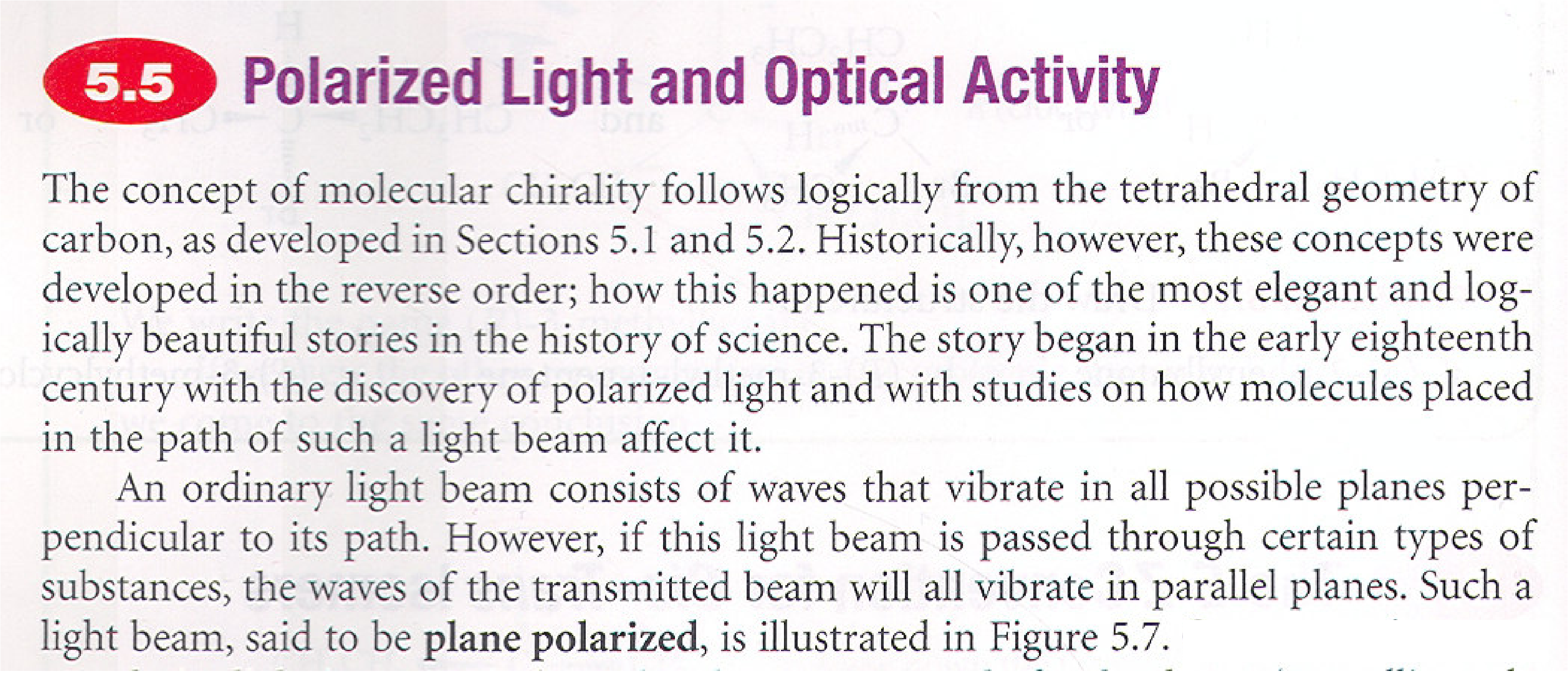
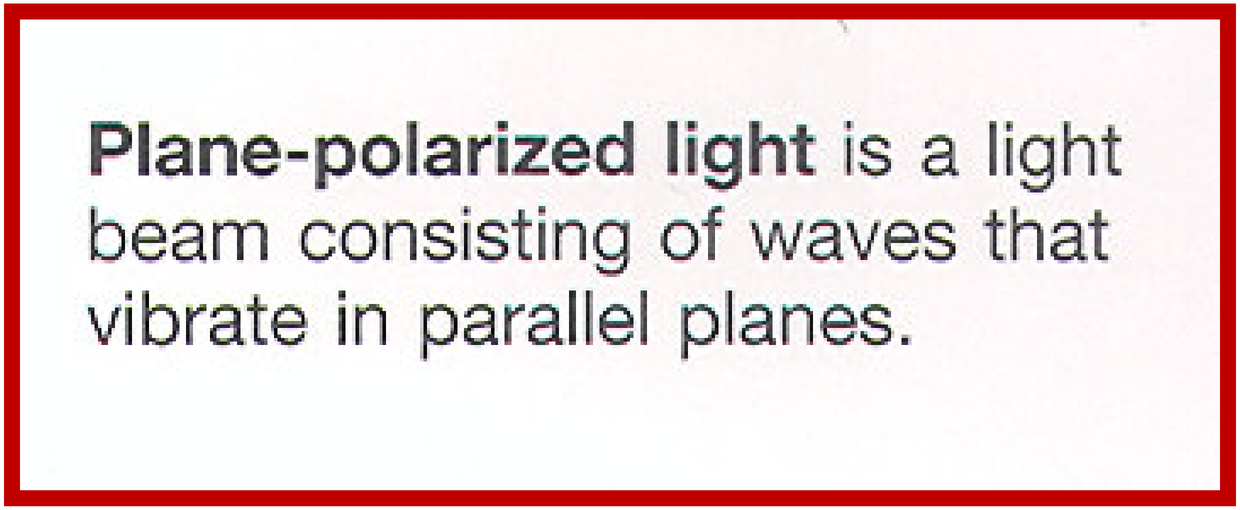


5.5 Polarized Light and Optical Activity

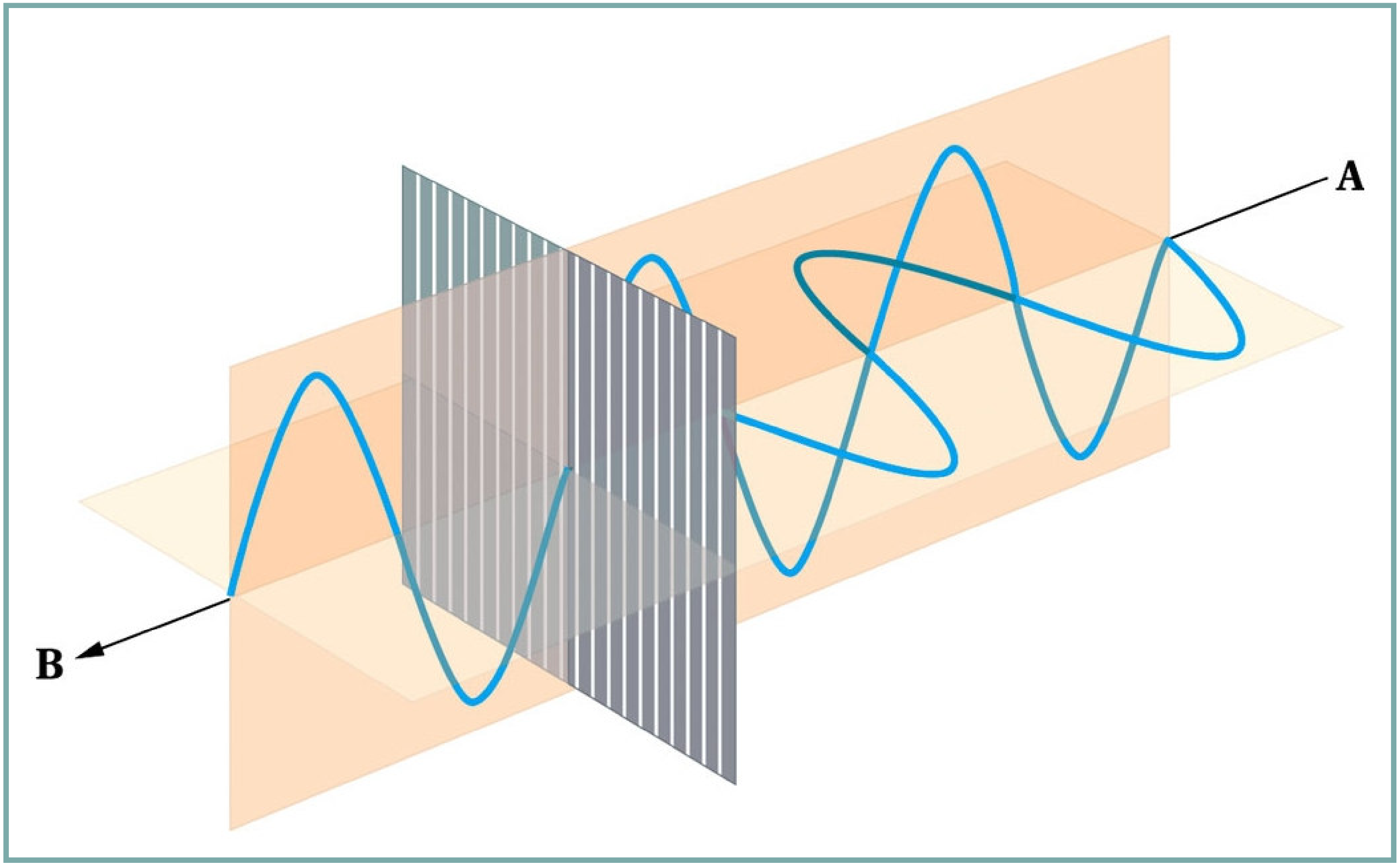
The concept of molecular chirality follows logically from the tetrahedral geometry of carbon, as developed in Sections 5.1 and 5.2. Historically, however, these concepts were developed in the reverse order; how this happened is one of the most elegant and logically beautiful stories in the history of science. The story began in the early eighteenth century with the discovery of polarized light and with studies on how molecules placed in the path of such a light beam affect it.

