Chiroptical Spectroscopy

Theory and Applications in Organic Chemistry

Lecture 1: It all started with a piece of quartz.

Masters Level Class (181 041)

Block course, october 2020

Outline of the lecture

Dates	topics	
Monday	Introduction	
	Polarization of light	
Tuesday	Theoretical basis of optical activity	
	Optical rotation	
Wednesday	Circular dichroism	
	Circular dichroism	
Thursday	Vibrational optical activity	
	Vibrational optical activity	
Oct 22?	applications	your part
Oct 29?	applications	

And there was (linearly polarized) light

Étienne-Louis Malus
(1775-1812)

Early 1800s:

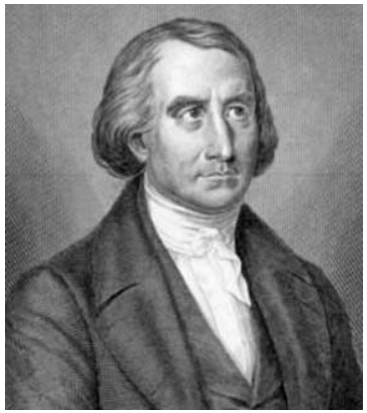
Physicist and mathematician Malus was curious about Christiaan Huygens‘ theory of light and conduced experiments to confirm them.

1809:

Discovery of polarization of light by reflection

Kahr and Claborn, *ChemPhysChem* **9** (2008) 43–58

Discovery of optical rotation



François Arago (1786-1853)

Jean-Baptiste Biot (1774-1862)

1811:

Arago showed that pieces of quarz rotate the plane of polarized light in one directions while others turn it in the opposite direction.

1812:

Biot showed that optical rotation is not property of certain crystals, by measuring optical rotation for solutions of camphor and tartaric acid

1817:

Biot showed that also vapor from oil of turpentine rotated polarization of light.

… and he found that $\alpha \propto \lambda^{-2}$

Discovery of optical rotation

Adam Arndtsen
(1829-1919)

1858:

Norwegian physicist Arndtsen used sunlight, and confirmed the wavelength dependence of OR using some of the Fraunhofer lines

He found that the OR of tartrate exhibits maximum.

A. Arndtsen, *Ann. Chim. Phys.* **54** (1858) 403-421

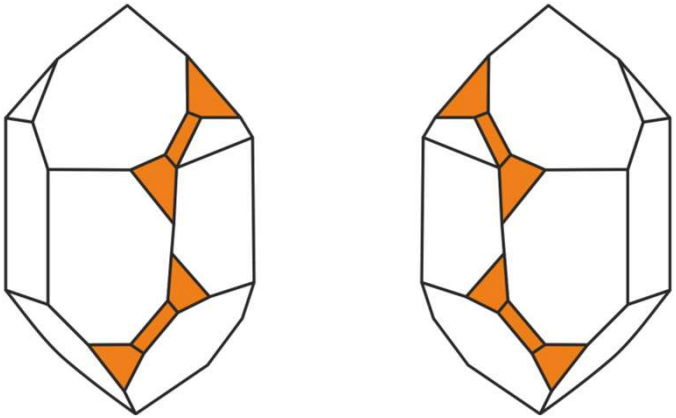
Later, Landolt termed this effect *„anomale Rotationsdispersion“ (anomaleous rotation dispersion).*

H. Landolt, *Liebigs Ann. Chem.* **189** (1877) 241-337

Discovery of hemihedrism

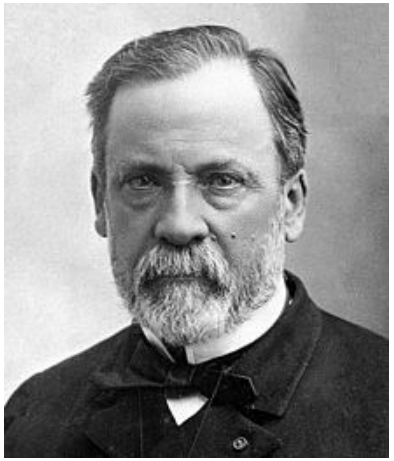
René Just Haüy (1743-1822)

Haüy developed the idea that the shape of a crystal reflects the inner structure, i.e. the periodic arrangement of the matter in the solid.



Hemihedrism of quartz crystals

Pasteur‘s important discovery

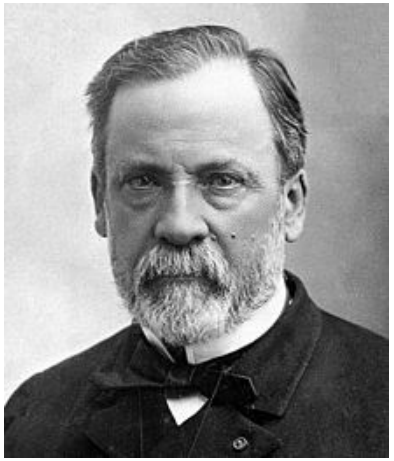


Louis Pasteur (1822-1895)

Pasteur (together with Gay-Lussac) found that the potassium salt of tartaric acid could be contaminated with another acid of the same chemical composition.

