Pericyclic Reactions

Definition:

1. Concerted reaction that proceed via a cyclic transition state
2. No distinct intermediates in the reaction
3. Bond forming and bond breaking steps are simultaneous but not necessarily synchronous

Classification:

1. Electrocyclic ring closing and ring opening reaction
2. Cycloaddition and Cycloreversion reaction
3. Sigmatropic Rearrangements
4. Chelotropic Reaction
5. Group transfer Reaction

Methods of Analyzing Pericyclic Reaction

1. Orbital symmetry correlation method
   (Woodward, Hoffmann, Longuet-Higgins and Abrahamson)
2. The frontier orbital method
   (Woodward, Hoffmann and Fukui)
3. Transition state aromaticity method
   (Dewar and Zimmerman)

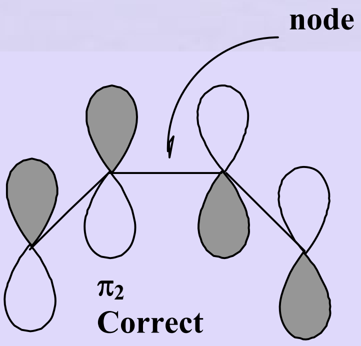
Woodward-Hoffmann Rules: Predicts the allowedness or otherwise of pericyclic reactions under thermal and photo- chemical conditions using the above methods. Therefore a basic understanding of molecular orbitals of conjugated polyene systems and their symmetry properties is essential to apply the above methods.

Constructing MO diagram of polyene systems:

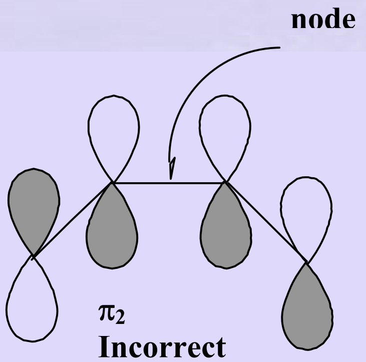
1. Although there are C-C and C-H sigma bonds present in the molecule, the π MOs can be constructed independently of them. Although there may be a change in the hybridization of carbon atoms during the course of a pericyclic reaction, the MO levels of the sigma framework are relatively unaffected.
2. For a conjugated polyene system containing n (n = even) π electrons, there will be n/2 π bonding molecular orbitals that are filled MOs and n/2 antibonding MOs that are empty in the ground state electronic configuration of the molecule.
3. The lowest energy MO has zero nodes, the next higher one has one node and the second higher has two nodes and so on.

   The nth MO will have (n-1) nodes.
4. The nodal points are found at the most symmetric points in a MO.

   In other words, no MO can be symmetric as well as antisymmetric at the same time with respect to any existing molecular symmetry element. For example the π_2 MO of butadiene has a node at the center of the bond connecting C2 and C3. It is incorrect to assign this node to the center of the bond connecting C1 and C2.