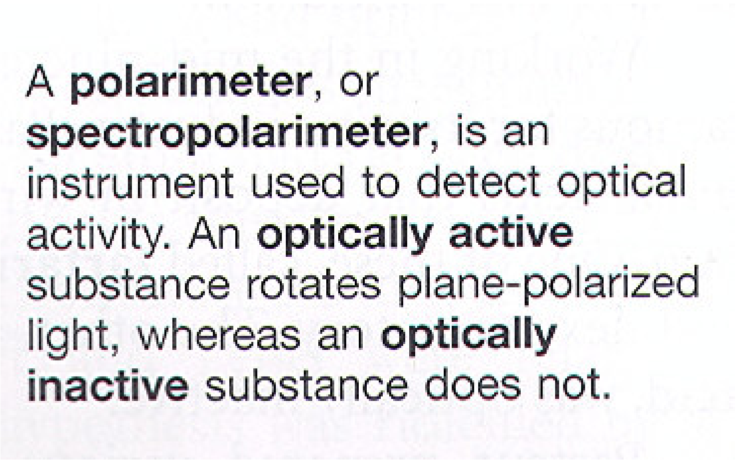
An ordinary light beam consists of waves that vibrate in all possible planes perpendicular to its path. However, if this light beam is passed through certain types of substances, the waves of the transmitted beam will all vibrate in parallel planes. Such a light beam, said to be **plane polarized**, is illustrated in Figure 5.7.



Plane-polarized light is a light beam consisting of waves that vibrate in parallel planes.

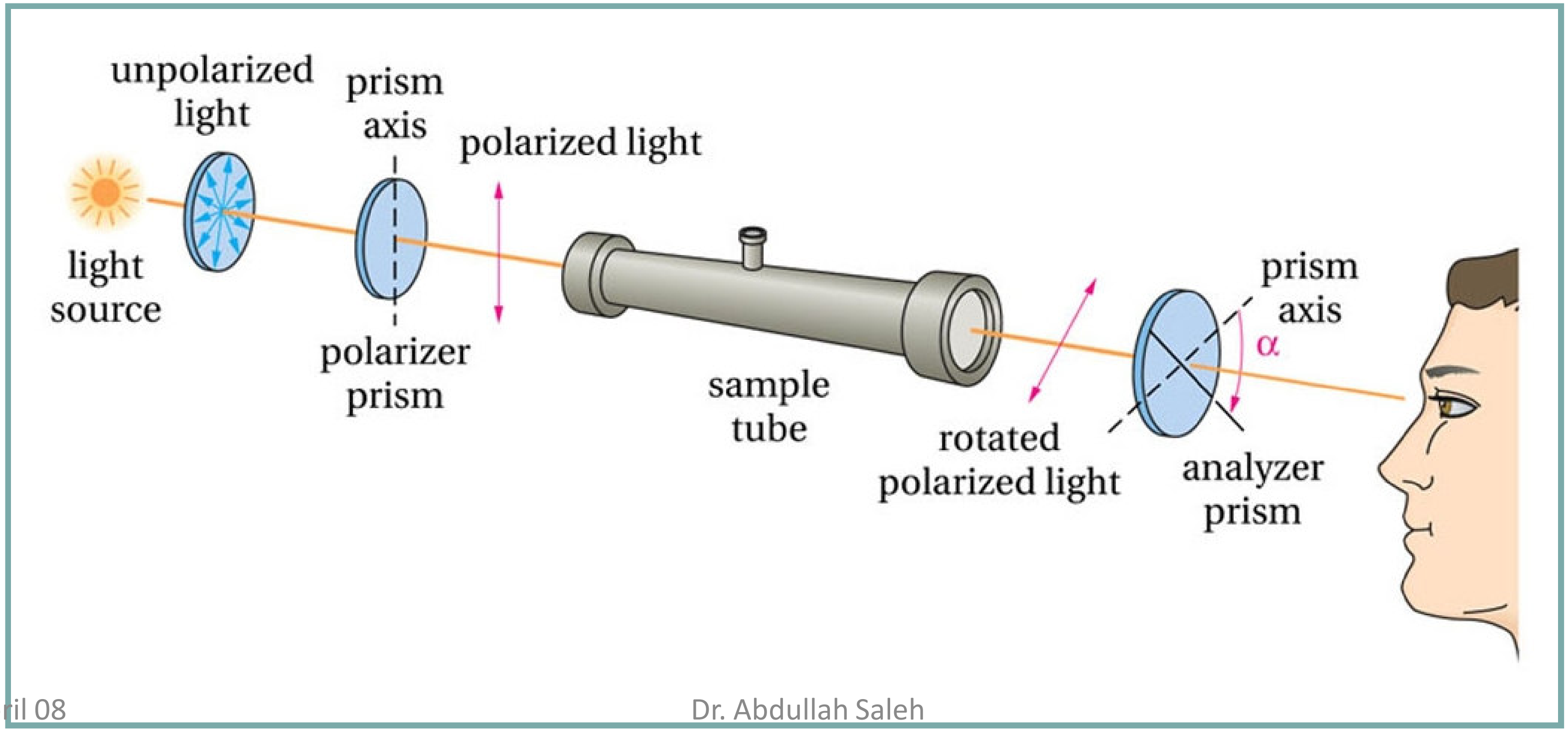
Figure 5.7 A plane polarized beam of light, AB

