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IB DIPLOMA CHEMISTRY · FIRST ASSESSMENT 2025

Structure 3.2 Stereoisomers

Booklet 6 (HL) · Understanding 3.2.7

Why some molecules with identical connectivity are different compounds: cis–trans isomers, chiral carbons, enantiomers and the rotation of plane-polarized light

Complete revision notes & memory points · Higher Level

How the level tags work in this booklet

HL **Everything in this booklet is Higher Level only.** Understanding 3.2.7 is not assessed at Standard Level. SL students do not need this booklet.

SL + HL Short reminder panels recap SL material that the HL work builds on: structural isomers (3.2.6), σ and π bonds and VSEPR shapes (Structure 2.2), and stereochemical formulas (Booklet 4).

Inside this booklet

1. What the syllabus actually asks of you
2. Isomers: the big picture
3. cis–trans isomerism
4. Chirality and optical isomers
5. Enantiomers: properties and optical activity
6. Key points to memorise
7. Check yourself
8. Answers

1 What the syllabus actually asks of you

Structural isomers (3.2.6) differ in which atoms are joined to which. **Stereoisomers** go one step further: every atom is joined to exactly the same neighbours by exactly the same kinds of bond, yet the two molecules are different compounds because their atoms point in different directions in space. A flat condensed formula cannot show the difference at all, so this topic is about thinking, and drawing, in three dimensions. It matters far beyond the exam: the two mirror-image forms of a drug can have completely different effects in the body.

Understanding	What it says	What you must be able to do	Level
3.2.7 Stereoisomers	Stereoisomers have the same constitution (atom identities, connectivities and bond multiplicities) but different spatial arrangements of atoms.	◆ Describe and explain the features that give rise to **cis–trans** isomerism; recognize it in non-cyclic alkenes and in C_3 and C_4 cycloalkanes. ◆ **Draw** stereochemical formulas showing the tetrahedral arrangement around a **chiral carbon**. ◆ Describe and explain a chiral carbon giving rise to stereoisomers with different **optical properties**. ◆ Recognize a pair of **enantiomers** as non-superimposable mirror images from 3D modelling (real or virtual).	HL

Notes from the guide that decide what you are asked

- Naming with the **E/Z system will not be assessed**. Use *cis* and *trans*.
- The terms **chiral, optical activity, enantiomer** and **racemic mixture** must be understood.
- The different chemical properties of enantiomers are limited to the fact that they **behave differently in chiral environments**.
- Enantiomers must be drawn with **wedge–dash** representations using **tapered** bonds.

Links and connections for 3.2.7

- **Structure 3.2.6:** structural isomers (chain, position, functional group) → section 2.1
- **Structure 2.2:** σ and π bonds explain why a C=C bond cannot rotate; VSEPR gives the tetrahedral and trigonal planar shapes → sections 3.1 and 4.2
- **Structure 3.1 (HL):** square planar complexes such as cisplatin also show *cis–trans* isomerism → section 3.5
- **Tool 2, Inquiry 2:** 3D models (real or virtual) are the best way to see that enantiomers cannot be superimposed → section 4.1
- **Nature of Science and TOK:** Pasteur and optical activity; thalidomide and the regulation of chiral drugs → sections 5.3 and 5.4

What the data booklet gives you — and what it does not

Almost nothing here is in the data booklet. The definitions, the conditions for *cis–trans* and optical isomerism and the drawing conventions must all be learned. One useful exception: the bond enthalpies in **Section 12** (C=C 614 kJ mol^{-1}, C–C 346 kJ mol^{-1}) show that the π bond is worth roughly 614 − 346 ≈ 270 kJ mol^{-1}, which is why it cannot be broken simply by twisting the molecule at room temperature.

2 Isomers: the big picture HL

2.1 Reminder: structural isomers SL + HL

Isomers are compounds with the same molecular formula but a different arrangement of atoms. In **structural isomers** the atoms are joined together in a different order. There are three kinds:

Type	What changes	Example (same molecular formula)
chain	the carbon skeleton (straight or branched)	C_4H_{10}: butane $CH_3CH_2CH_2CH_3$ and methylpropane $CH_3CH(CH_3)CH_3$
position	the position of the functional group on the chain	C_3H_8O: propan-1-ol $CH_3CH_2CH_2OH$ and propan-2-ol $CH_3CH(OH)CH_3$
functional group	the functional group itself (a different class)	C_3H_6O: propanal CH_3CH_2CHO and propanone CH_3COCH_3; $C_3H_6O_2$: propanoic acid and methyl ethanoate

2.2 Stereoisomers

Definitions to learn

- **Stereoisomers** have the same **constitution** (the same atoms, joined to the same neighbours by the same types of bond) but a different **spatial arrangement** of the atoms.
- **Configurational isomers** can only be interconverted by **breaking** a covalent bond. They are separate compounds that can be isolated. *cis–trans* isomers and optical isomers are both configurational.
- **Conformational isomers** (conformers) interconvert simply by **rotation about σ bonds**, usually so quickly that they cannot be separated. They are not required for this course.