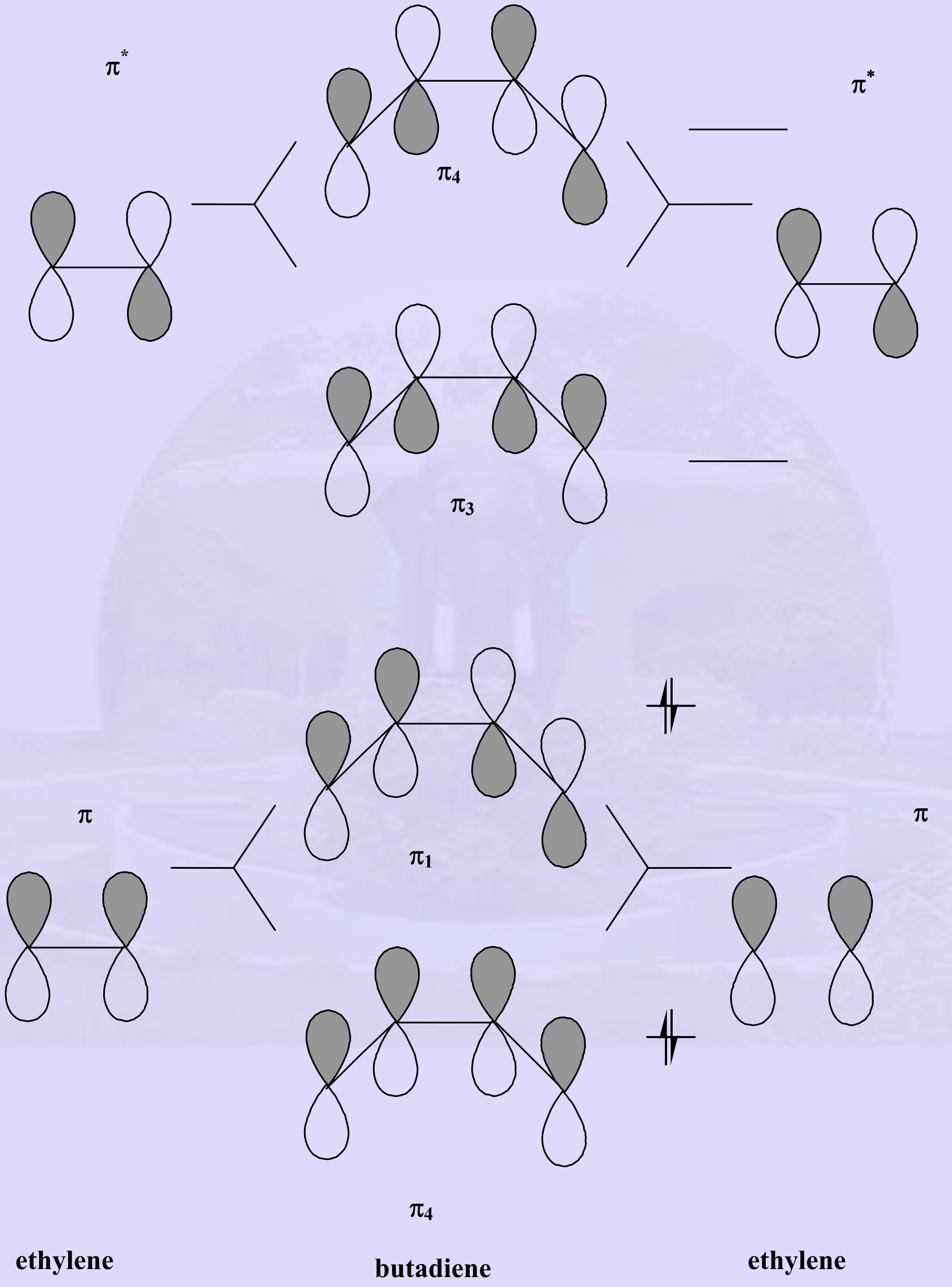


π_2
Correct

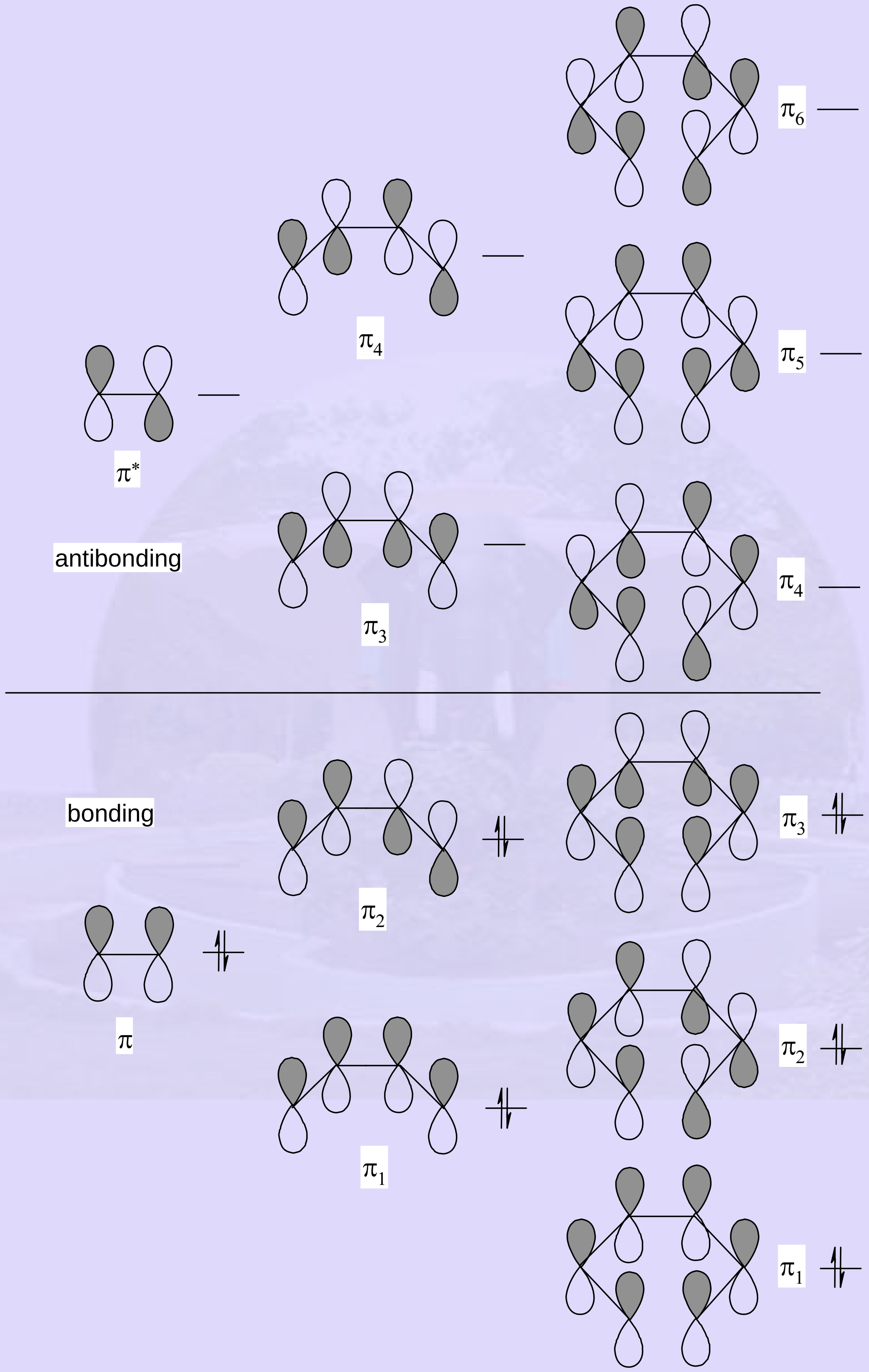


π_2
Incorrect

Formation of MOs of butadiene from MOs of ethylene



MOs of ethylene Butadiene and hexatriene



Frontier orbital method:

Highest occupied MO (HOMO) – filled

Lowest unoccupied MO (LUMO) – empty

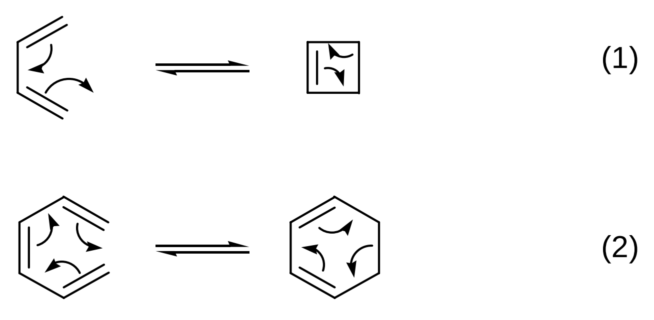
Analysis based on the interaction of HOMO of one Component and LUMO of the other component.