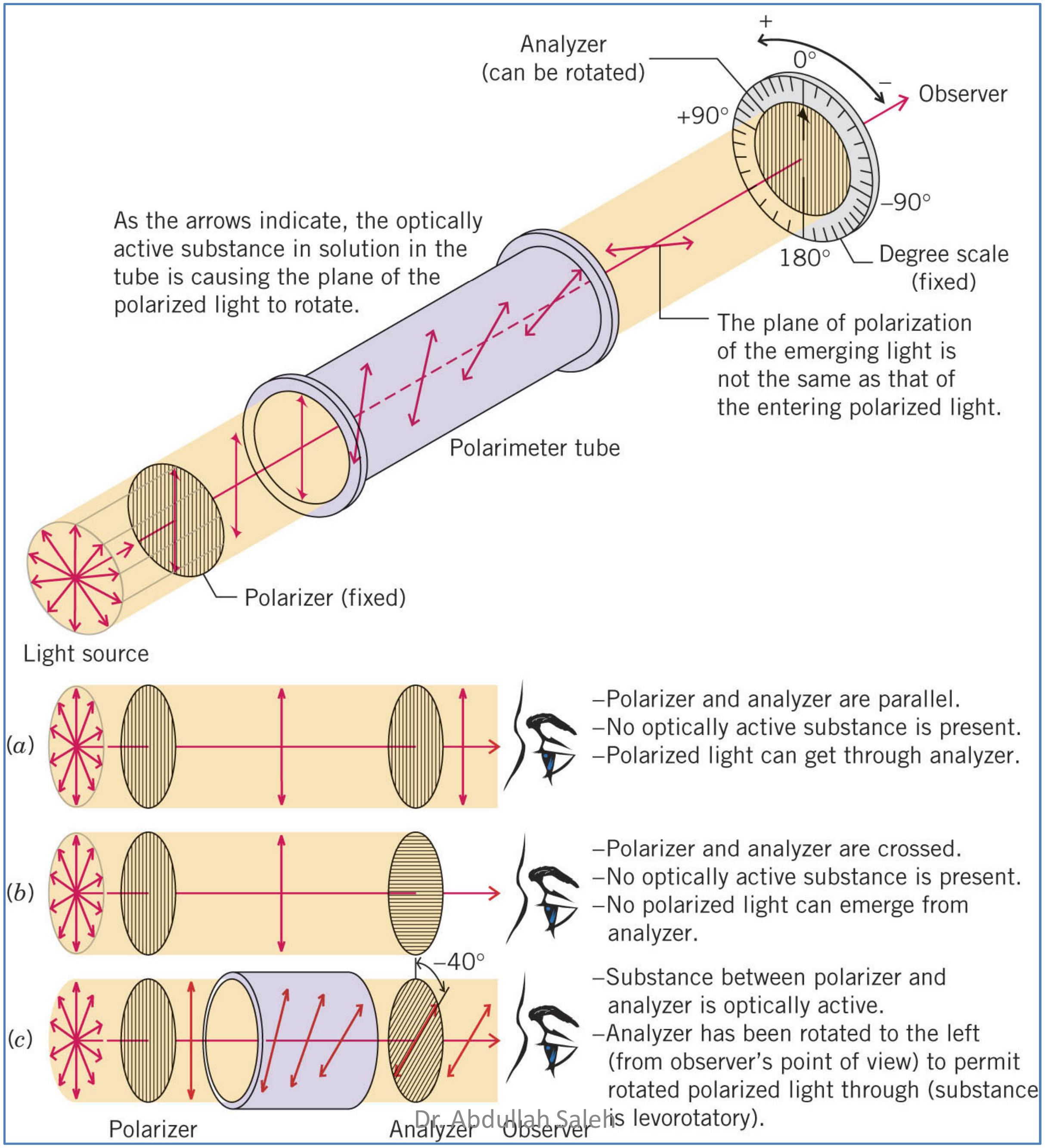




A **polarimeter**, or **spectropolarimeter**, is an instrument used to detect optical activity. An **optically active** substance rotates plane-polarized light, whereas an **optically inactive** substance does not.

Figure 5.8 Diagram of a polarimeter





As the arrows indicate, the optically active substance in solution in the tube is causing the plane of the polarized light to rotate.

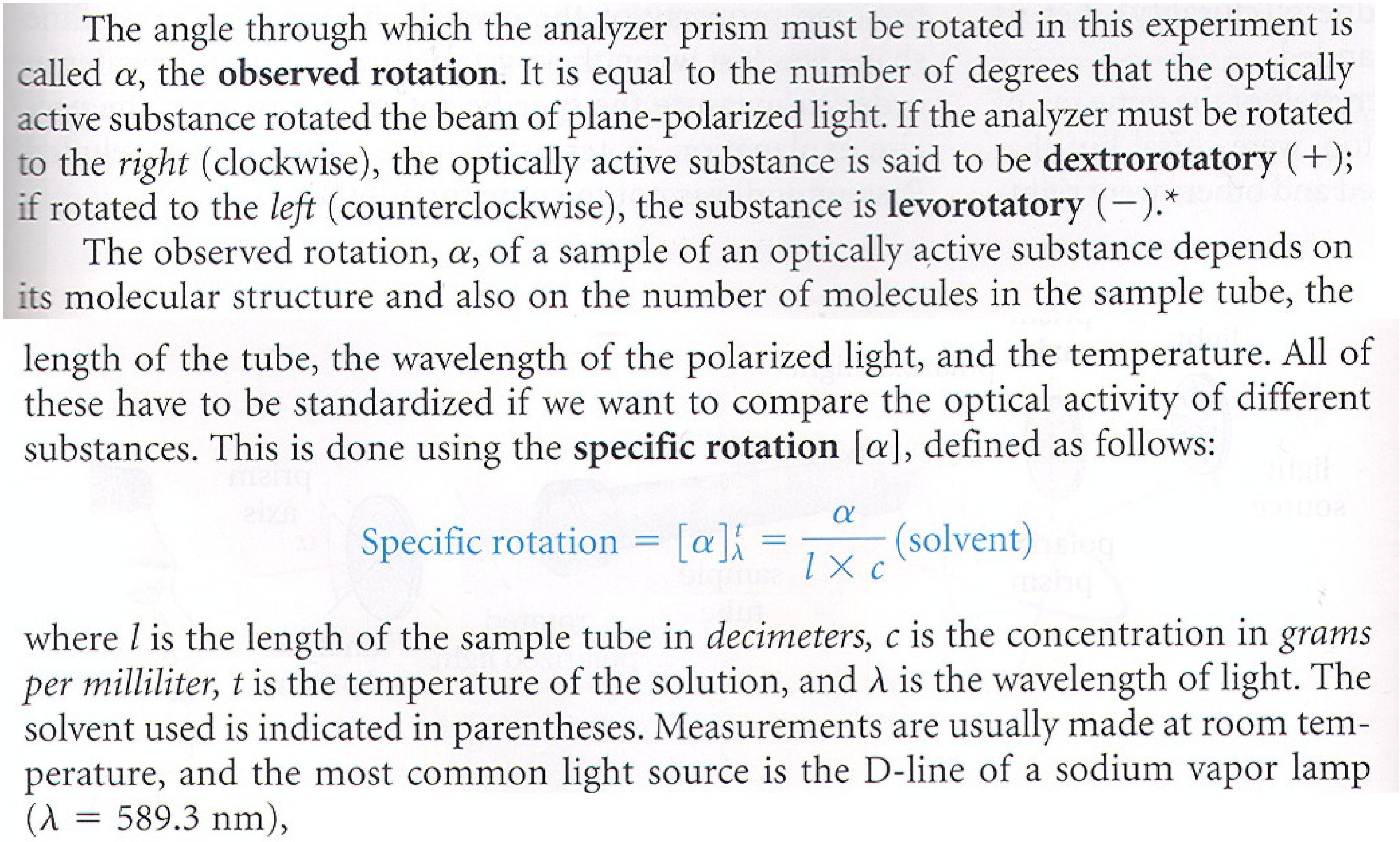
The plane of polarization of the emerging light is not the same as that of the entering polarized light.

(a)
- Polarizer and analyzer are parallel.
- No optically active substance is present.
- Polarized light can get through analyzer.

(b)
- Polarizer and analyzer are crossed.
- No optically active substance is present.
- No polarized light can emerge from analyzer.

(c)
- Substance between polarizer and analyzer is optically active.
- Analyzer has been rotated to the left (from observer's point of view) to permit rotated polarized light through (substance is levorotatory).

