction of propagation of the light wave:



In normal light, the electric and magnetic fields of light oscillates in all planes. Considering only the electric field components:



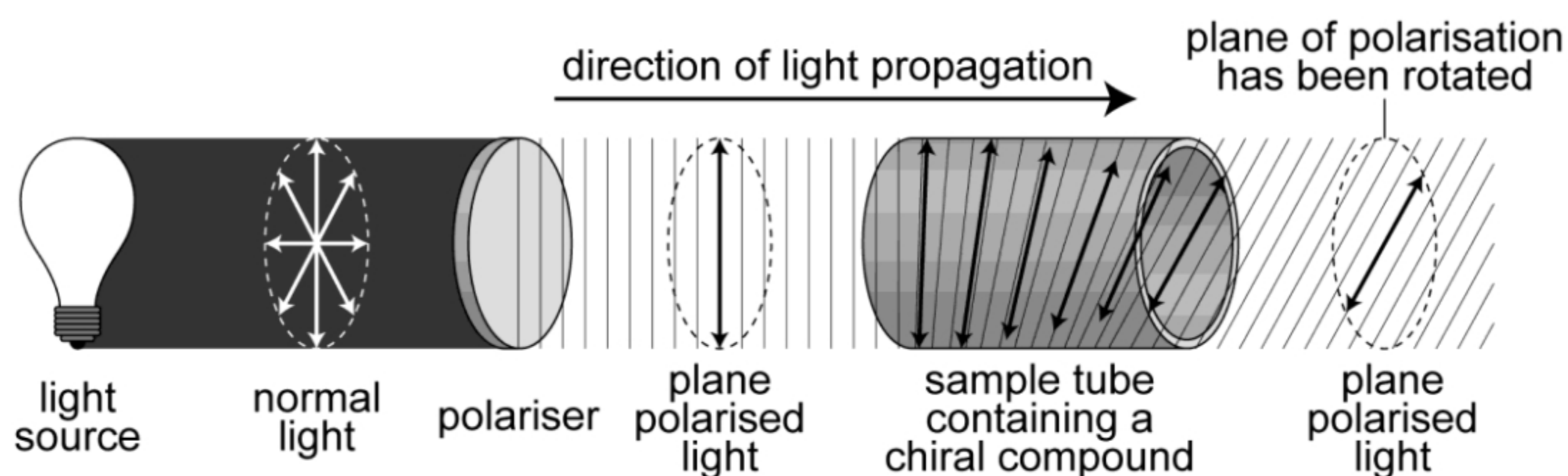
When a beam of normal light is passed through a device called a **polariser**, that in effect acts as a filter, only light waves that are oscillating in a single plane are allowed to pass through. The polariser thus serves to block the passage of light that is oscillating in all other planes. The light that emerges from the polariser is said to be **plane polarised**.

In 1815 the French physicist Biot made the important observation that when a beam of **plane polarised light** is passed through a solution of certain naturally occurring organic compounds, the plane of polarised light is rotated either to the left or to the right.