If HOMO-LUMO interaction leads to bonding then the reaction is allowed. If not it is forbidden.

HOMO-LUMO gap is important. The closer it is the faster the reaction.

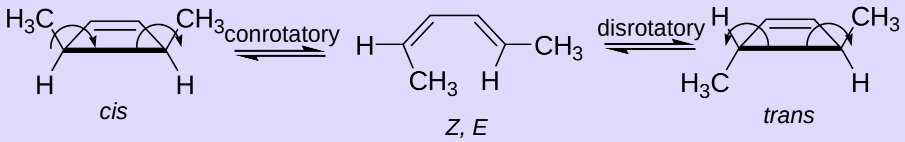
ELECTROCYCLIC REACTIONS

1. Cyclization of an acyclic conjugated polyene system
2. The terminal carbons interact to form a sigma bond
3. Cyclic transition state involving either 4n electrons or 4n+2 electrons.



Electrocyclization of butadiene (4n) and hexatriene (4n+2)

Modes of ring closing/ring opening reactions - Stereochemistry



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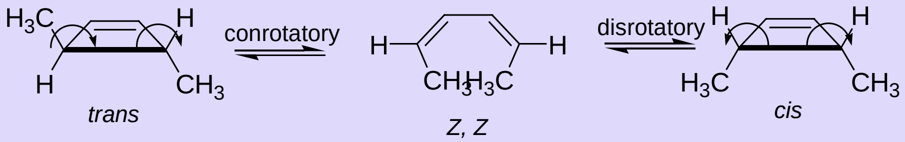

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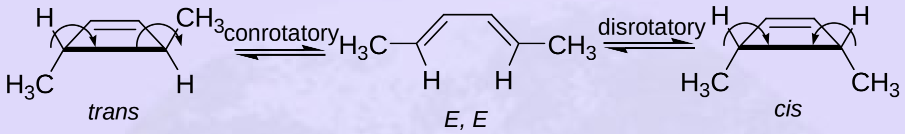

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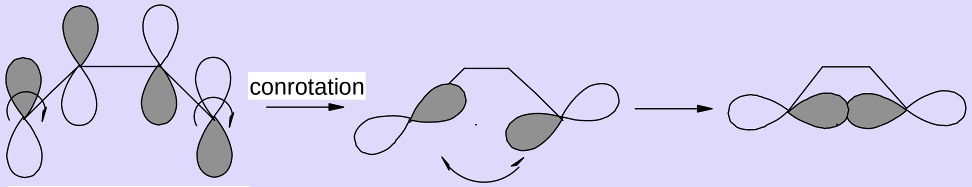
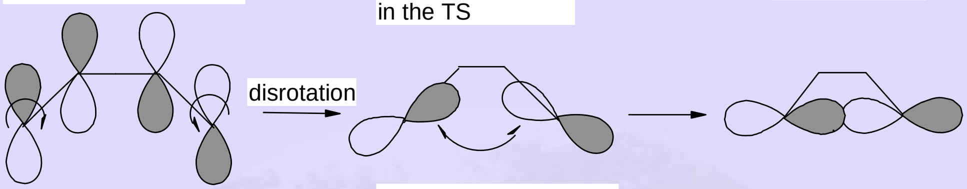
Frontier orbital method for electrocyclic reactions