Observed & Specific Rotations

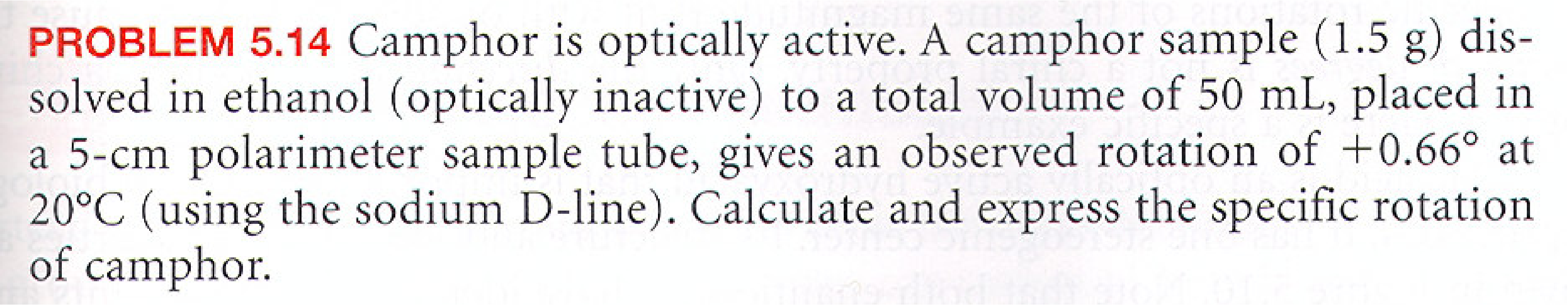


The angle through which the analyzer prism must be rotated in this experiment is called α, the **observed rotation**. It is equal to the number of degrees that the optically active substance rotated the beam of plane-polarized light. If the analyzer must be rotated to the *right* (clockwise), the optically active substance is said to be **dextrorotatory** (+); if rotated to the *left* (counterclockwise), the substance is **levorotatory** (−).*

The observed rotation, α, of a sample of an optically active substance depends on its molecular structure and also on the number of molecules in the sample tube, the length of the tube, the wavelength of the polarized light, and the temperature. All of these have to be standardized if we want to compare the optical activity of different substances. This is done using the **specific rotation** $[\alpha]$, defined as follows:

$$\text{Specific rotation} = [\alpha]_\lambda^t = \frac{\alpha}{l \times c}\,(\text{solvent})$$

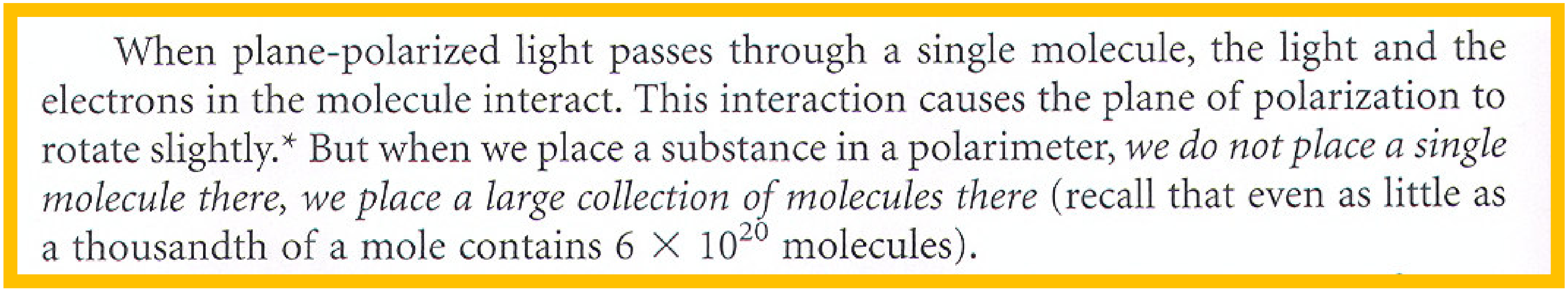
where l is the length of the sample tube in *decimeters*, c is the concentration in *grams per milliliter*, t is the temperature of the solution, and λ is the wavelength of light. The solvent used is indicated in parentheses. Measurements are usually made at room temperature, and the most common light source is the D-line of a sodium vapor lamp (λ = 589.3 nm),



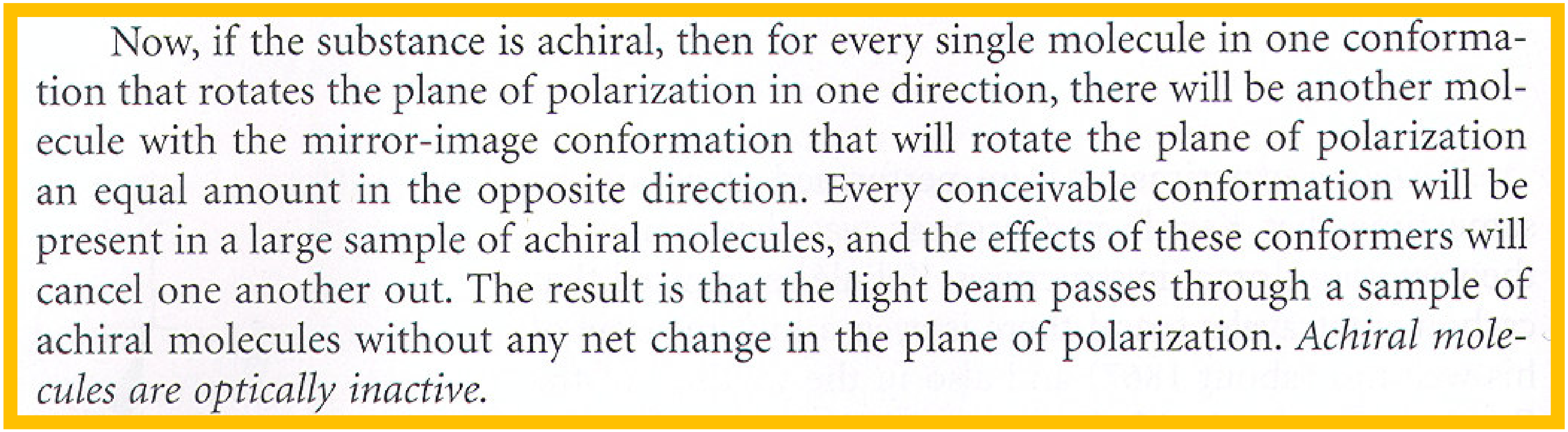
PROBLEM 5.14 Camphor is optically active. A camphor sample (1.5 g) dissolved in ethanol (optically inactive) to a total volume of 50 mL, placed in a 5-cm polarimeter sample tube, gives an observed rotation of +0.66° at 20°C (using the sodium D-line). Calculate and express the specific rotation of camphor.

5.14 $$[\alpha]_D^{20} = \frac{+0.66}{0.5 \times \frac{1.5}{50}} = 44^o \quad \text{(ethanol)}$$