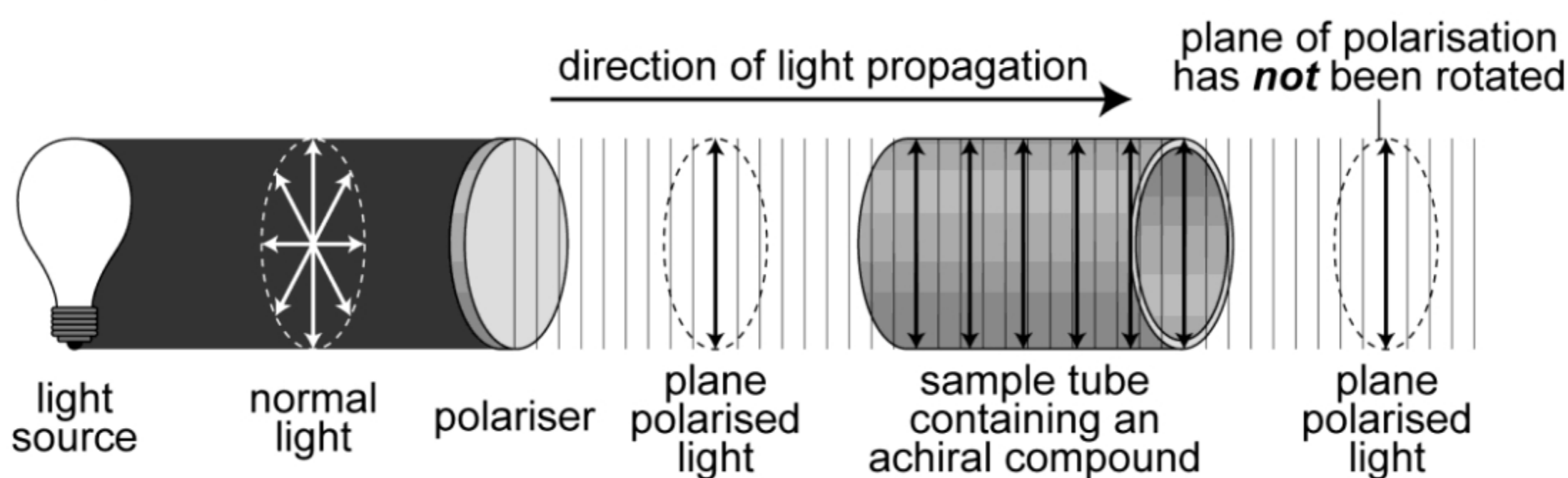
Molecules that are able to rotate the plane of polarisation of a beam of transmitted plane-polarised light is said to possess **optical activity** (or to be **optically active**).

An enantiomer causing rotation in a clockwise direction (when viewed in the direction facing the oncoming light beam) under specified conditions is called dextrorotatory and its chemical name or formula is designated by the prefix (+)-; one causing rotation in the opposite sense is laevorotatory and designated by the prefix (-)-.

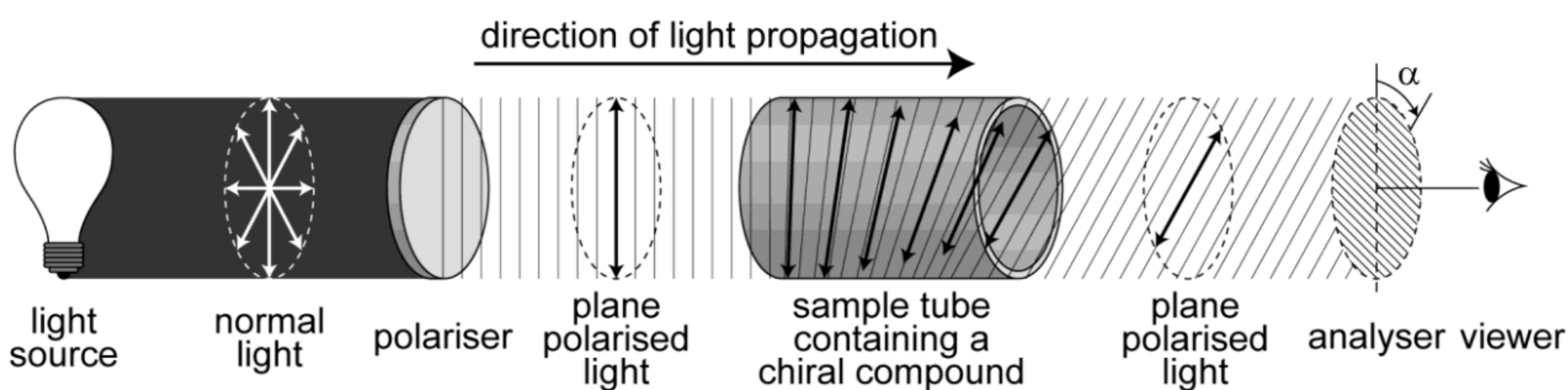
An **equimolar** mixture of a pair of enantiomers, known as a **racemate or racemic mixture**, **does not** exhibit optical activity. The chemical name or formula of a racemate is distinguished from those of the enantiomers by the prefix ($\pm$)-.



The plane of polarisation is also **not** rotated in the case of an **achiral** compound:



Measurements of optical activity are carried out with a **polarimeter**, which is shown schematically in the figure below:



The direction and extent of the rotation, α , of the plane of polarised light is the basis of **specific rotation**, $[\alpha]$.