Biot showed that tartaric acid and its salt rotate the plane of polarized light while racemic acid itself was inactive.

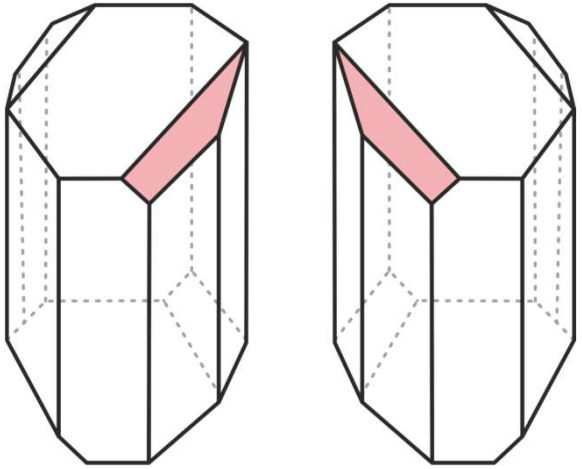
Pasteur‘s important discovery



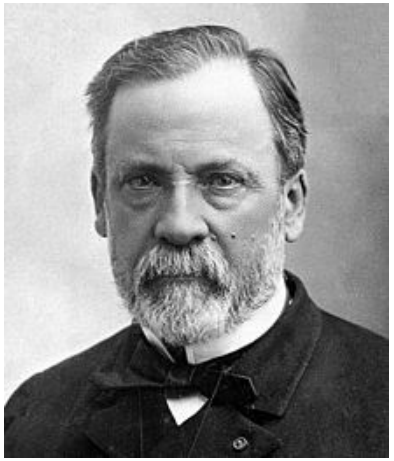
Louis Pasteur (1822-1895)

Pasteur found the solution (1848):

He observed that crystals of tartaric acid have hemihedral faces, while crystals of the racemic acid were found to have crystals with hemihedral faces which are mirror images of each other. One of the types of crystals was identical with those of the optically active form.



Pasteur‘s important discovery



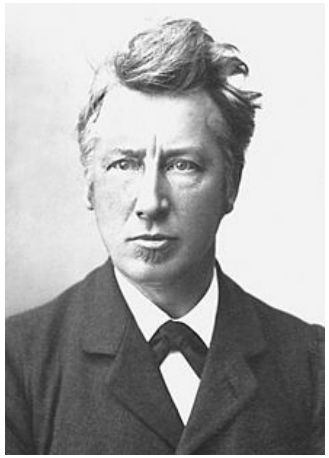
Louis Pasteur (1822-1895)

In solution, this form showed identical dextrorotatory rotation as the optically active (known) form of tartaric acid, while the other one was levorotatory.

As the shape of the crystals was enantiomorph, Pasteur concluded that the molecules must be as well, and called them dissymmetric.

Almost 30 years later…

Joseph Achille
Le Bel (1847-1930)



Jacobus Henricus
van 't Hoff (1852-1911)

1874:

Relationship between molecular structure and optical activity and the concept of the tetrahedral carbon atom.

„Let us consider a molecule of a chemical compound having the formula MA_4. […] let us replace three of them (As) by monoatomic, simple or complex radicals nonidentical to M; the body thus obtained will be dissymmetric. […]

Therefore, in general, a body derived from our original molecule MA_4 by substitution of A with three distinct atoms or radicals will be dissymmetric and have the power of optical rotation. […]"

J. A. Le Bel, *Bull. Soc. Chim. Paris* ***22*** (1874) 337
Translation taken from Amouri, Gruselle, *Chirality in transition metal chemistry*, Wiley, 2008

Cotton‘s important discovery

Aimé Cotton
(1869-1951)

1895:

Two short papers by PhD student Cotton

„Unequal absorption of right and left circularly polarized light by certain optically active substances“