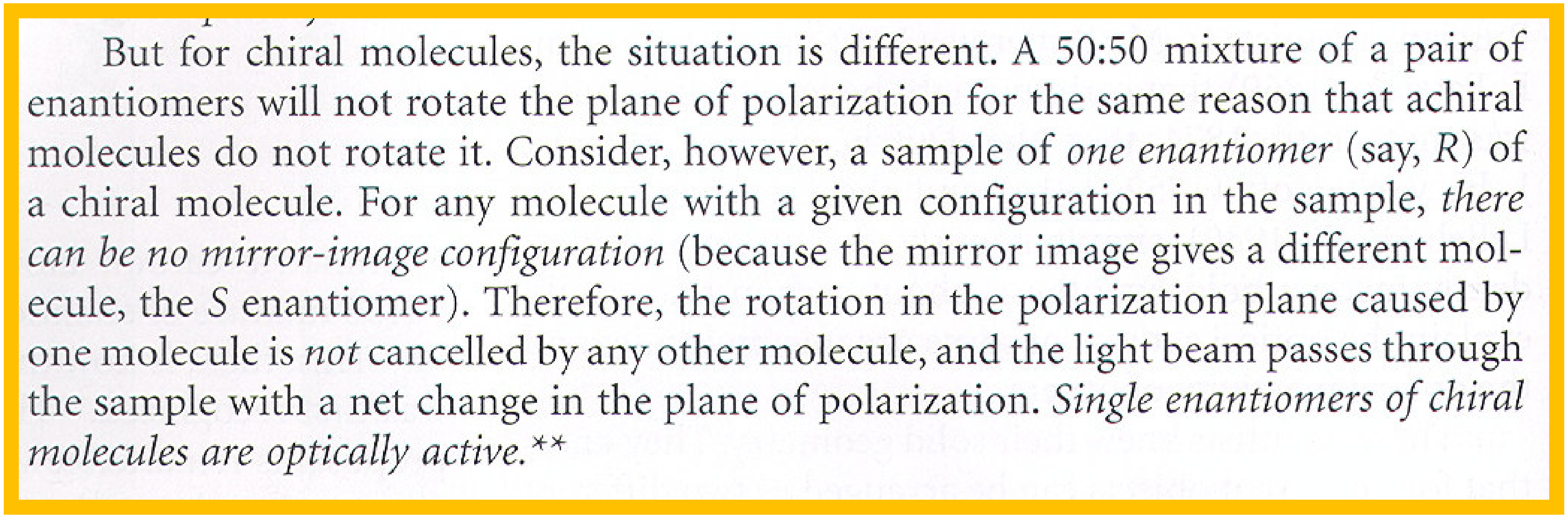
Chirality & Optical Activity



When plane-polarized light passes through a single molecule, the light and the electrons in the molecule interact. This interaction causes the plane of polarization to rotate slightly.* But when we place a substance in a polarimeter, *we do not place a single molecule there, we place a large collection of molecules there* (recall that even as little as a thousandth of a mole contains 6 × 10^{20} molecules).

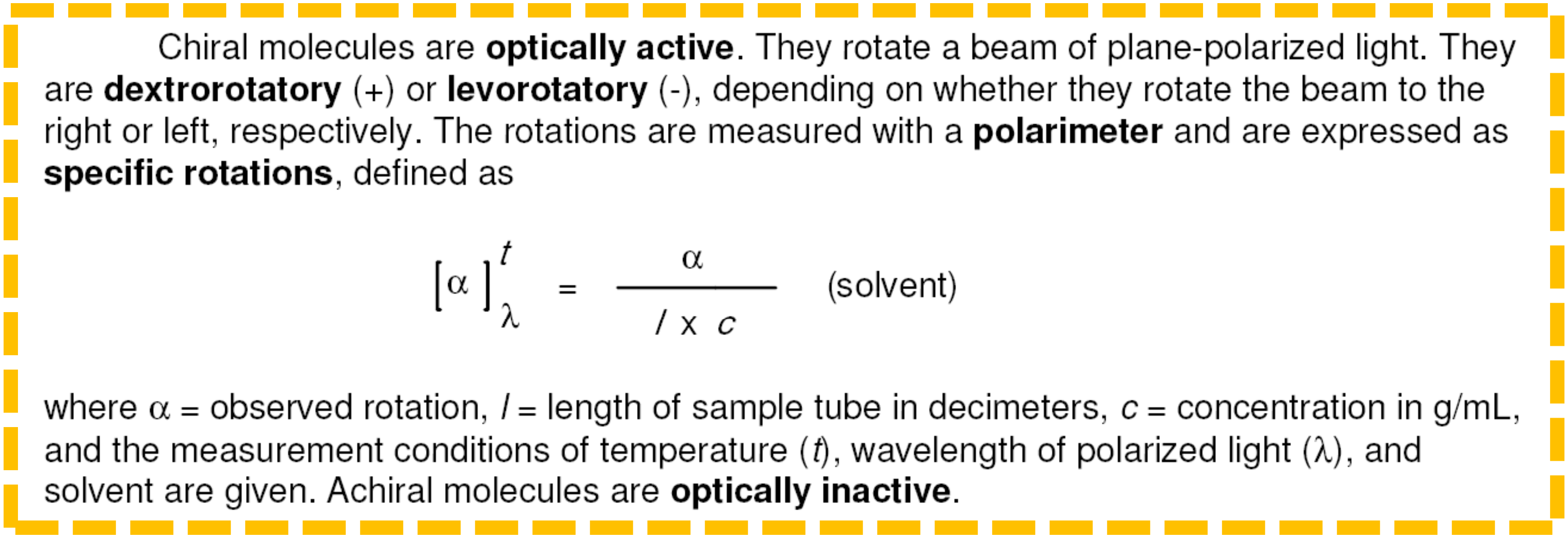


Now, if the substance is achiral, then for every single molecule in one conformation that rotates the plane of polarization in one direction, there will be another molecule with the mirror-image conformation that will rotate the plane of polarization an equal amount in the opposite direction. Every conceivable conformation will be present in a large sample of achiral molecules, and the effects of these conformers will cancel one another out. The result is that the light beam passes through a sample of achiral molecules without any net change in the plane of polarization. *Achiral molecules are optically inactive.*



But for chiral molecules, the situation is different. A 50:50 mixture of a pair of enantiomers will not rotate the plane of polarization for the same reason that achiral molecules do not rotate it. Consider, however, a sample of *one enantiomer* (say, *R*) of a chiral molecule. For any molecule with a given configuration in the sample, *there can be no mirror-image configuration* (because the mirror image gives a different molecule, the *S* enantiomer). Therefore, the rotation in the polarization plane caused by one molecule is *not* cancelled by any other molecule, and the light beam passes through the sample with a net change in the plane of polarization. *Single enantiomers of chiral molecules are optically active.***

i.e.



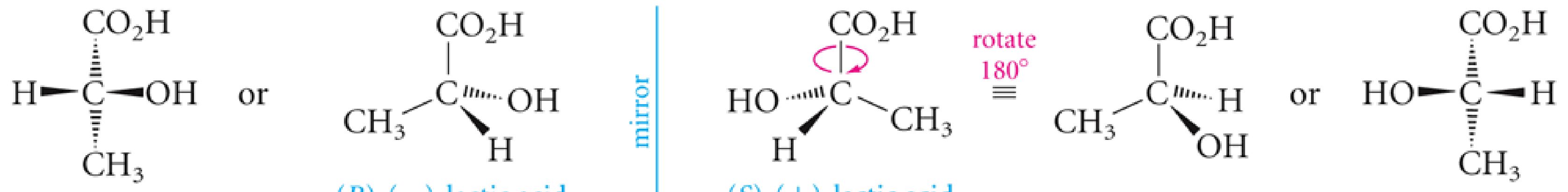
Chiral molecules are **optically active**. They rotate a beam of plane-polarized light. They are **dextrorotatory** (+) or **levorotatory** (-), depending on whether they rotate the beam to the right or left, respectively. The rotations are measured with a **polarimeter** and are expressed as **specific rotations**, defined as

$$[\alpha]_{\lambda}^{t} = \frac{\alpha}{l \times c} \quad \text{(solvent)}$$

where α = observed rotation, l = length of sample tube in decimeters, c = concentration in g/mL, and the measurement conditions of temperature (t), wavelength of polarized light (λ), and solvent are given. Achiral molecules are **optically inactive**.

5.6 Properties of Enantiomers

Enantiomers have identical achiral properties, such as melting point, boiling point, density, and various types of spectra. Their solubilities in an ordinary, achiral solvent are also identical. However, *enantiomers have different chiral properties*, one of which is the *direction* in which they rotate plane-polarized light (clockwise or counterclockwise). Although enantiomers rotate plane-polarized light in opposite directions, they have specific rotations of the same magnitude (but with opposite signs), because the *number of degrees* is not a chiral property. Only the *direction* of rotation is a chiral property. Here is a specific example.