7.2.3 Biological Importance of Stereochemistry

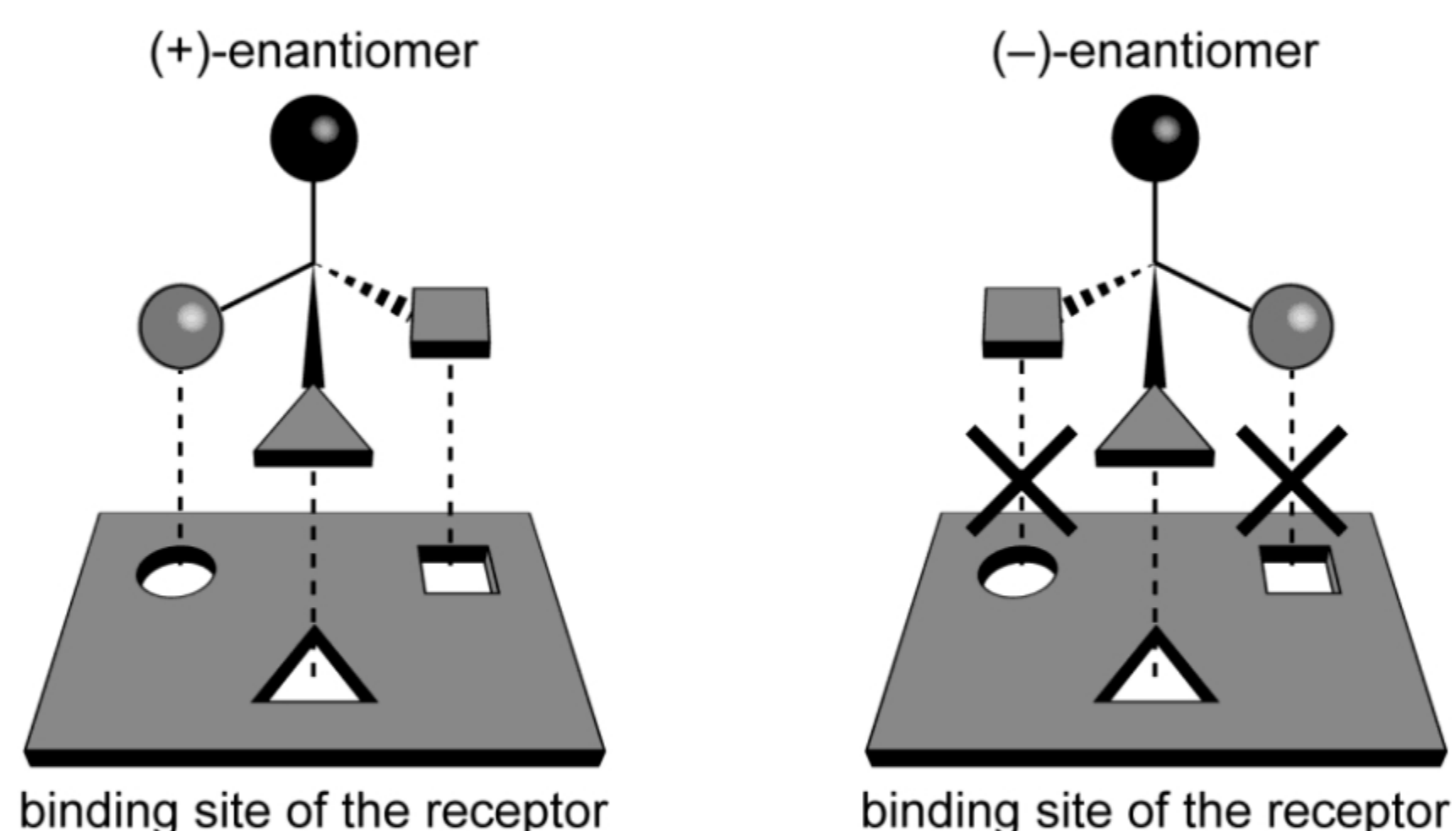
LO (h) recognise that different stereoisomers exhibit different biological properties, for example in drug action

The origin of biological properties relating to chirality is often likened to the specificity of our hands for their respective gloves; the binding specificity for a chiral molecule (like a hand) at a chiral receptor site (a glove) is only favourable in one way.