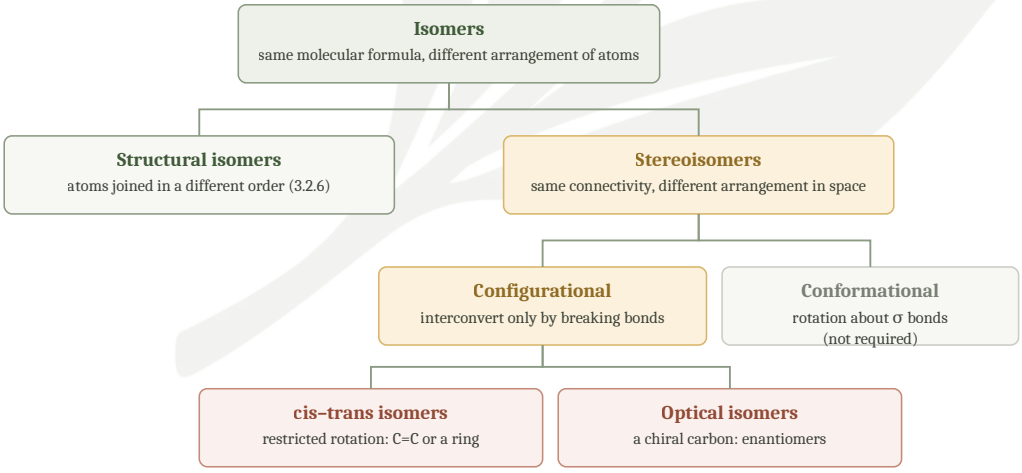


Figure 1 — The family tree of isomerism. This booklet covers the two configurational types highlighted at the bottom.

TOK — the chair and the boat

Cyclohexane, C_6H_{12}, constantly flips between conformations that chemists nicknamed the 'chair' and the 'boat' because of their shapes. Naming a molecular shape after an everyday object is an act of imagination. What is the role of imagination and analogy in forming hypotheses in the natural sciences?

3 cis–trans isomerism HL

3.1 Why a C=C bond cannot rotate

A C=C double bond consists of one **σ bond**, along the line between the nuclei, and one **π bond**, formed by the **sideways overlap of two p orbitals** above and below that line (Structure 2.2). Rotating one carbon relative to the other would twist the p orbitals out of alignment and destroy the overlap, which means **breaking the π bond**. That needs far more energy than is available at room temperature, so there is **restricted rotation** about a C=C bond. A C–C single bond, by contrast, is a σ bond only, and rotation about it does not affect the overlap at all.

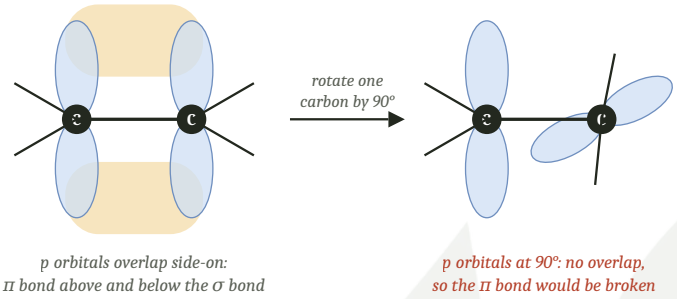


Figure 2 — The π bond locks the two halves of an alkene in one plane. The atoms attached to the C=C carbons are fixed either on the same side or on opposite sides of the double bond.

3.2 The two conditions

Definition and conditions to learn

cis–trans* isomers** are stereoisomers that differ in the positions of groups relative to a reference plane, which runs through a C=C bond or through a ring. In the ***cis isomer two identical (or matching) groups are on the **same side**; in the ***trans*** isomer they are on **opposite sides**.

cis–trans isomerism needs **both** of these:

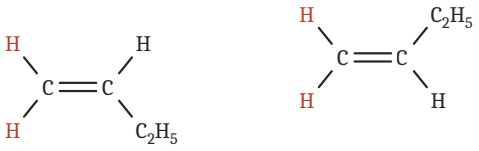
1. **Restricted rotation**, caused by a C=C double bond or by a ring.
2. **Two different groups on each** of the two carbons concerned. If either carbon carries two identical groups, swapping them gives the same molecule and there is no isomerism.



cis-but-2-ene
b.p. 4 °C

trans-but-2-ene
b.p. 1 °C

Figure 3 — Each C=C carbon carries an H and a CH_3, so there are two isomers. The C=C carbons are trigonal planar, so draw the bonds at 120°.



but-1-ene — the 'other' arrangement: the same molecule

Figure 4 — But-1-ene has no *cis–trans* isomers: one C=C carbon carries two H atoms (red), so swapping the groups on the other carbon simply gives the same molecule turned over.

Method — does an alkene show cis–trans isomerism?

1. Draw the C=C with the four attached groups at 120°, using a full structural or stereochemical formula. A condensed formula such as $CH_3CH{=}CHCH_3$ cannot show the difference.
2. Look at the **left** carbon: are its two groups different? Then look at the **right** carbon: are its two groups different?
3. Only if the answer is yes for **both** carbons are there two isomers. Compare the **whole groups**: $-CH_3$ and $-CH_2CH_3$ are different groups.

Alkene	Groups on C=C carbon 1	Groups on C=C carbon 2	cis–trans?
propene, $CH_2{=}CHCH_3$	H, H	H, CH_3	no
1,1-dichloroethene, $CCl_2{=}CH_2$	Cl, Cl	H, H	no
1,2-dichloroethene, CHCl=CHCl	H, Cl	H, Cl	**yes**
2-methylbut-2-ene, $(CH_3)_2C{=}CHCH_3$	CH_3, CH_3	H, CH_3	no
pent-2-ene, $CH_3CH{=}CHCH_2CH_3$	H, CH_3	H, C_2H_5	**yes**
but-2-enedioic acid, HOOCCH=CHCOOH	H, COOH	H, COOH	**yes**

When all four groups are different

In a molecule such as 1-bromo-1-chloropropene, $CBrCl{=}CHCH_3$, the two isomers still exist, but it is no longer obvious which pair of groups 'cis' refers to. IUPAC solves this with the *E/Z* system, which ranks the groups by atomic number. *E/Z* naming is **not assessed**: you only need to recognize that two isomers exist.