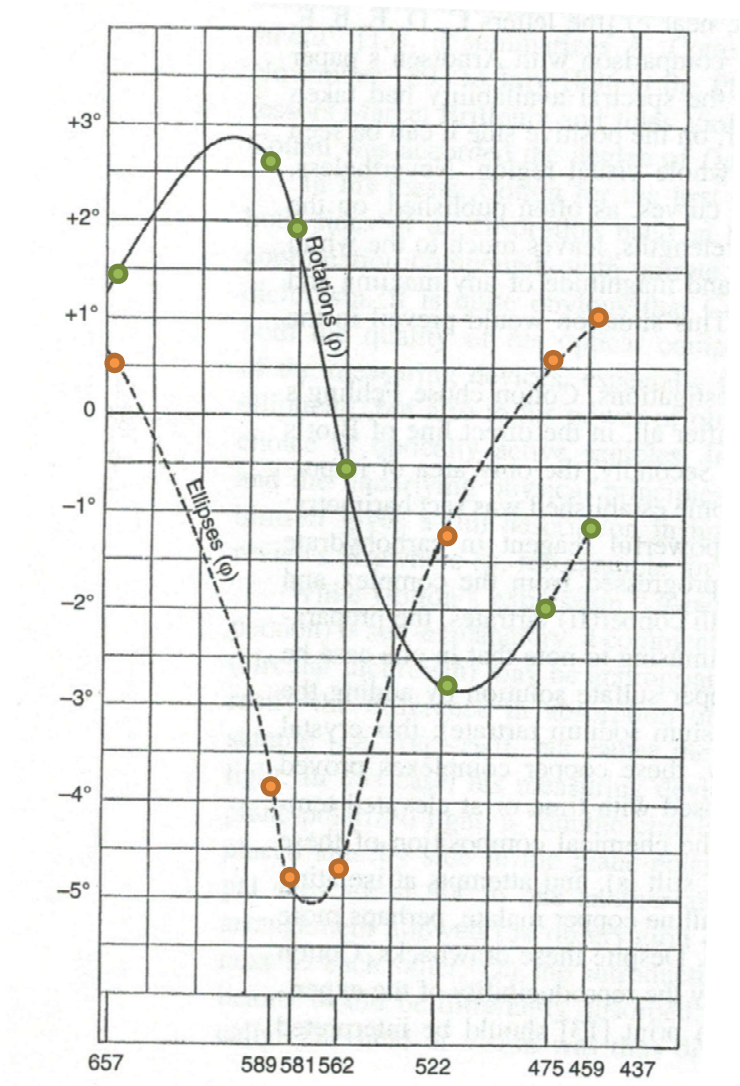
C. R. H. Acad. Sci., **120** (1895) 989-991

„Anomaleous rotatory dispersion of absorbing substances“

C. R. H. Acad. Sci., **120** (1895) 1044-1046

… in which he describes for the first time *„dïchroisme circulaire“* and *„dispersion rotatoire anomale“* , i.e. the effects we today call circular dichroism (CD) and optical rotatory dispersion (ORD).

Cotton‘s important discovery



Taken from Berova et al.
Comprehensive Chiroptical Spectroscopy, Vol. 2, Wiley VCH 2012

Following up on Biot‘s work, Cotton first measured ORD and CD data for Fehling‘s solution (copper tartrates).

Most striking data:

Potassium chromium (III) tartrate in H_2O showing a complete „Cotton effect“

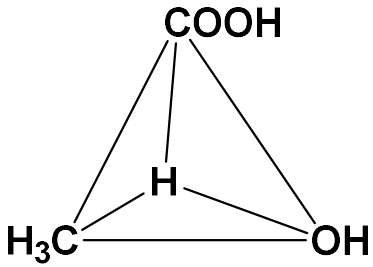
A. Cotton, *Ann. Chim. Physique* **8** (1896) 347

The Cotton effect

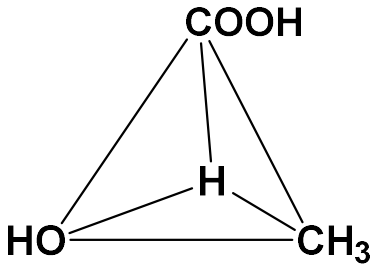
Change of OR near absorbance band

positive Cotton effect: OR↑ when λ↓ (see left figure)

Requirements for optical activity



(S)-(+)-lactic acid
$[\alpha]_D$ = +2.6° (H_2O)

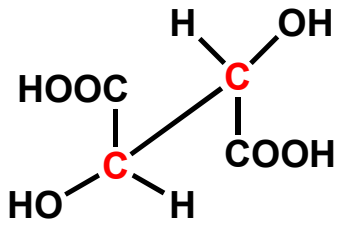


(R)-(-)-lactic acid
$[\alpha]_D$ = -2.6° (H_2O)

Le Bel / van‘t Hoff:

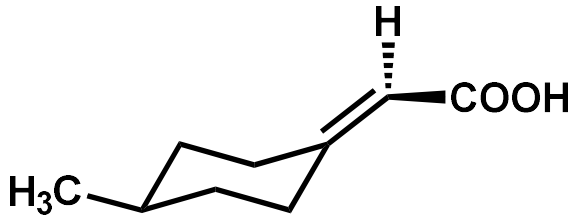
Requirement for optical activity is presence of at least one asymmetrically substituted carbon atom.