If either the molecule or the biological receptor site had the wrong handedness, the natural physiological response (e.g., neural impulse, reaction catalysis) would not occur.

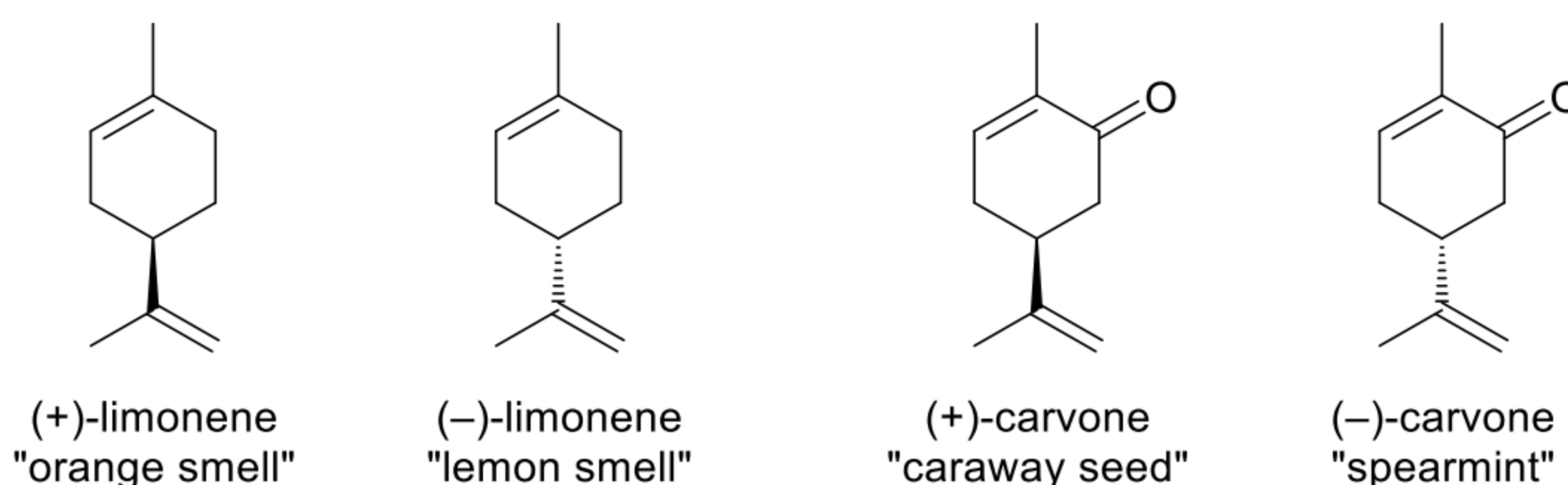
A diagram showing how only the (+)-isomer in a pair of enantiomers can interact in an optimal way with a hypothetical binding site (e.g., in an enzyme) is shown below.

Because of the chiral centre of the enantiomer, three-point binding can occur with proper alignment for only one of the two enantiomers.



Chiral molecules can show their handedness in many ways, including the way they affect human beings.

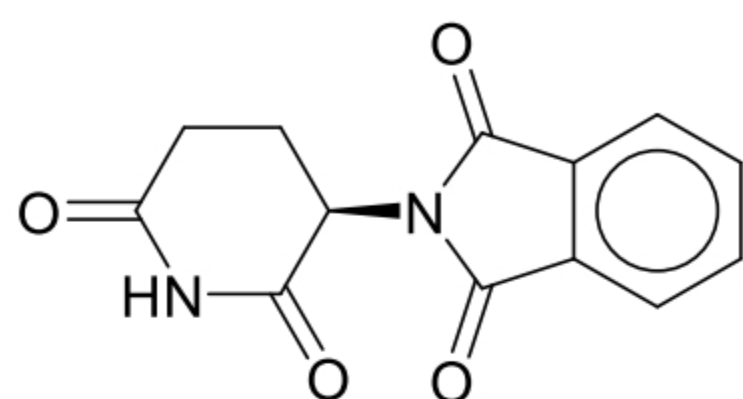
The (+)-enantiomeric form of a compound called limonene is primarily responsible for the odour of oranges and the other (–)-enantiomer for the odour of lemons.