π_2 HOMO of butadiene

bonding interaction
in the TS

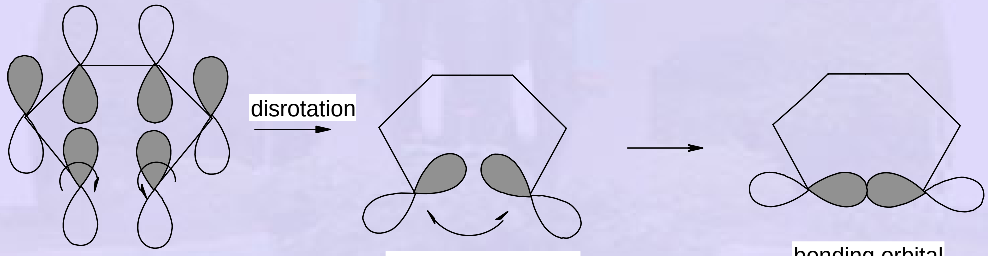
bonding orbital



π_2 HOMO of butadiene

antibonding interaction
in the TS

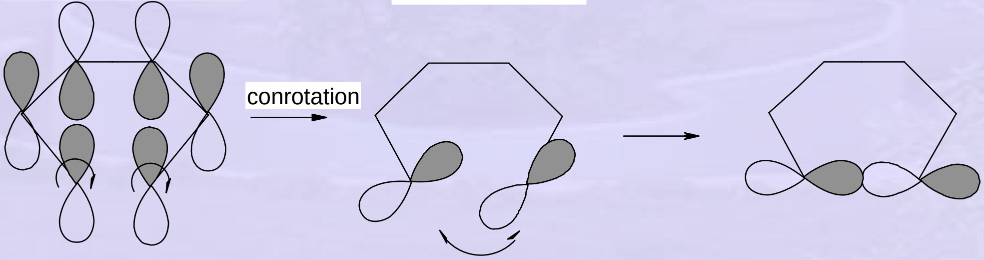
antibonding orbital



π_3 HOMO of hexatriene

bonding interaction
in the TS

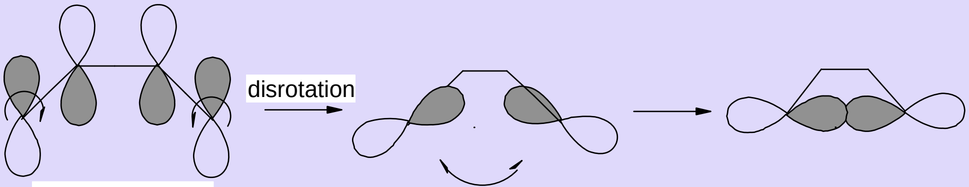
bonding orbital



π_3 HOMO of hexatriene

antibonding interaction
in the TS

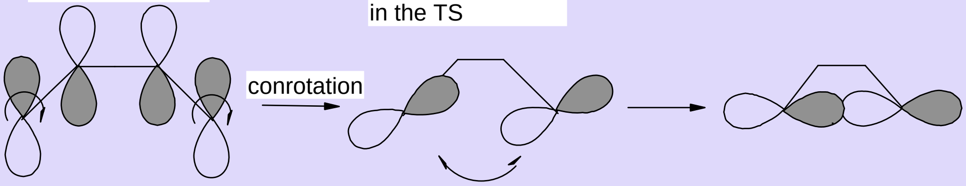
antibonding orbital



HOMO of excited state butadiene

bonding interaction in the TS

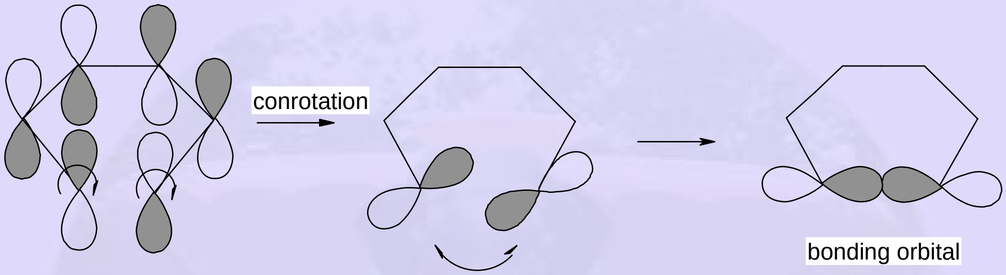
bonding orbital



HOMO of excited state butadiene

antibonding interaction in the TS

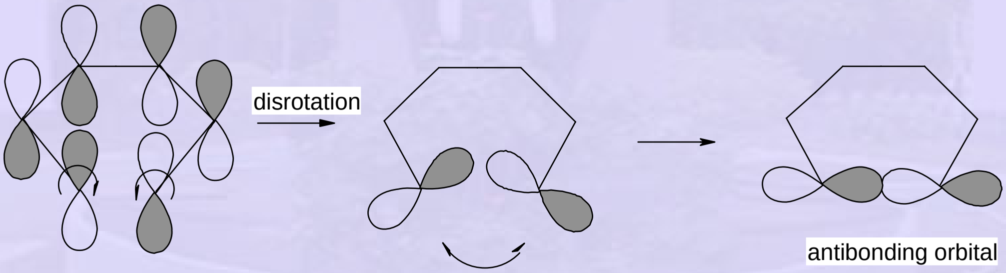
antibonding orbital