3.3 cis–trans isomers in rings: C3 and C4 cycloalkanes

A ring also prevents rotation: to turn one carbon over, you would have to break the ring. In cyclopropane the carbon atoms form a triangle (bond angles 60°) and in cyclobutane a slightly puckered square (about 90°), so both rings are close to flat and the **plane of the ring** acts as the reference plane. If two ring carbons each carry one substituent (and one H), the substituents can be on the **same face** of the ring (*cis*) or on **opposite faces** (*trans*).



cis-1,2-dimethylcyclopropane — *trans*-1,2-dimethylcyclopropane — *cis*-1,3-dichlorocyclobutane — *trans*-1,3-dichlorocyclobutane

Figure 5 — The ring is drawn in perspective; vertical bonds point above or below its plane. The substituents do not have to be on neighbouring carbons: in 1,3-dichlorocyclobutane they are across the ring.

If both substituents are on the **same** ring carbon, as in 1,1-dichlorocyclopropane, there is no *cis–trans* isomerism: every other ring carbon carries two H atoms, so condition 2 fails.

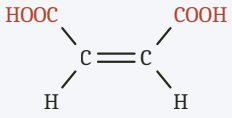
3.4 cis and trans isomers are different compounds

Because they have different shapes, *cis* and *trans* isomers have different **polarities** and pack differently in the solid, so their physical properties differ. Where the functional groups are close together in the *cis* isomer, their chemistry can differ too.

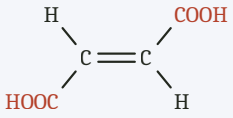
Compound	*cis* isomer	*trans* isomer	Why
1,2-dichloroethene	polar; b.p. 60 °C	non-polar; b.p. 48 °C	in *trans* the two C–Cl bond dipoles point in opposite directions and cancel; *cis* has a net dipole, so it has dipole–dipole forces as well
but-2-ene	b.p. 4 °C; m.p. −139 °C	b.p. 1 °C; m.p. −106 °C	*cis* is slightly polar (higher b.p.); the more symmetrical *trans* packs better in the solid (higher m.p.)
but-2-enedioic acid	m.p. about 135 °C; very soluble in water	m.p. about 287 °C; much less soluble	*cis* forms a hydrogen bond within the molecule, leaving fewer for intermolecular bonding; *trans* forms hydrogen bonds between molecules and packs well

Worked example — the cis–trans isomers of butenedioic acid

Draw and name the *cis–trans* isomers of butenedioic acid, HOOCCH=CHCOOH, and suggest one chemical difference between them.



cis-butenedioic acid
(maleic acid)



trans-butenedioic acid
(fumaric acid)

Each C=C carbon carries an H and a –COOH, so both conditions are met. Chemical difference: on heating, only the *cis* isomer readily loses water to form a cyclic anhydride, because its two –COOH groups are held close together on the same side of the double bond. In the *trans* isomer they are too far apart.

The biological difference is just as striking: fumaric acid is an intermediate in aerobic respiration (the Krebs cycle), whereas maleic acid does not fit the enzyme that processes fumaric acid. Enzymes recognize the shape, not just the formula.

3.5 cis–trans isomerism beyond organic chemistry

- **Vision:** light converts the *cis* form of retinal, bound in the pigment rhodopsin in the eye, into the *trans* form. The change of shape triggers the nerve signal.
- **Fats:** partial hydrogenation of vegetable oils to make margarine can convert natural *cis* C=C bonds into *trans* ones. *Trans* fats are linked to heart disease.
- **Cisplatin**, $Pt(NH_3)_2Cl_2$, is a square planar complex used in cancer treatment. Only the *cis* isomer is active. Square planar and octahedral complexes can show *cis–trans* isomerism; tetrahedral complexes cannot, because all four positions are adjacent to each other (Structure 3.1, HL).

Model answer: "Explain why but-2-ene exists as cis–trans isomers but but-1-ene does not." (3 marks)

Rotation about the C=C bond is restricted because it would break the π bond (formed by sideways overlap of p orbitals) **[1]**. In but-2-ene each carbon of the C=C carries two different groups (H and CH_3), so the CH_3 groups can be on the same side (*cis*) or opposite sides (*trans*) **[1]**. In but-1-ene one C=C carbon carries two identical H atoms, so only one arrangement is possible **[1]**.

Model answer: "Explain why cis-1,2-dichloroethene has a higher boiling point than trans-1,2-dichloroethene." (2 marks)

In the *trans* isomer the C–Cl bond dipoles are on opposite sides and cancel, so the molecule is non-polar; in the *cis* isomer they do not cancel and the molecule is polar **[1]**. The *cis* isomer therefore has dipole–dipole forces in addition to London dispersion forces, so more energy is needed to separate its molecules **[1]**.