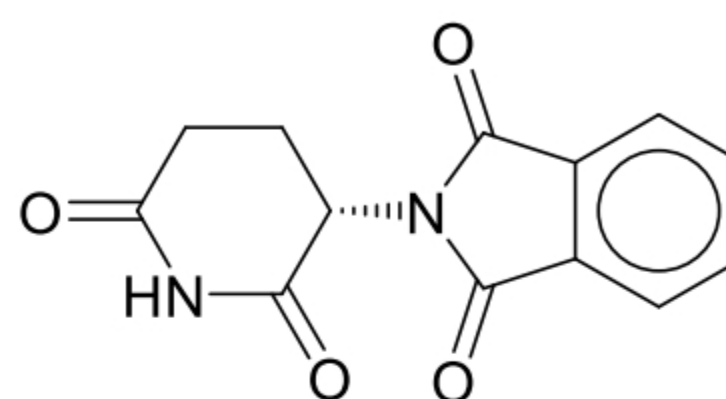
The (+)-enantiomer of a compound called carvone is the essence of caraway, and the other is the essence of spearmint.

The activity of drugs containing chirality centres can similarly vary between enantiomers, sometimes with serious or even tragic consequences.

For several years before 1963 the drug thalidomide was used to alleviate the symptoms of morning sickness in pregnant women. In 1963 it was discovered that thalidomide was the cause of horrible birth defects in many children born subsequent to the use of the drug.



(+)-thalidomide
(sleep-inducing)



(-)-thalidomide
(teratogenic)

Even later, evidence began to appear indicating that whereas one of the thalidomide enantiomers (the right-handed molecule) has the intended effect of curing morning sickness, the other enantiomer, which was also present in the drug (in an equal amount), may be the cause of the birth defects.

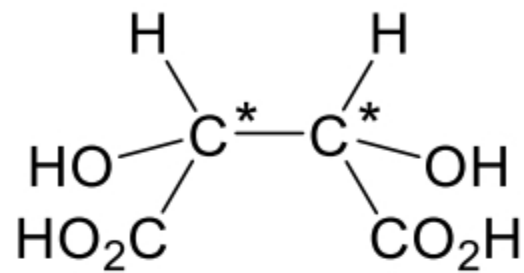
The evidence regarding the effects of the two enantiomers is complicated by the fact that, under physiological conditions, the two enantiomers are interconverted.

Now, however, thalidomide is approved under highly strict regulations for treatment of some forms of cancer and a serious complication associated with leprosy. Its potential for use against other conditions including AIDS and rheumatoid arthritis is also under investigation.