bonding orbital

HOMO of excited state hexatriene

bonding interaction in the TS



antibonding orbital

HOMO of excited state hexatriene

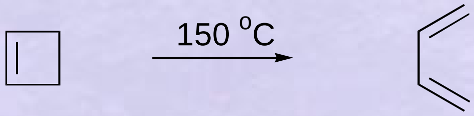
antibonding interaction in the TS

Woodward – Hoffmann rules for electrocyclic reactions

System (no of electrons)	**Mode of reaction**	**Allowedness of the reaction**	
		Thermal	Photochemical
4*n*	conrotatory	allowed	forbidden
4*n*	disrotatory	forbidden	allowed
4*n*+2	conrotatory	forbidden	allowed
4*n*+2	disrotatory	allowed	forbidden

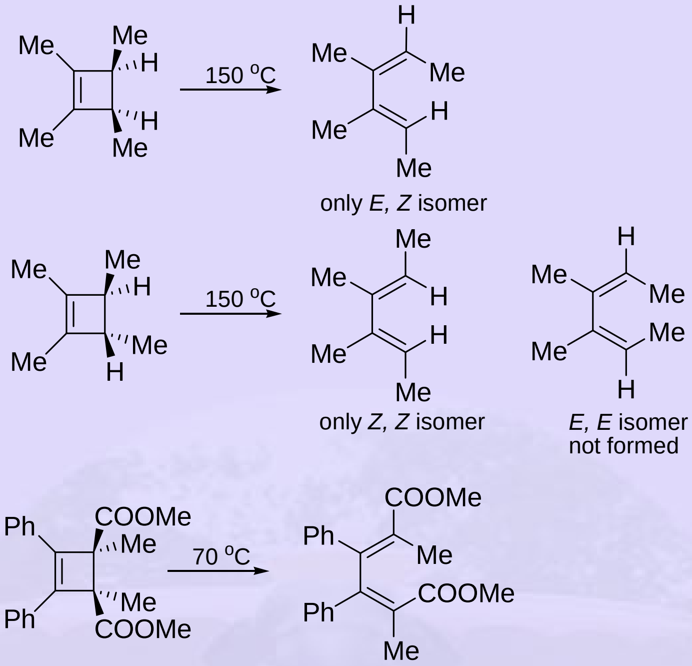
Four-membered Ring Systems:

The synthesis of cyclobutene was first reported by Willstätter. The thermal ring opening of cyclobutene occurs readily at 150 °C to give 1,3-butadiene.