Examiner traps in cis–trans isomerism

- Give the reason for restricted rotation in terms of the **π bond** (sideways p-orbital overlap) that would have to break. 'Double bonds are strong' is not enough.
- Check **both** carbons of the C=C. One carbon with two identical groups is enough to rule out isomerism.
- Draw the isomers with **120° angles** at the C=C carbons, not as a condensed formula and not with 90° angles that hide which side a group is on.
- Write *cis* and *trans* in italics in typed work (underline them by hand) and join them to the name with a hyphen: *cis*-but-2-ene.
- In rings, *cis* and *trans* refer to the faces of the ring (above or below its plane), not to neighbouring positions.
- Do not use *E/Z* unless you are confident; it is not assessed, and *cis/trans* is expected.

4 Chirality and optical isomers HL

4.1 Chiral carbons and enantiomers

Definitions to learn

- A **chiral carbon** (also called an asymmetric carbon or stereocentre) is a carbon atom bonded to **four different atoms or groups**. Mark it with an asterisk, C*.
- A molecule with one chiral carbon is **chiral**: it has no plane of symmetry, and its mirror image cannot be superimposed on it.
- **Enantiomers** (optical isomers) are a pair of stereoisomers that are **non-superimposable mirror images** of each other.

Your hands are the classic example; the word *chiral* comes from the Greek for 'hand'. Your left hand is the mirror image of your right, but however you turn it, you cannot lay one exactly on top of the other with every finger matching. A carbon atom with four different groups arranged tetrahedrally behaves in exactly the same way. If any two of the four groups are identical, the molecule has a plane of symmetry, its mirror image **can** be superimposed on it, and there are no optical isomers.

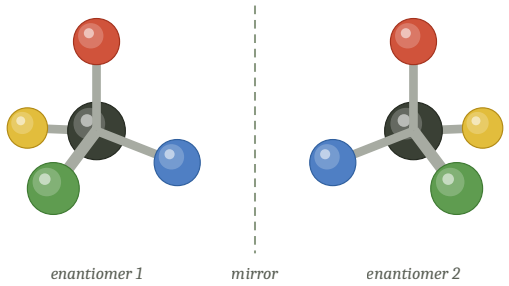


Figure 6 — Two 3D models of a carbon with four different groups. They are mirror images. Rotate the right-hand model however you like: you can line up any three groups with the left-hand one, but never all four. Building these with a molecular model kit, or rotating them in modelling software, is the clearest way to convince yourself.

4.2 Drawing enantiomers

The guide requires **wedge–dash** stereochemical formulas with **tapered** bonds, showing the tetrahedral arrangement around the chiral carbon: two bonds in the plane of the paper (plain lines), one coming towards you (solid wedge) and one going away (hashed wedge).

Method — draw a pair of enantiomers

1. Find the chiral carbon and list its four different groups.
2. Draw the first enantiomer: two groups on plain lines in the plane of the paper, one on a solid wedge and one on a hashed wedge. Mark the carbon C*.
3. Draw a vertical dashed line for the mirror.
4. Draw the reflection: each group stays at the same height and the same distance from the mirror, on the opposite side. Wedges stay wedges and dashes stay dashes; only left and right swap.
5. Check: the two drawings must differ only by reflection. (Swapping any **two** groups on a chiral carbon also produces the other enantiomer.)

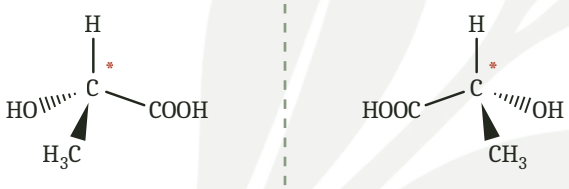


Figure 7 — The enantiomers of 2-hydroxypropanoic acid (lactic acid), $CH_3CH(OH)COOH$. The chiral carbon carries H, OH, CH_3 and COOH. Each group is the same distance from the mirror on both sides.

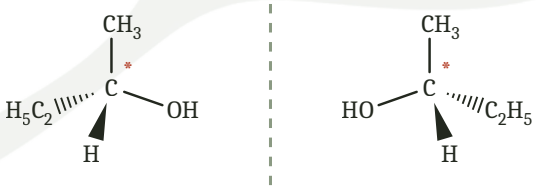


Figure 8 — The enantiomers of butan-2-ol, $CH_3CH(OH)CH_2CH_3$. The chiral carbon carries H, OH, CH_3 and C_2H_5: the methyl and ethyl groups count as different.

4.3 Finding chiral carbons

Look at each carbon in turn and ask whether its four groups are all different. Several kinds of carbon can be ruled out at a glance:

- a carbon with **two or three H atoms** (–CH_2– or –CH_3) can never be chiral;
- a carbon in a **C=C or C=O** double bond has only three groups attached, so it cannot be chiral;
- a carbon carrying **two identical alkyl groups**, such as the central carbon of propan-2-ol, $(CH_3)_2CHOH$, is not chiral.

Then compare the remaining groups **as whole groups**, following each chain to its end. In 3-methylhexane, $CH_3CH_2CH(CH_3)CH_2CH_2CH_3$, carbon 3 carries H, CH_3, C_2H_5 and C_3H_7: four different groups, so it is chiral. With 2,3-dimethylpentane it is one of the two smallest chiral alkanes (C_7H_{16}); no alkane with six or fewer carbons is chiral. The smallest chiral alcohol is butan-2-ol.