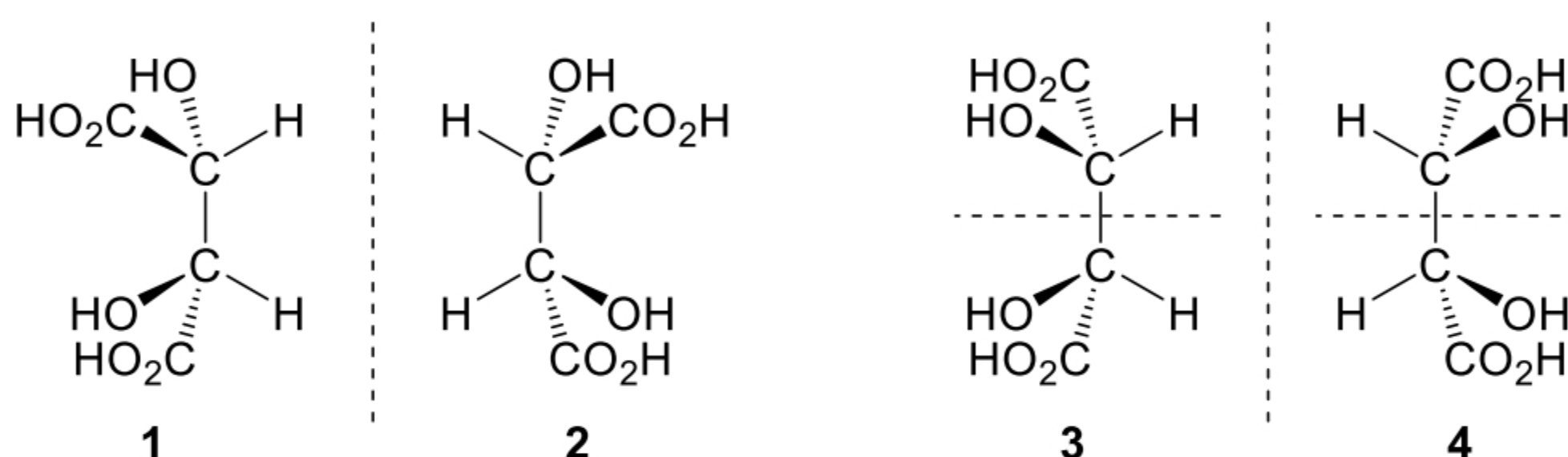
7.2.4 Number of Stereoisomers

The **maximum** number of stereoisomers possible for a molecule with n **chiral centres** is given by 2^n .

The **actual number may be fewer since some of the isomers may possess internal symmetry elements**.

E.g., consider tartaric acid, , with two chiral centres. So there is a maximum of $2^2 = 4$ stereoisomers.

There are two pairs of mirror images possible:



1 and **2** are a distinct pair of mirror images which are non-superposable.

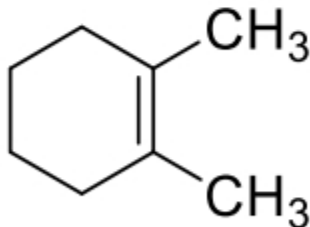
3 and **4**, although distinct from **1** and **2**, are however superposable (due to the presence of an internal mirror plane). They are in fact the *same*!! This is the *meso* compound that we have seen earlier on page 37.

Hence there are only **3 distinct stereoisomers** for tartaric acid.

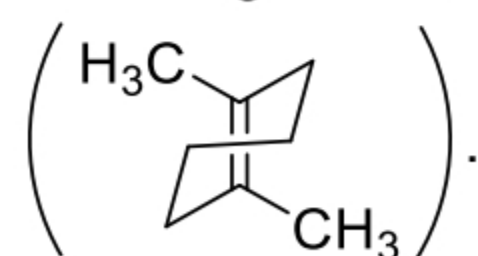
The **maximum** number of stereoisomers possible for a molecule with m ***cis-trans* double bond** is also given by 2^m .

Again, the actual number may be less as some of the isomers are in fact the same compound due to the presence of internal symmetry elements.

In addition, it is not possible to have *cis-trans* isomerism for double bond in a small ring system.