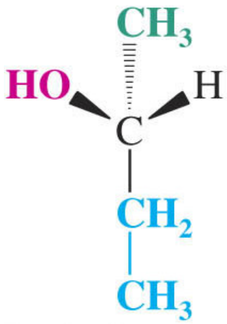


(R)-(−)-lactic acid
$[\alpha]_D^{25°C}$ − 3.33(H_2O)
mp 53°C

(S)-(+)-lactic acid
$[\alpha]_D^{25°C}$ + 3.33(H_2O)
mp 53°C

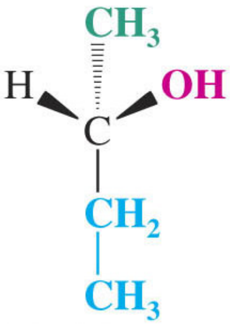
i.e.

- Enantiomers have almost all identical physical properties (melting point, boiling point, density)
- However enantiomers rotate the plane of plane-polarized light in equal but opposite directions
- The specific rotation of the two pure enantiomers of 2-butanol are equal but opposite



(*R*)-2-Butanol

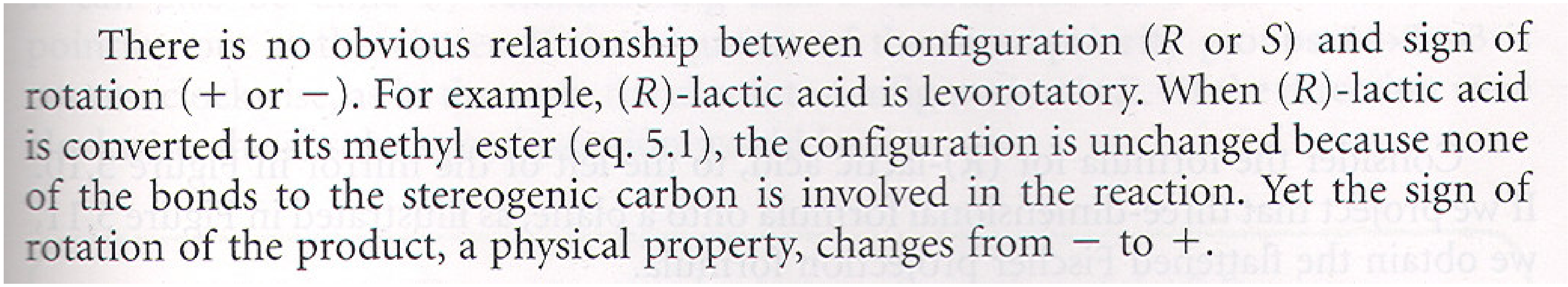
$[\alpha]_D^{25} = -13.52°$



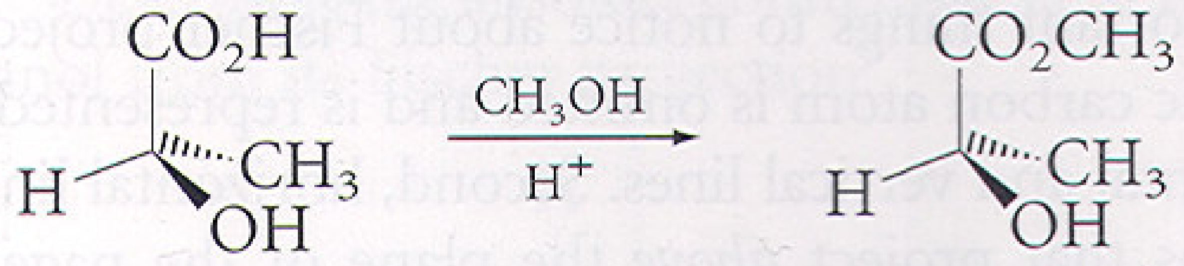
(*S*)-2-Butanol

$[\alpha]_D^{25} = +13.52°$

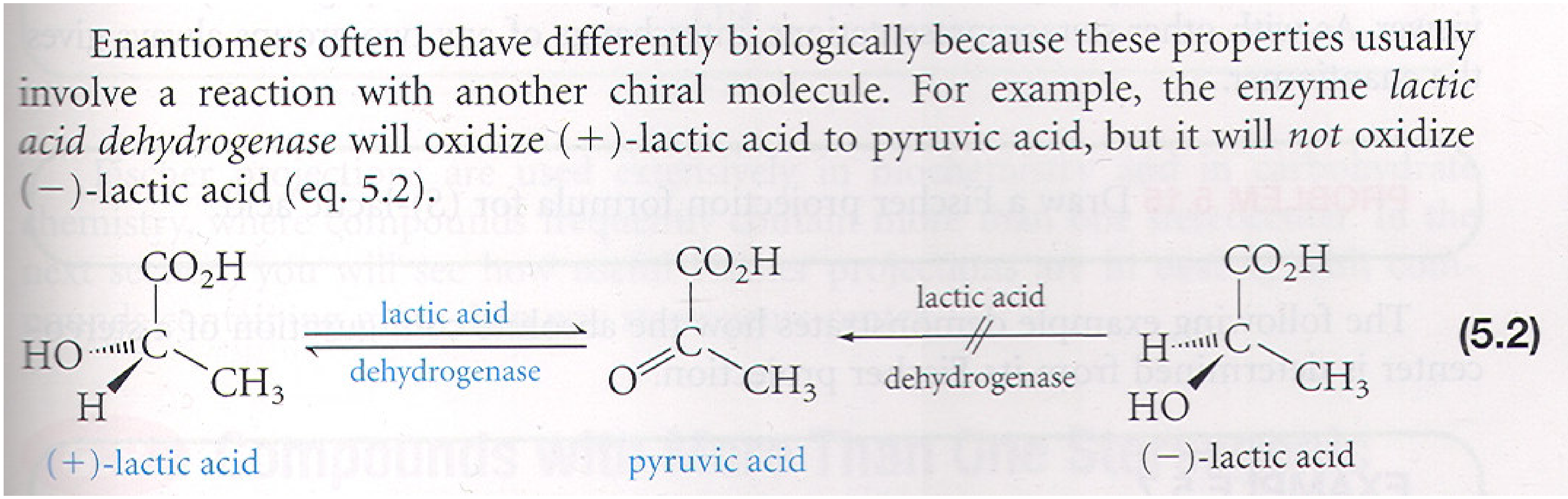
- There is no straightforward correlation between the *R,S* designation of an enantiomer and the direction [(+) or (-)]in which it rotates plane polarized light



There is no obvious relationship between configuration (*R* or *S*) and sign of rotation (+ or −). For example, (*R*)-lactic acid is levorotatory. When (*R*)-lactic acid is converted to its methyl ester (eq. 5.1), the configuration is unchanged because none of the bonds to the stereogenic carbon is involved in the reaction. Yet the sign of rotation of the product, a physical property, changes from − to +.



(*R*)-(−)-lactic acid (*R*)-(+)-methyl lactate



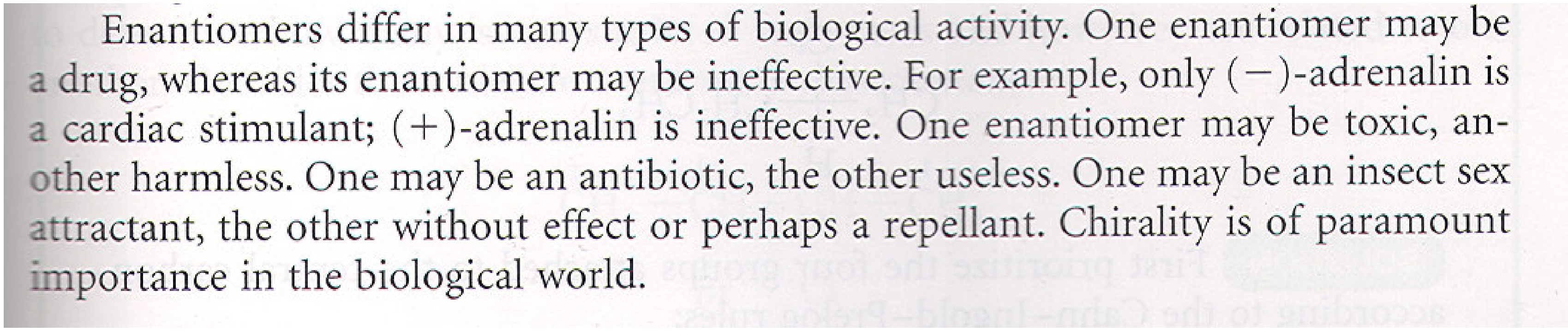
Enantiomers often behave differently biologically because these properties usually involve a reaction with another chiral molecule. For example, the enzyme *lactic acid dehydrogenase* will oxidize (+)-lactic acid to pyruvic acid, but it will *not* oxidize (−)-lactic acid (eq. 5.2).