Compound	Candidate carbon and its four groups	Chiral?
propan-2-ol, $CH_3CH(OH)CH_3$	C2: H, OH, CH_3, CH_3	no
butan-2-ol, $CH_3CH(OH)CH_2CH_3$	C2: H, OH, CH_3, C_2H_5	**yes**
2-aminopropanoic acid (alanine), $CH_3CH(NH_2)COOH$	C2: H, NH_2, CH_3, COOH	**yes**
2-bromobutane, $CH_3CHBrCH_2CH_3$	C2: H, Br, CH_3, C_2H_5	**yes**
2-bromo-2-methylpropane, $(CH_3)_3CBr$	C2: Br, CH_3, CH_3, CH_3	no
pentan-3-ol, $CH_3CH_2CH(OH)CH_2CH_3$	C3: H, OH, C_2H_5, C_2H_5	no

Model answer: "Explain why butan-2-ol exists as a pair of enantiomers." (2 marks)

Carbon 2 is a chiral carbon: it is bonded to four different groups (H, OH, CH_3 and C_2H_5) **[1]**. The groups can be arranged tetrahedrally in two ways that are mirror images of each other and cannot be superimposed **[1]**.

4.4 More than one chiral carbon: diastereomers

Many molecules, especially in biology, contain several chiral carbons. Each one can have either of two arrangements, so a molecule with ***n*** chiral carbons has at most $\mathbf{2^n}$ stereoisomers. (Cholesterol has eight chiral carbons, so $2^8 = 256$ are possible, yet living things make only one of them.)

Definitions to learn

- **Enantiomers** have the **opposite** arrangement at **every** chiral carbon, so they are mirror images.
- **Diastereomers** are stereoisomers that are **not** mirror images: the arrangement is opposite at some, but not all, of the chiral carbons. Unlike enantiomers, diastereomers have **different physical and chemical properties**. Glucose and galactose are diastereomers.

Stereoisomer of $CH_3CHBrCHClCH_3$	Arrangement at C2	Arrangement at C3	Relationship
1	a	a	1 and 2 are enantiomers
2	a′ (mirror of a)	a′	
3	a	a′	3 and 4 are enantiomers
4	a′	a	1 and 3 (also 1 and 4, 2 and 3, 2 and 4) are diastereomers

Table — 2-bromo-3-chlorobutane has two chiral carbons, C2 and C3, so $2^2 = 4$ stereoisomers: two pairs of enantiomers.

5 Enantiomers: properties and optical activity HL

5.1 Identical in almost every way

Two enantiomers have the same bonds, the same bond lengths and angles and the same intermolecular forces. So they have **identical physical properties** (melting point, boiling point, density, solubility in ordinary solvents, IR spectrum) and **identical chemical properties** towards reagents that are not themselves chiral. There are only **two** differences:

1. they rotate the plane of **plane-polarized light** by the same angle but in **opposite directions**;
2. they react differently, and have different effects, in a **chiral environment**: with another single enantiomer, or with enzymes and receptors in the body.

5.2 Optical activity and the polarimeter

Ordinary light consists of electromagnetic waves vibrating in every plane at right angles to the direction of travel. A **polarizer** (like the filter in polarized sunglasses) lets through only the waves vibrating in one plane, giving **plane-polarized light**. When this light passes through a solution of one enantiomer, the plane of vibration is **rotated**. A substance that does this is **optically active**.

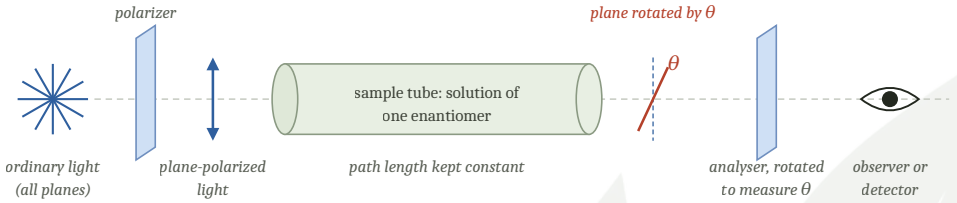


Figure 9 — A polarimeter. The analyser is turned until the light passing through the sample is again at maximum (or minimum) intensity; the angle turned is the angle of rotation, θ.

Definitions to learn

- **Optical activity** is the ability of a substance to rotate the plane of plane-polarized light.
- One enantiomer rotates the plane **clockwise** (labelled +); the other rotates it by the **same angle anticlockwise** (−), under the same conditions.
- A **racemic mixture** (racemate) contains **equal amounts** of the two enantiomers. The two rotations cancel exactly, so a racemic mixture is **optically inactive**.

To compare samples fairly, the concentration, the path length of the sample tube, the wavelength of the light and the temperature must all be kept the same, because the angle of rotation depends on each of them. Reactions carried out in the laboratory from non-chiral starting materials normally give a racemic mixture, whereas chiral compounds made in living cells are usually a single enantiomer.

A note on labels you may meet

(+) and (−) describe the direction of rotation. Older books use d- and l- for the same thing. Capital D- and L- (used for sugars and amino acids) and *R*/*S* describe the actual 3D arrangement and are worked out by different rules. You do not need to assign any of these labels: you only need to know that the two enantiomers of a pair are given opposite labels.

5.3 Enantiomers in chiral environments

A left hand fits a mug just as well as a right hand, because the mug is not chiral. But a left hand fits only a left-handed glove. Molecules behave the same way: both enantiomers react identically with an achiral reagent, but they react **differently** with an-

other chiral molecule. Living things are full of chiral molecules: enzymes and receptors are built from L-amino acids, so each enantiomer of a drug, a flavour or a scent can fit a different site.