E.g. for 1,2-dimethylcyclohexene, , the two methyl groups can only assume a

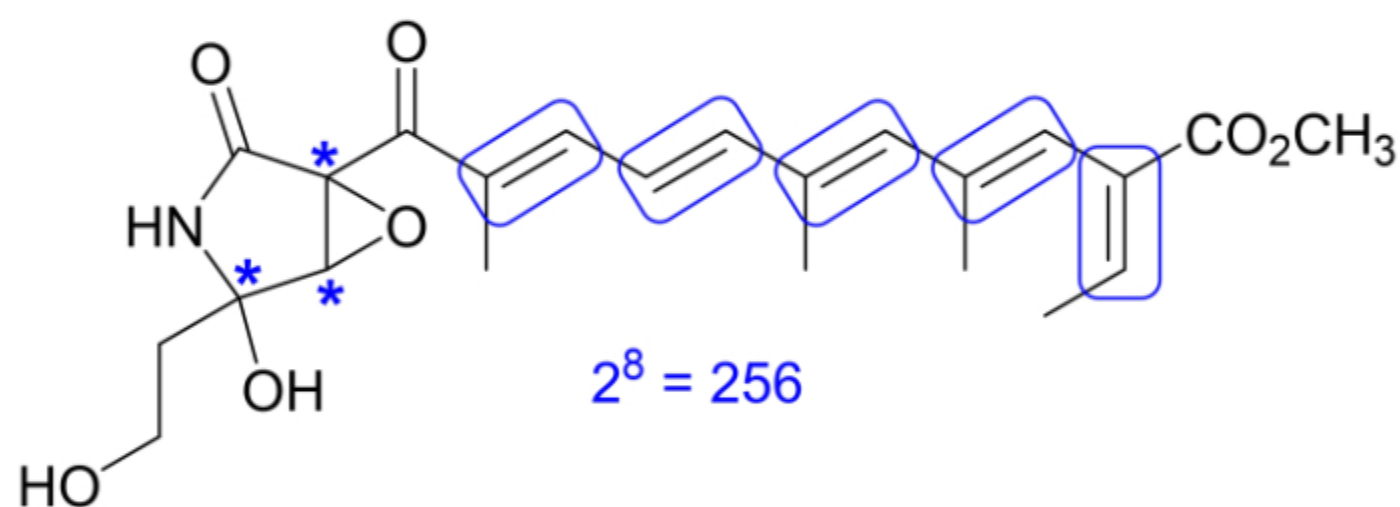
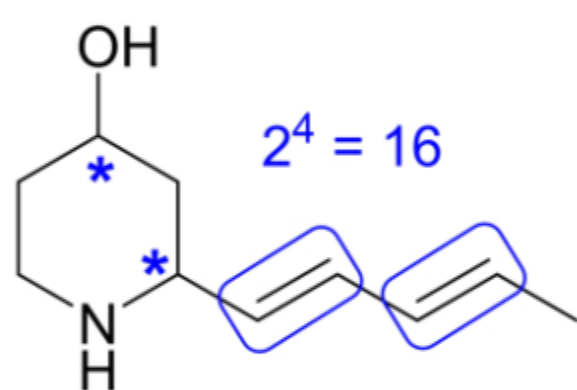
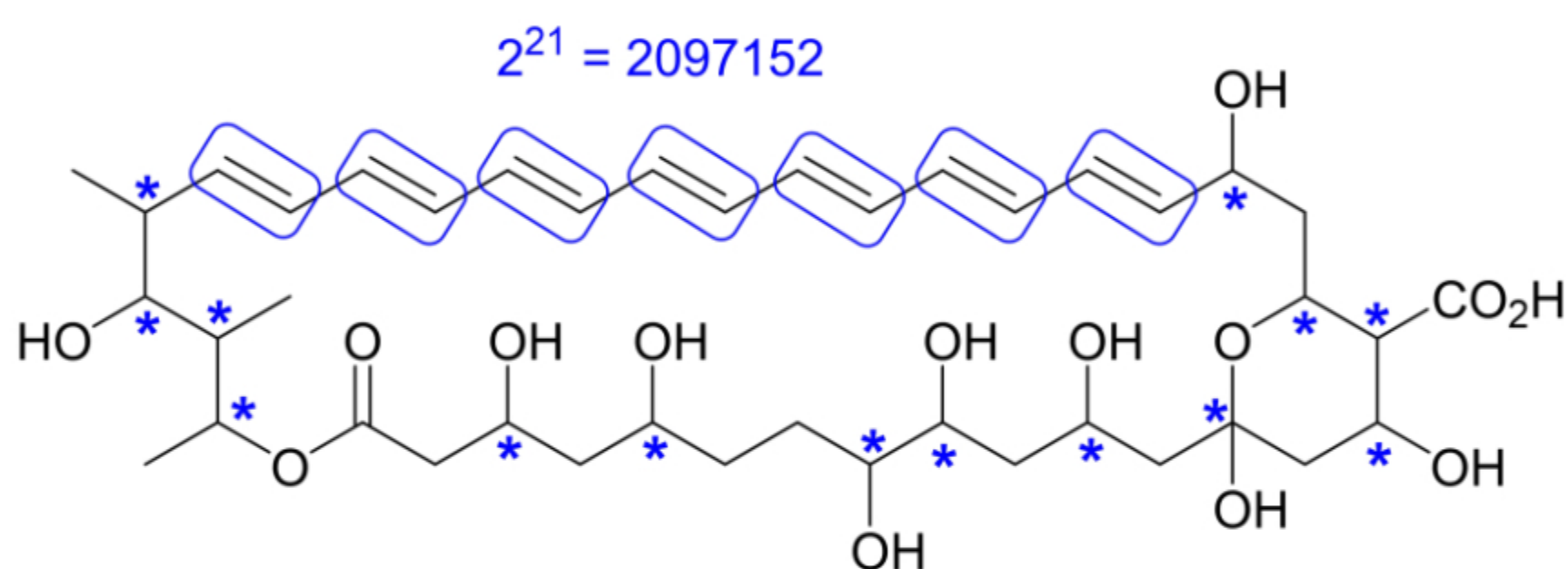
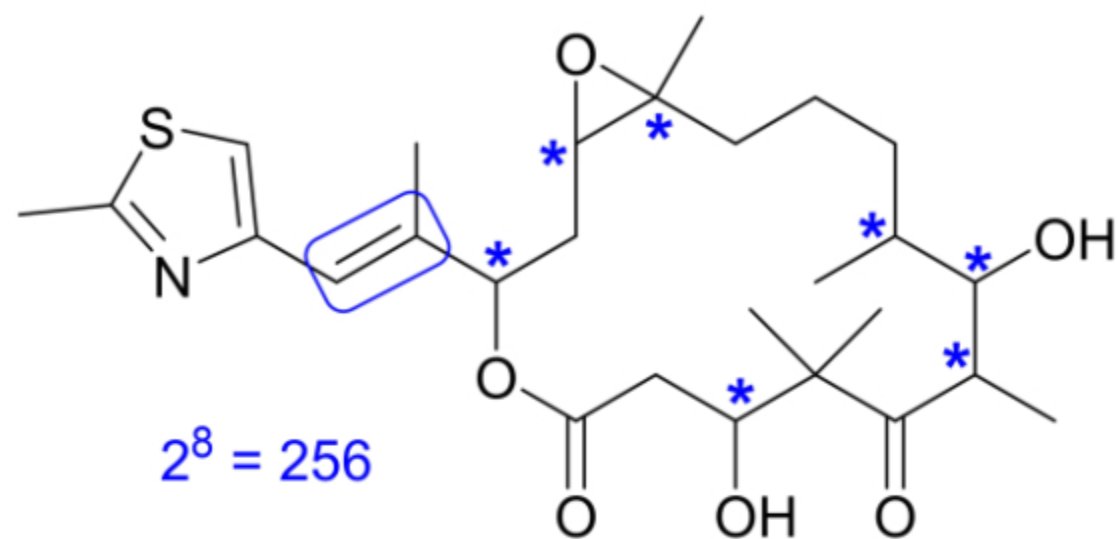
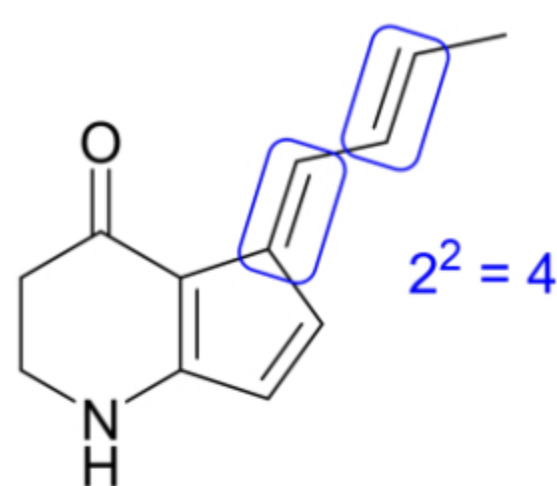
cis-configuration, since it is geometrically **not** possible to bend the ring to be in a *trans*-configuration



For a molecule with n **chiral centres** and m ***cis-trans* double bond**, the **maximum** number of stereoisomers possible is given by 2^{n+m} .

Example 7C

Determine the maximum number of stereoisomers possible for the following compounds.

**Checkpoint**

☐ I know the following definitions related to chirality:

- **chiral carbon or chiral centre:** an asymmetric carbon attached to four different substituents
- **chiral molecule:** consists of at least one chiral centre with no internal plane of symmetry and able to rotate plane polarised light (optically active).
- **racemic mixture (or racemate):** contains equimolar of the two enantiomers and is not optically active

☐ I know the general formula to *determine the total number of stereoisomers: 2^{n+m} , where n is the number chiral centres and m is the number *cis-trans* double bonds in the given molecule.*

Answers to Self-Check Questions:

1A: TFFFT TFFTF

5A: (i) 4-bromo-3-methylbutanoic acid; (ii) 3-iodo-2,2-dimethylpropan-1-ol; (iii) 2-amino-2,3,3-trimethylbutanoic acid; (iv) 3-bromo-3-methylbutanal