(+)-lactic acid

pyruvic acid

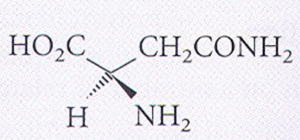
(−)-lactic acid

(5.2)

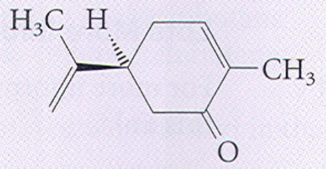


Enantiomers differ in many types of biological activity. One enantiomer may be a drug, whereas its enantiomer may be ineffective. For example, only (−)-adrenalin is a cardiac stimulant; (+)-adrenalin is ineffective. One enantiomer may be toxic, another harmless. One may be an antibiotic, the other useless. One may be an insect sex attractant, the other without effect or perhaps a repellant. Chirality is of paramount importance in the biological world.

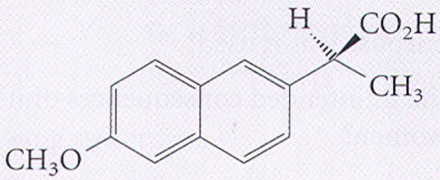
Here are some examples: The amino acid (*R*)-asparagine tastes sweet, while (*S*)-asparagine tastes bitter; (*R*)-carvone has the odor of spearmint, whereas (*S*)-carvone is responsible for the smell of caraway; (*S*)-naproxen is an important anti-inflammatory drug, while its enantiomer is a liver toxin; (*R*,*R*)-chloramphenicol is a useful antibiotic but its enantiomer is harmless to bacteria; (*R*,*R*)-paclobutrazol is a fungicide, while its enantiomer is a plant growth regulator; and (*R*)-thalidomide is a sedative and hypnotic, while its enantiomer is a potent teratogen.



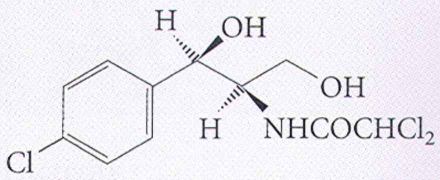
(*R*)-asparagine



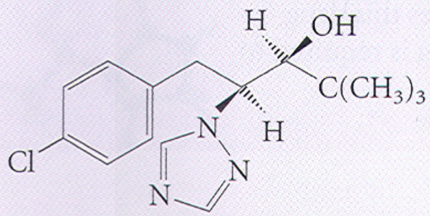
(*S*)-carvone



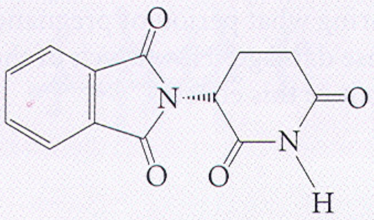
(*S*)-naproxen



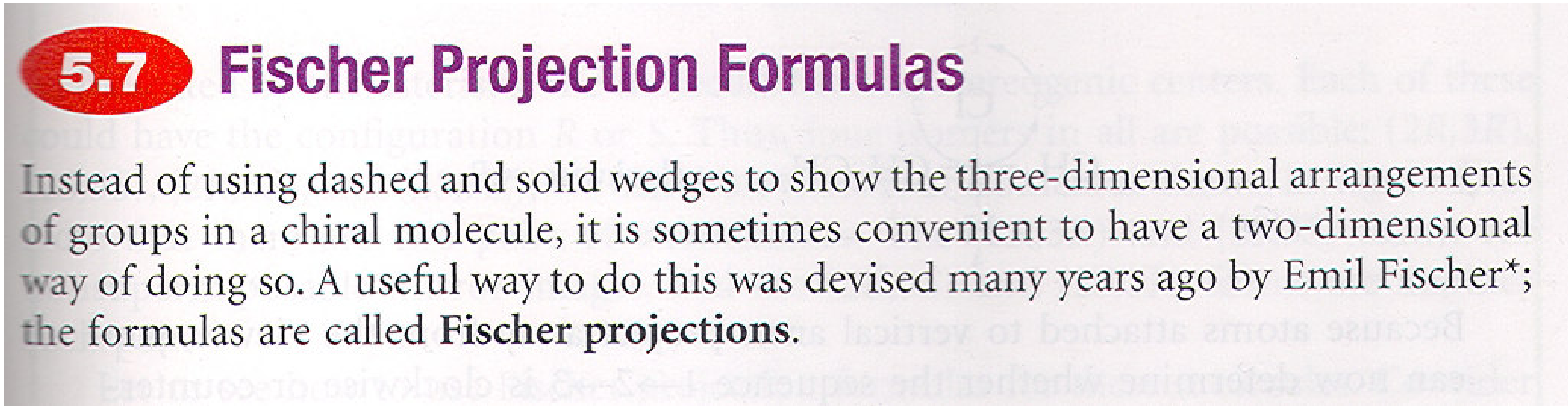
(*R*,*R*)-chloramphenicol



(*S*,*S*)-paclobutrazol

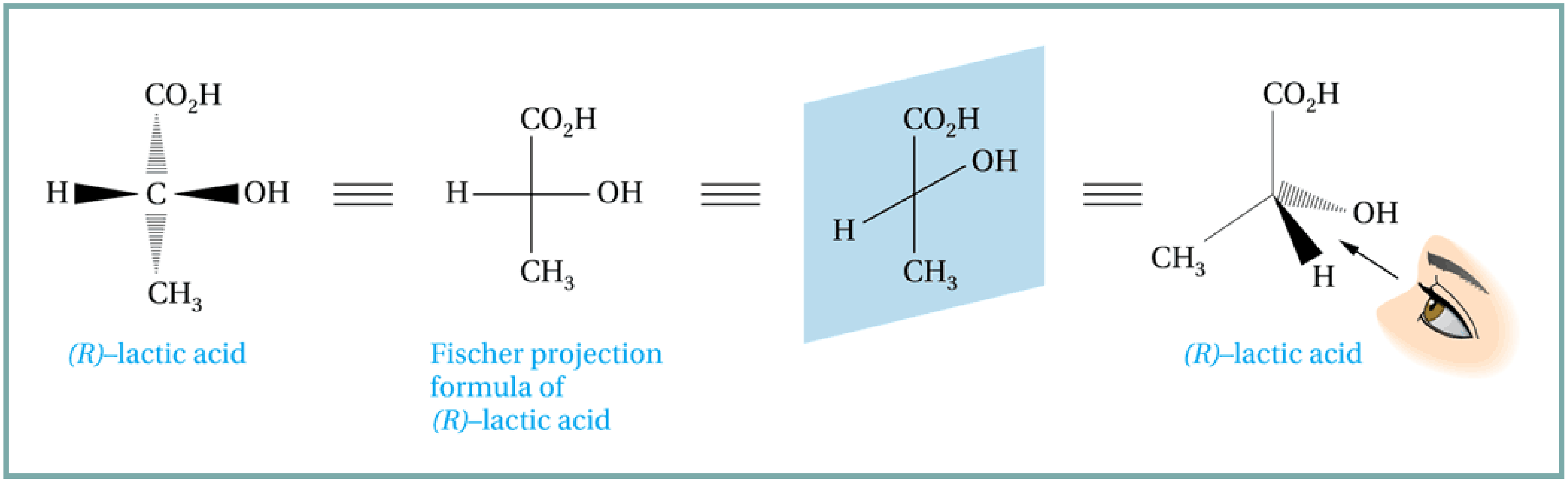


(*R*)-thalidomide



5.7 Fischer Projection Formulas

Instead of using dashed and solid wedges to show the three-dimensional arrangements of groups in a chiral molecule, it is sometimes convenient to have a two-dimensional way of doing so. A useful way to do this was devised many years ago by Emil Fischer*; the formulas are called **Fischer projections.**