- **Smell:** one enantiomer of carvone smells of spearmint; the other smells of caraway seeds.
- **Drugs:** often only one enantiomer has the intended effect. Many modern drugs are therefore made as a single enantiomer, using chiral catalysts (**asymmetric synthesis**, recognized by the Nobel Prizes in Chemistry in 2001 and 2021).
- **Resolution:** reacting a racemic mixture with a single enantiomer of another chiral compound gives two products that are **diastereomers**. These have different physical properties, so they can be separated, and the original enantiomers recovered.

Global impact and TOK — thalidomide

Thalidomide was prescribed in the late 1950s and early 1960s to treat morning sickness in pregnant women. One enantiomer has the intended sedative effect, but the other is **teratogenic**: it caused severe birth defects in thousands of babies. A complication is that the two enantiomers interconvert in the body, so even a pure sample of the 'safe' enantiomer would not have prevented the harm. The drug was never approved in the USA, largely because the FDA reviewer Frances Kelsey insisted on further safety data. The tragedy transformed drug testing: each enantiomer of a chiral drug is now treated as a separate substance with its own tests.

TOK: who should judge the balance of risk and benefit of a new drug — the manufacturer, a regulator, the doctor or the patient?

5.4 Nature of Science — Biot and Pasteur

In the early 1800s the French physicist Jean-Baptiste Biot found that some quartz crystals rotate polarized light one way and others the opposite way, and then that solutions of natural substances such as sugar do the same, so the effect must come from the molecules themselves. In 1848 Louis Pasteur noticed that crystals of a salt of optically inactive 'racemic acid' came in two mirror-image shapes. He separated them by hand with tweezers, and found that solutions of the two sets rotated light equally in opposite directions. He had performed the first resolution of a racemic mixture, decades before anyone knew that carbon is tetrahedral.

Model answer: "Describe how a polarimeter could be used to distinguish the two enantiomers of lactic acid and a racemic mixture of them." (3 marks)

Pass plane-polarized light through a solution of each sample (same concentration, path length and wavelength) and measure the angle of rotation with the analyser **[1]**. The two enantiomers rotate the plane by the same angle in opposite directions (one clockwise, one anticlockwise) **[1]**. The racemic mixture gives no rotation, because the effects of the two enantiomers cancel **[1]**.

Model answer: "State how the properties of a pair of enantiomers differ." (2 marks)

They rotate plane-polarized light in opposite directions (by the same angle) **[1]**. They react differently with other chiral molecules / in a chiral environment such as an enzyme; otherwise their physical and chemical properties are identical **[1]**.

Examiner traps in optical isomerism

- A chiral carbon needs four different **groups**, not four different atoms: in butan-2-ol two of the groups start with C (CH_3 and C_2H_5) but are still different.
- Use **tapered** wedges and dashes, keep the tetrahedral shape (two bonds in the plane, one wedge, one dash) and draw the mirror line. A flat 90° drawing does not show enantiomers.
- In the mirror image, wedges stay wedges and dashes stay dashes. If you also swap a wedge for a dash, you may have drawn the same molecule twice.
- Enantiomers rotate light by the **same** amount in **opposite** directions. They do not 'rotate light by different amounts'.
- A racemic mixture is **optically inactive** even though each molecule in it is chiral.
- 'Enantiomers have different chemical properties' is only true in a chiral environment. With achiral reagents they react identically.
- Diastereomers are **not** mirror images and **do** have different physical properties.

6 Key points to memorise

Everything below is either wording that examiners look for, or knowledge you must carry into the exam yourself.

A Definitions — near-verbatim

- **Stereoisomers:** same constitution (atoms, connectivity, bond multiplicity), different spatial arrangement.
- **Configurational isomers:** interconvert only by breaking bonds (*cis–trans*, optical). **Conformational isomers:** interconvert by rotation about σ bonds (not required).
- ***cis*:** matching groups on the same side of the C=C or ring. ***trans*:** on opposite sides.
- **Chiral carbon:** a carbon bonded to four different groups. **Chiral molecule:** non-superimposable on its mirror image.
- **Enantiomers:** non-superimposable mirror images. **Diastereomers:** stereoisomers that are not mirror images.
- **Optical activity:** rotation of the plane of plane-polarized light. **Racemic mixture:** equal amounts of two enantiomers; optically inactive.

B cis–trans isomerism

- Needs restricted rotation (C=C or ring) **and** two different groups on each carbon concerned.
- C=C cannot rotate because the π bond (sideways overlap of p orbitals) would break.
- Found in non-cyclic alkenes and in C_3 and C_4 cycloalkanes (reference plane = plane of ring).
- *cis* and *trans* isomers have different physical properties (polarity, packing) and sometimes different chemistry (only *cis*-butenedioic acid forms an anhydride). *E/Z* is not assessed.

C Optical isomerism

- One chiral carbon → two enantiomers. *n* chiral carbons → at most 2^n stereoisomers.
- Draw with tapered wedge–dash bonds around a tetrahedral C*, with a mirror line; reflect left ↔ right.
- Enantiomers: identical physical and chemical properties except (1) opposite rotation of plane-polarized light by the same angle, (2) different behaviour in chiral environments.
- Polarimeter: polarizer → sample → analyser; keep concentration, path length, wavelength, temperature the same.
- Living systems usually make one enantiomer; laboratory synthesis from achiral reagents usually gives a racemate. Resolution: convert to diastereomers with a single enantiomer, separate, recover.