Exceptions to the „rule“



Meso-tartaric acid

Not optically active, although it even possesses two asymmetric carbons!

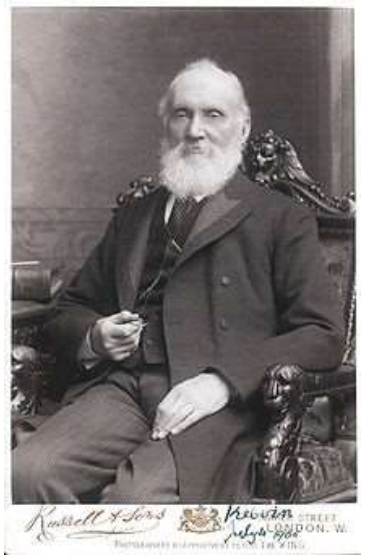


2-(4-methylcyclohexylidene)acetic acid

$[\alpha]_D$ = +95° (H_2O)

Prepared enantiopure in 1909

Definition „chirality“



William Thompson
aka. Lord Kelvin
(1824-1907)

1884:

Referencing back to Pasteur‘s idea that molecules which lack a certain symmetry are optically active, Lord Kelvin suggested that molecules which cannot be superimposed on their mirror imaged isomers are to be called „chiral molecules“.

The most general definition of chirality

… is given by the IUPAC

The geometric property of a rigid object (or spatial arrangement of points or atoms) of being non-superimposable on its mirror image; such an object has no symmetry elements of the second kind (a mirror plane, $\sigma = S_1$, a centre of inversion, $i = S_2$, a rotation reflection axis, S_n). If the object is superimposable on its mirror image the object is described as being achiral.

Knowledge of symmetry point group allows us to decide whether a molecule is chiral or not.

Symmetry operations

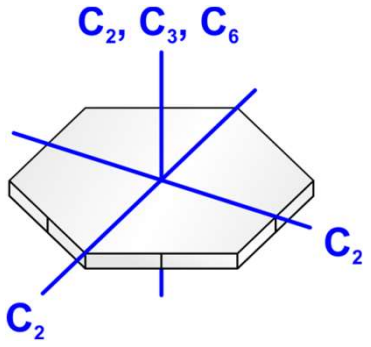
E The **identity** operation, the act of doing nothing.

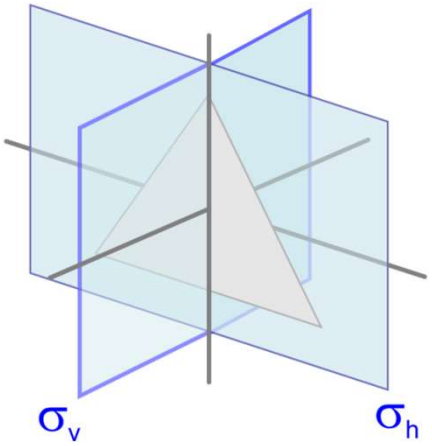
$\mathbf{C_n}$ An **n-fold rotation**, a rotation by $2\pi/n$ around the **axis of symmetry**.

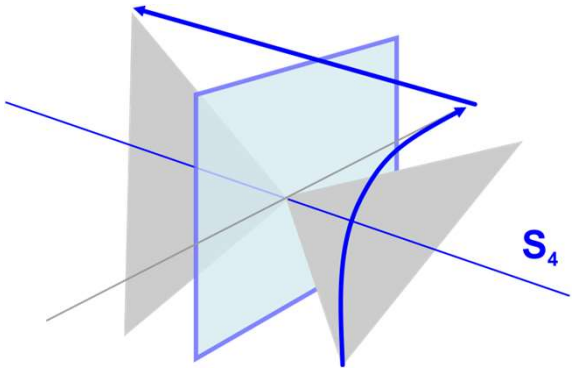
σ A **reflection in a mirror**

i An **inversion** through a **centre of symmetry**

$\mathbf{S_n}$ An **n-fold improper rotation** (a rotary reflection) occurs about an **improper axis**