(R)–lactic acid

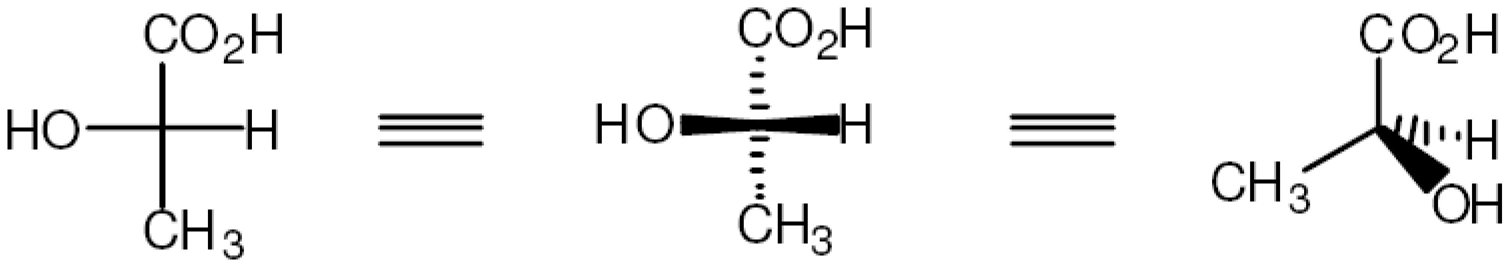
Fischer projection formula of *(R)*–lactic acid

(R)–lactic acid

There are two important things to notice about Fischer projection formulas. First, the C for the stereogenic carbon atom is omitted and is represented simply as the crossing point of the horizontal and vertical lines. Second, horizontal lines connect the stereogenic center to groups that project *above* the plane of the page, *toward* the viewer; vertical lines lead to groups that project *below* the plane of the page, *away* from the viewer. As with other stereorepresentations, interchange of any two groups always gives the enantiomer.

PROBLEM 5.15 Draw a Fischer projection formula for (*S*)-lactic acid.

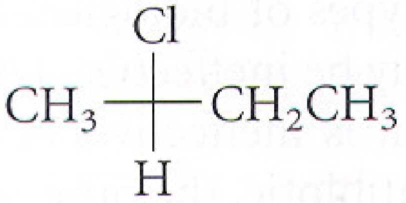
5.15



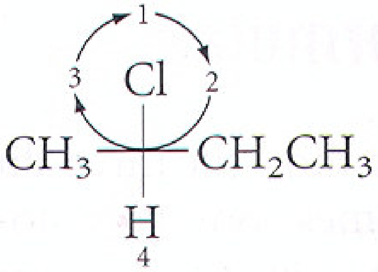
(*S*)-lactic acid

EXAMPLE 5.7

Determine the absolute (*R* or *S*) configuration of the stereoisomer of 2-chlorobutane shown in the Fischer projection below.

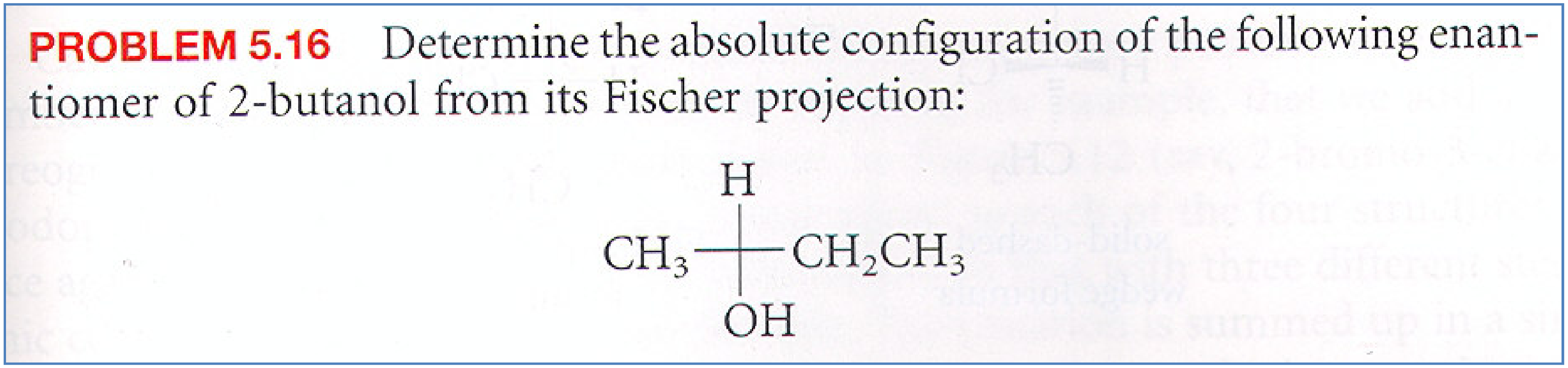


SOLUTION First prioritize the four groups attached to the central carbon according to the Cahn–Ingold–Prelog rules:



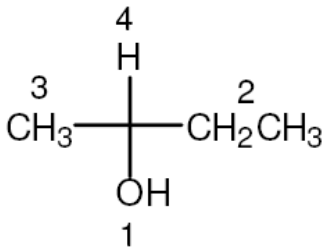
clockwise = *R*

Because atoms attached to vertical arms project away from the viewer, you can now determine whether the sequence 1→2→3 is clockwise or counterclockwise. In this case, it is clockwise, so the absolute configuration of this enantiomer of 2-chlorobutane is *R*.



PROBLEM 5.16 Determine the absolute configuration of the following enantiomer of 2-butanol from its Fischer projection:

5.16 There are several ways to approach this problem. Here's one. Assign priorities to the four groups.



If the lowest priority group is in a vertical position, determine whether the sequence of the remaining three groups (1→2→3) is clockwise (*R*) or counterclockwise (*S*). In this case, it is and the Fischer projection represents (*S*)-2-butanol.

counterclockwise

Selected Problems

58. Which of these is a comparatively insignificant factor affecting the magnitude of specific optical rotation?

A) Concentration of the substance of interest
B) Purity of the sample
C) Temperature of the measurement
D) Length of the sample tube
E) All of the above are equally significant.

60. An alkane which can exhibit optical activity is:

A) Neopentane
B) Isopentane
C) 3–Methylpentane
D) 3–Methylhexane
E) 2,3–Dimethylbutane

61. In the absence of specific data, it can only be said that (R)–2–bromopentane is:

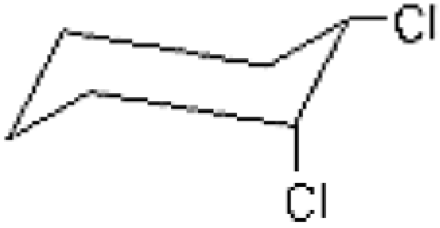
A) dextrorotatory (+).
B) levorotatory (–).
C) optically inactive.
D) achiral.
E) analogous in absolute configuration to (R)–2–chloropentane.

62. If a solution of a compound (30.0 g/100 mL of solution) has a measured rotation of +15° in a 2 dm tube, the specific rotation is:

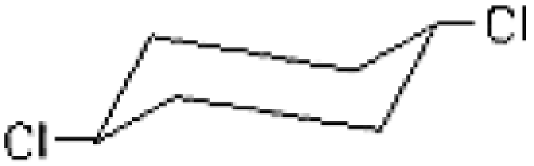
A) +50°
B) +25°
C) +15°
D) +7.5°
E) +4.0°

$$= \frac{+15}{\frac{30}{100}\times 2} = +25$$

63. Which compound would show optical activity?



I



II

III

A) I
B) II
C) III
D) More than one of these
E) None of these