D Command terms — what each one is actually asking for

- **Draw** (stereoisomers) — full structural or stereochemical formulas, with 120° angles at C=C, or tapered wedge–dash bonds and a mirror line for enantiomers.
- **Identify** (a chiral carbon) — mark it with an asterisk; no explanation needed.
- **Explain** (why isomers exist) — name the structural feature (π bond and restricted rotation; four different groups) and the condition that makes two arrangements possible.
- **Describe** (a difference in properties) — state what is observed, e.g. 'rotate plane-polarized light by equal angles in opposite directions'.
- **Outline** (how a racemic mixture can be resolved) — the key steps in order, briefly.

7 Check yourself

Cover the answers on the next pages. Marks are shown in brackets where a question is written in exam style. All questions are Higher Level.

1. Which pair are stereoisomers?

   A butane and methylpropane
   B propan-1-ol and propan-2-ol
   C *cis*- and *trans*-but-2-ene
   D propanal and propanone

2. Define the term *stereoisomers*, and state the difference between configurational and conformational isomers. **[3]**

3. Explain why there is no free rotation about a carbon–carbon double bond. **[2]**

4. For each alkene, state whether it shows *cis*–*trans* isomerism. Where it does, draw both isomers. (a) methylpropene (b) 1-chloropropene (c) 2-methylpent-2-ene (d) 2-ethylpent-1-ene (e) 3-methylpent-2-ene (f) but-1-ene (g) 3,4-dimethylhex-3-ene (h) 2-bromo-3-chlorobut-2-ene. **[8]**

5. Which compound can exist as *cis* and *trans* isomers?

   A CH_2=CHCl
   B CH_3CH=CCl_2
   C CHCl=CHCl
   D $(CH_3)_2C$=$CHCH_3$

6. Draw and name the *cis* and *trans* isomers of 1,2-dibromoethene, CHBr=CHBr. **[2]**

7. *cis*-1,2-Dichloroethene boils at 60 °C and *trans*-1,2-dichloroethene at 48 °C. Explain the difference. **[3]**

8. Draw *cis*-1,3-dimethylcyclobutane and *trans*-1,2-dichlorocyclopropane. **[2]**

9. Explain why 1,2-dichlorocyclopropane shows *cis*–*trans* isomerism but 1,1-dichlorocyclopropane does not. **[2]**

10. Which statement about the isomers of butenedioic acid is correct?

    A They have the same melting point.
    B Only the *cis* isomer readily forms a cyclic anhydride on heating.
    C They are a pair of enantiomers.
    D Only the *trans* isomer contains a C=C bond.

11. State what is meant by a *chiral carbon*. **[1]**

12. For each compound, state whether it shows optical isomerism. Where it does, identify the chiral carbon. (a) propan-2-ol (b) 2-chlorobutane (c) 1-chlorobutane (d) 3-methylhexane (e) butanone (f) 2-methylbutanoic acid (g) butan-2-ol (h) 1-chloro-3-methylpentane. **[8]**

13. Draw the two enantiomers of 2-aminopropanoic acid (alanine), $CH_3CH(NH_2)COOH$, showing the mirror plane. **[3]**

14. How many chiral carbon atoms are present in $CH_3CH(OH)CH(CH_3)CH_2CH_3$?

A 0 B 1 C 2 D 3

15. Which compound is optically active?

A $CH_3CH_2CH(OH)CH_2CH_3$ B $CH_3CH_2CHClCH_3$
C $(CH_3)_2CHCH_2OH$ D $CH_3COCH_2CH_3$

16. Deduce the structure of the alcohol with the fewest carbon atoms that shows optical isomerism, and name it. **[2]**

17. Describe how plane-polarized light could be used to distinguish between the two enantiomers of butan-2-ol. **[2]**

18. Explain why a racemic mixture is optically inactive. **[2]**

19. State **two** properties that are identical for a pair of enantiomers and **two** ways in which they differ. **[2]**

20. A molecule has three chiral carbons. (a) State the maximum number of stereoisomers. (b) Distinguish between enantiomers and diastereomers. **[3]**

21. Which statements about diastereomers are correct? I. They are not mirror images of each other. II. They have identical boiling points. III. They differ in arrangement at some, but not all, of their chiral carbons.

A I and II only B I and III only C II and III only D I, II and III

22. Many drugs are now manufactured as a single enantiomer. Explain why. **[2]**

23. Outline how a racemic mixture of a chiral acid could be separated into its two enantiomers. **[2]**

24. Which compound shows both *cis–trans* isomerism and optical isomerism?

A $CH_3CH=CHCH_3$ B $CH_3CH(OH)CH_2CH_3$
C $CH_3CH=CHCH(OH)CH_3$ D $CH_2=CHCH_2CH_3$

25. State the relationship between each pair: structural isomers, *cis–trans* isomers, enantiomers, or identical. (a) $CH_3CH_2CH_2OH$ and $CH_3CH(OH)CH_3$ (b) the two drawings in Figure 8 (c) *cis*- and *trans*-pent-2-ene (d) a molecule of propan-2-ol and its mirror image. **[4]**

26. Explain why the *cis* and *trans* isomers of but-2-ene cannot be distinguished using the condensed formula $CH_3CH=CHCH_3$, and state what kind of formula should be used. **[2]**