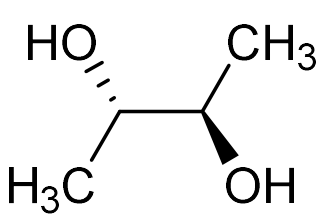


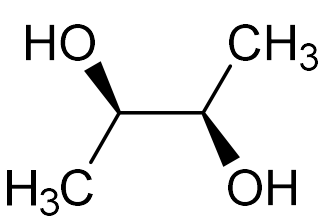
Symmetry point groups

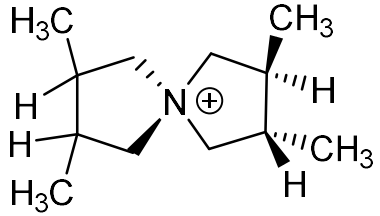
Point group	Symmetry elements	Point group	Symmetry elements
C_1	E	**T_d**	E, 3 C_2, 4 C_3, 3 S_4, 6 σ_d
C_i	E, i	O_h	E, 3S_4, 3C_4, 6 C_2, 4 S_6, 4 C_3, 3 σ_h, 6 σ_d, i
C_s	E, s	I_h	E, 6 S_{10},10 S_6, 6 C_5, 10 C_3, 15 C_2,15 σ
C_n	E, C_n	**D_n**	E, C_n, n C_2
C_{nh}	E, C_n, n σ_v	D_{nh}	E, C_n, σ_h, n C_2
C_{nv}	E, C_n, σ_h, S_n	D_{nd}	E, C_n, σ_d, n C_2
S_n	E, S_n		

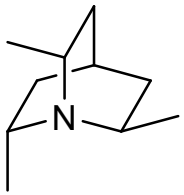
* Molecules of this point group are always chiral

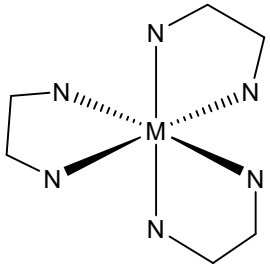
Exercise: Who‘s chiral?

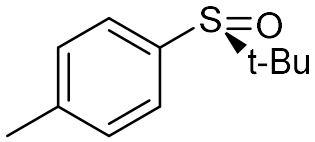


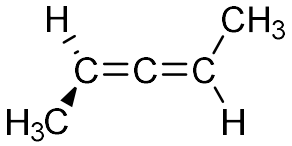


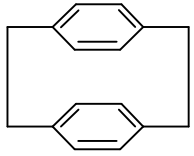


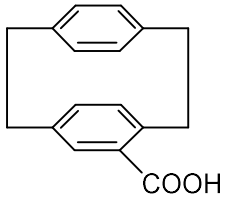


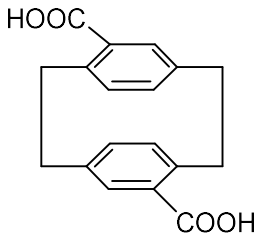


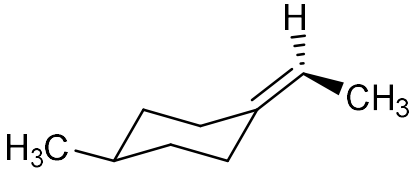


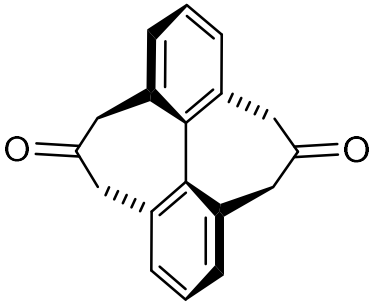


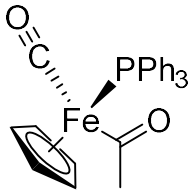


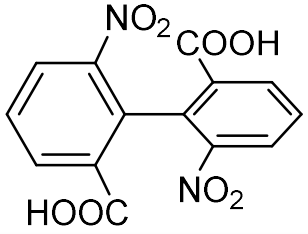




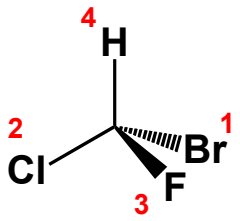


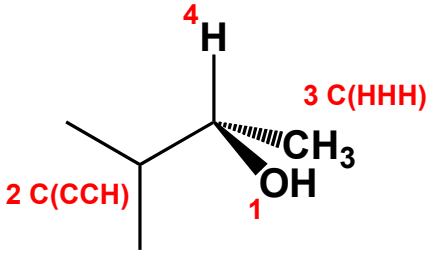


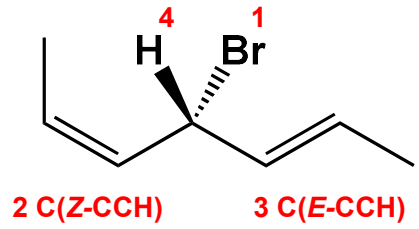




Stereochemical nomenclature







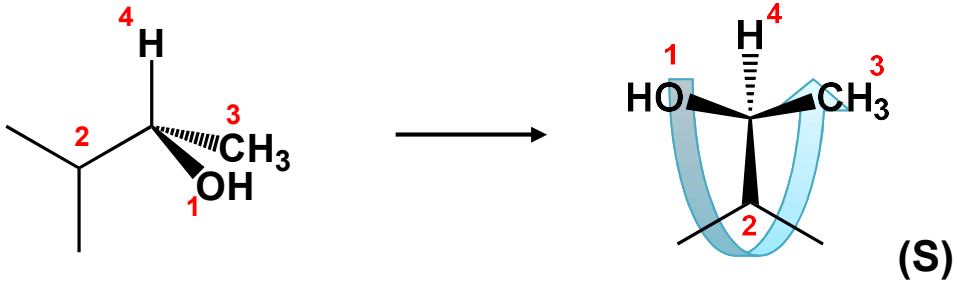
Cahn-Ingold-Prelog priority rules (CIP)

Assignment of priorities:

1. atomic number (electron lone pair = 0)
2. In case of a tie, consider atoms as distance 2 from stereocenter
3. … or third sphere
4. Double bonds: Z > E

Stereochemical nomenclature

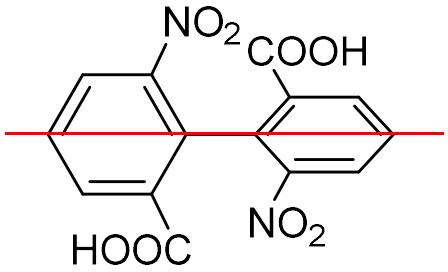
After assignment of priorities, place substituent with lowest priority in the back



… and determine handedness of orientation of the other three:

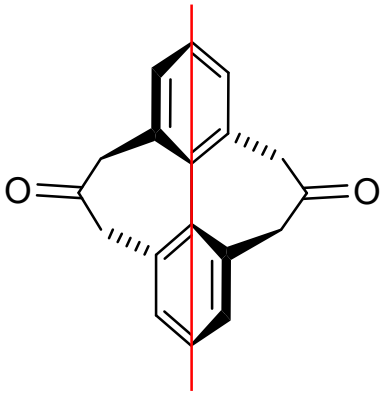
Clockwise: *(R)*-configuration (from lat. *rectus*)
Counter-clockwise: *(S)*-configuration (from lat. *sinister*)

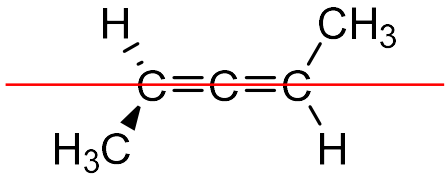
Stereochemical nomenclature: axial chirality

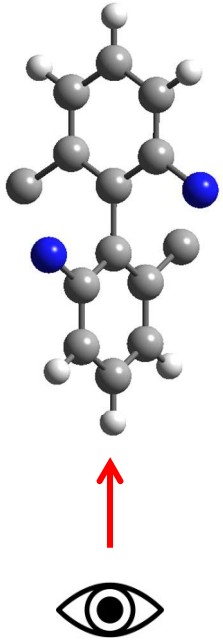


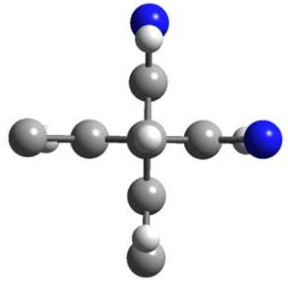
No stereogenic center, but axis of chirality

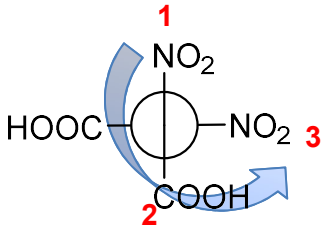
most commonly observed in biaryl compounds such as biphenyls, binaphthyls…



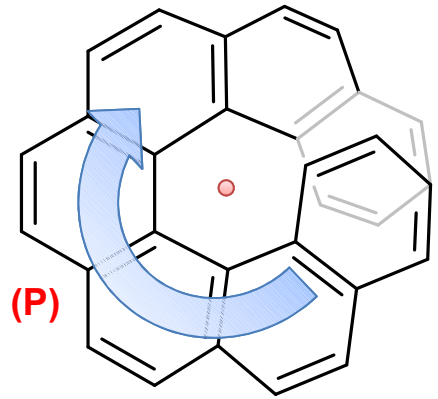








Stereochemical nomenclature: axial chirality

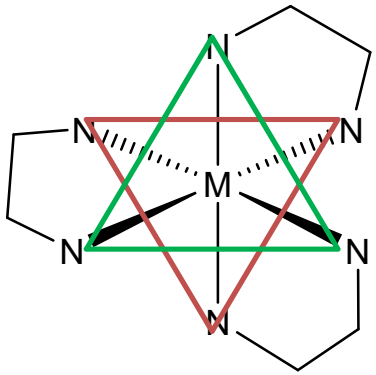


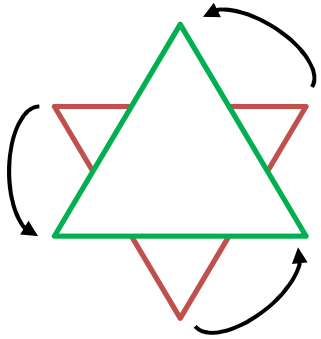
Helical screw sense:

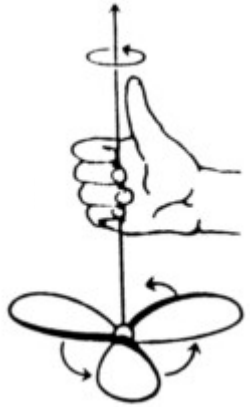
Look along helix propagation direction and determine whether it rotates clockwise or counter-clockwise

Clockwise: (P)-helical

Counterclockwise: (M)-helical



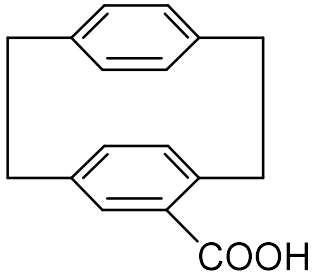




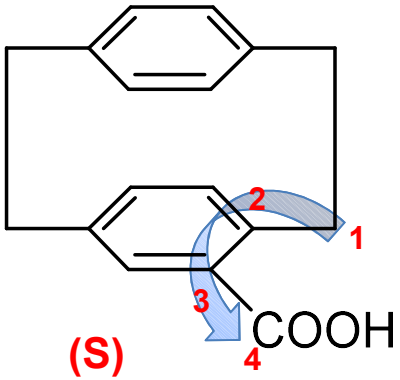
Ligand connectivity follows fingers of right hand: Δ-stereoisomer

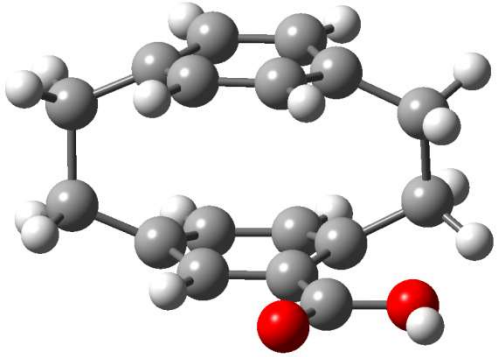
follows fingers of left hand: Λ-stereoisomer

Stereochemical nomenclature: planar chirality

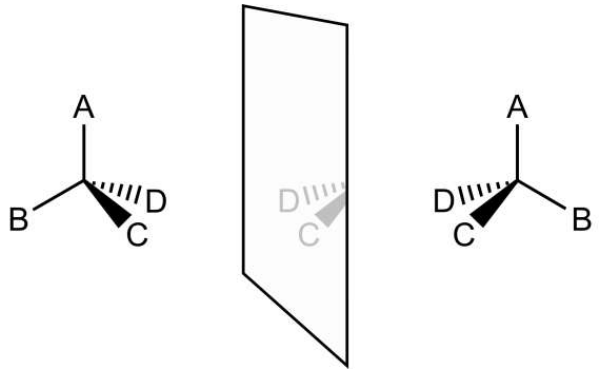


Applicable for molecules lacking an asymmetric carbon atom, but possessing two non-coplanar rings that are each dissymmetric and which cannot easily rotate about the chemical bond connecting them

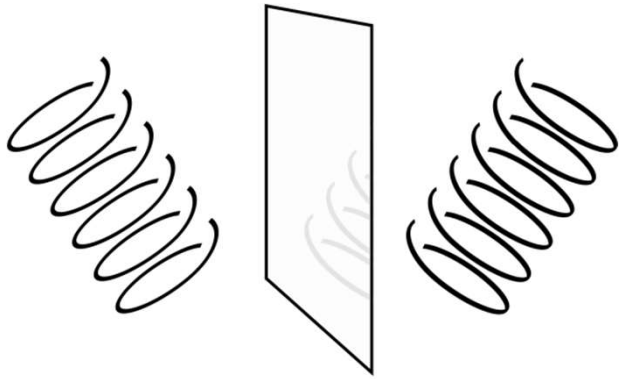




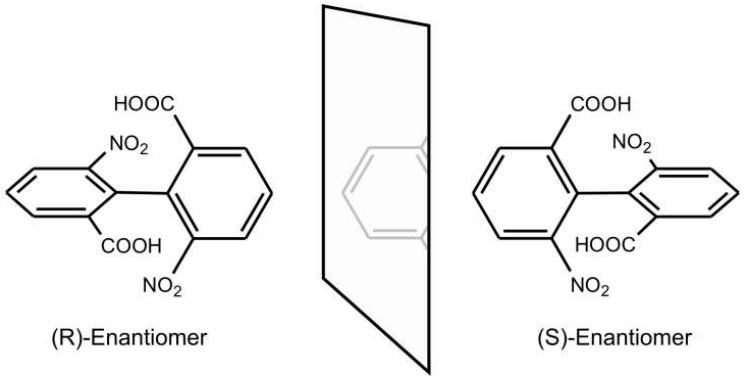
Chiral molecule structures and topologies