8 Answers

1. **C.** A is chain isomerism, B position isomerism, D functional group isomerism.
2. Stereoisomers have the same constitution / same structural formula (same atoms joined in the same order by the same bonds) but a different arrangement of the atoms in space **[1]**. Configurational isomers can only be interconverted by breaking a bond **[1]**; conformational isomers interconvert by rotation about σ (single) bonds **[1]**.
3. A C=C contains a π bond formed by sideways overlap of p orbitals above and below the plane of the bond **[1]**. Rotation would twist the p orbitals out of line, breaking the π bond, which needs too much energy **[1]**.
4. (a) no (b) yes (c) no (d) no (e) yes (f) no (g) yes (h) yes **[1]** each, with both isomers drawn at 120° for b, e, g and h.
5. **C.** Each carbon carries H and Cl. In A and B one carbon carries two identical atoms; in D one carbon carries two CH_3 groups.
6. Both Br on the same side: *cis*-1,2-dibromoethene **[1]**; Br on opposite sides: *trans*-1,2-dibromoethene **[1]**.
7. *trans*: the two C–Cl dipoles point in opposite directions and cancel, so the molecule is non-polar **[1]**. *cis*: the dipoles do not cancel, so the molecule is polar and has dipole–dipole forces as well as London dispersion forces **[1]**. More energy is needed to separate the *cis* molecules **[1]**.
8. *cis*-1,3-dimethylcyclobutane: both CH_3 groups on the same face of the ring, on carbons 1 and 3 **[1]**. *trans*-1,2-dichlorocyclopropane: the two Cl atoms on adjacent carbons, one above and one below the ring **[1]**.
9. The ring prevents rotation, and in the 1,2-isomer each of the two carbons carries two different groups (H and Cl), so the Cl atoms can be on the same or opposite faces **[1]**. In the 1,1-isomer both Cl atoms are on one carbon and the other carbons carry two H atoms each, so only one arrangement exists **[1]**.
10. **B.** The *cis* isomer's two –COOH groups are close enough to lose water.
11. A carbon atom bonded to four different atoms or groups **[1]**.
12. (a) no (b) yes, C2 (c) no (d) yes, C3 (e) no (f) yes, C2 (g) yes, C2 (h) yes, C3 **[1]** each.
13. Correct tetrahedral wedge–dash drawing of one enantiomer with H, NH_2, CH_3 and COOH around C* **[1]**; mirror line **[1]**; correct mirror image, with groups reflected left to right **[1]**.
14. **C.** C2 (H, OH, CH_3, $CH(CH_3)C_2H_5$) and C3 (H, CH_3, C_2H_5, $CH(OH)CH_3$).
15. **B.** 2-Chlorobutane: C2 carries H, Cl, CH_3, C_2H_5. A has two C_2H_5 groups on C3.
16. $CH_3CH(OH)CH_2CH_3$ **[1]**; butan-2-ol **[1]**. (Propan-2-ol has two identical CH_3 groups.)
17. Pass plane-polarized light through solutions of each enantiomer under the same conditions **[1]**; they rotate the plane by the same angle in opposite directions **[1]**.
18. It contains equal amounts of the two enantiomers **[1]**, which rotate the plane of polarized light equally in opposite directions, so the rotations cancel **[1]**.
19. Identical: any two of melting point, boiling point, density, solubility, reactions with achiral reagents **[1]**. Differ: direction of rotation of plane-polarized light; reactions in a chiral environment (with other chiral molecules, enzymes or receptors) **[1]**.
20. (a) $2^3 = 8$ **[1]**. (b) Enantiomers are mirror images, with the opposite arrangement at every chiral carbon **[1]**; diastereomers have the opposite arrangement at some but not all chiral carbons, are not mirror images and have different properties **[1]**.
21. **B.** Diastereomers have different physical properties, so II is false.
22. The body is a chiral environment: enzymes and receptors are chiral, so each enantiomer interacts differently **[1]**. Often only one enantiomer has the desired effect, and the other may be inactive or harmful (e.g. thalidomide) **[1]**.

23. React the racemic mixture with a single enantiomer of another chiral compound (e.g. a chiral base) to form a pair of diastereomers **[1]**, which have different physical properties and can be separated (e.g. by crystallization); then reverse the reaction to recover each enantiomer **[1]**.

24. **C.** It has a C=C with two different groups on each carbon and a chiral C bearing H, OH, CH_3 and $CH{=}CHCH_3$.

25. (a) structural (position) isomers (b) enantiomers (c) *cis–trans* isomers (d) identical (propan-2-ol is not chiral) **[1]** each.

26. A condensed formula shows only which atoms are bonded to which, and the two isomers have the same connectivity **[1]**. A full structural or stereochemical formula with 120° bond angles is needed to show whether the CH_3 groups are on the same or opposite sides **[1]**.

Where this fits in Structure 3.2

- **Booklet 4** — 3.2.1 to 3.2.4: formulas, functional groups and classes, homologous series and physical trends.
- **Booklet 5** — 3.2.5 and 3.2.6: IUPAC nomenclature and structural isomers.
- **Booklet 6** (this booklet, HL) — 3.2.7: stereoisomers, *cis–trans* isomerism and optical isomerism.
- **Next** — HL 3.2.8 and 3.2.9: identifying organic compounds from mass spectra, IR and ^{1}H NMR spectra.
- Links: **Structure 2.2** (σ and π bonds, VSEPR), **Structure 3.1 HL** (isomerism in complexes), **Reactivity 3.4** (reactions of alkenes and halogenoalkanes, where stereochemistry matters).

These notes are a free resource, shared for any IB student who finds them useful.

If a particular idea here still isn't clicking, specialist one-to-one support in Physics, Chemistry and Maths from a past A Level examiner is available at iBLaurel — call or message **+44 7404 710097**, or use the contact form at **www.iBLaurel.com**.

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