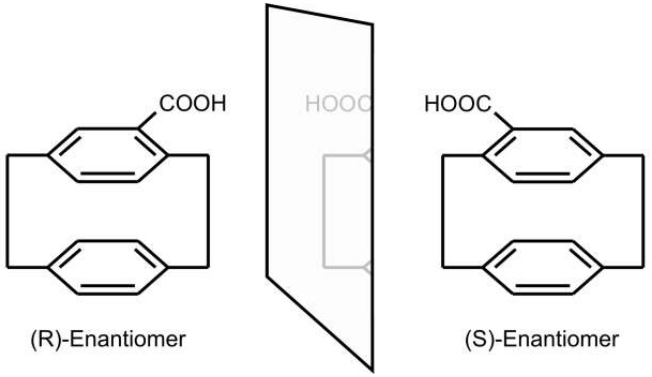
central chirality



helical chirality

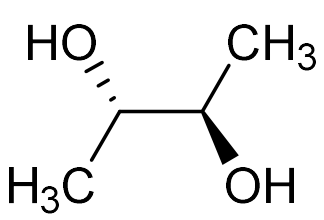


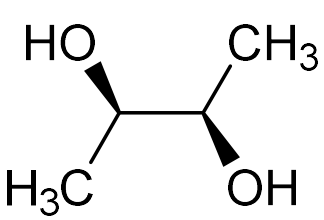
axial chirality

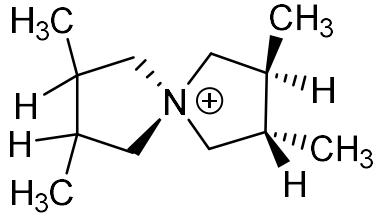


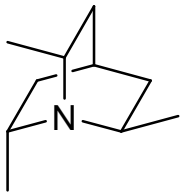
planar chirality

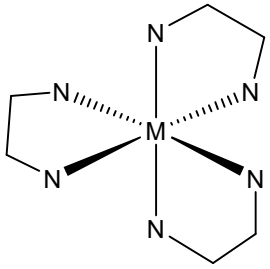
Exercise: Who‘s chiral?

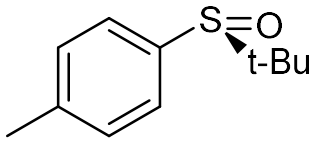


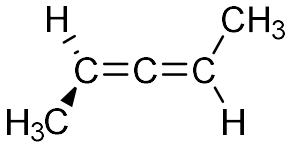


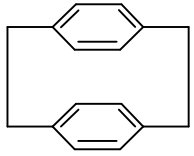


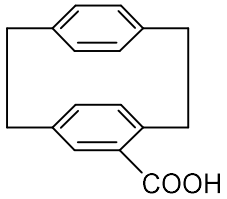


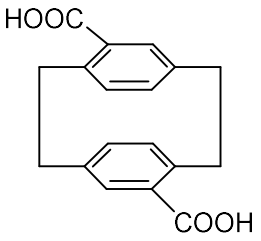


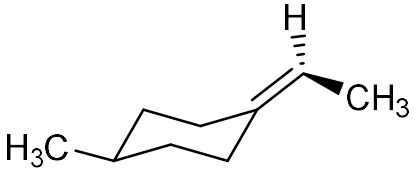


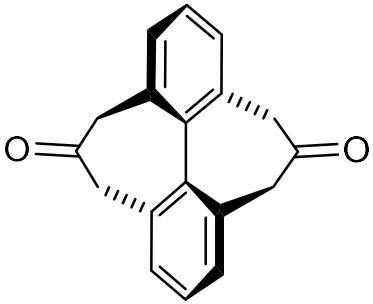


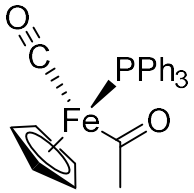


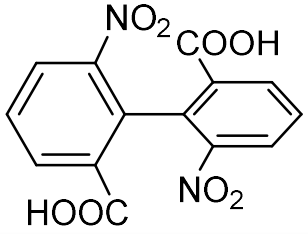












Outline of the lecture

	Dates	topics	
✓	Monday	Introduction	
		Polarization of light	
	Tuesday	Theoretical basis of optical activity	
		Optical rotation	
	Wednesday	Circular dichroism	
		Circular dichroism	
	Thursday	Vibrational optical activity	
		Vibrational optical activity	
	Oct 22?	applications	your part
	Oct 29?	applications	