Thermal isomerization of cyclobutene to 1,3-butadiene

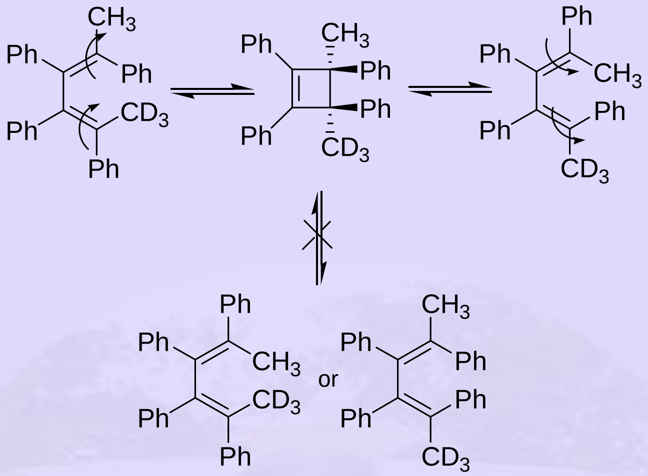
The stereochemistry of the ring opening has been studied systematically in detail by Vogel and Criegee even before the theory of pericyclic reactions and Woodward-Hoffmann rules were developed. The electrocyclic ring opening of 3,4-disubstitued cyclobutenes yield products arising from the conrotatory mode of ring opening with high stereospecificity as illusrated below.



Stereochemistry of thermal electrocyclic ring opening of cyclobutenes.

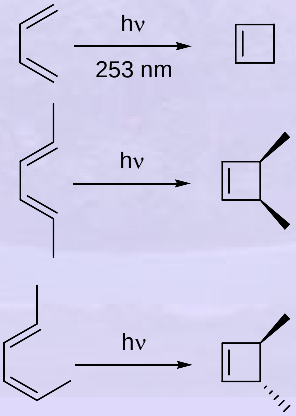
Thermal isomerization of the highly substituted dienes shown below takes place through the formation of the cyclobutene intermediate by a conrotatory pathway. None of the symmetry disallowed disrotatory products were formed even after 51 days at +124 ^{o}C which allowed the estimation of a lower limit of 7.3 kcal/mole of energy difference between the conrotatory and disrotatory modes of reaction.

Stereoselective thermal isomerization of 1,3-butadiene derivatives.



51 days at 140° C

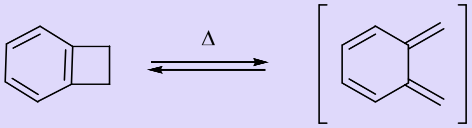
The photochemical ring closing of butadiene and *E,E* and *Z,E*-hexa-2,4-diene has been studied by Srinivasan and the reaction follows the disroatory mode as predicted by the Woodward-Hoffmann rules.



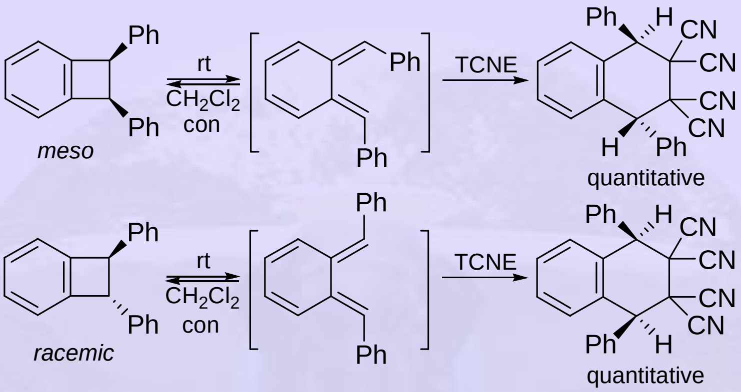
Photochemical electrocyclization of 1,3-butadiene derivatives.

Benzocyclobutene is another well studied 4 electron system and the electrocyclic ring opening gives a very reactive intermediate, namely *ortho* quinodimethane.

Thermal isomerization of benzocyclobutene to *ortho* quinodimethane.

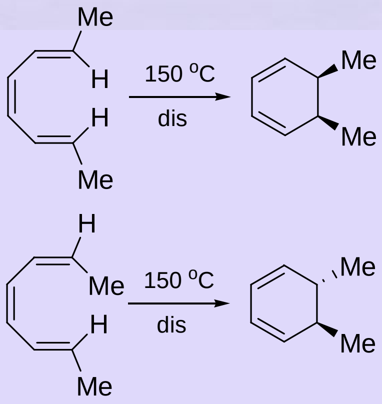


Stereoselective thermal isomerization of benzocyclobutene derivatives



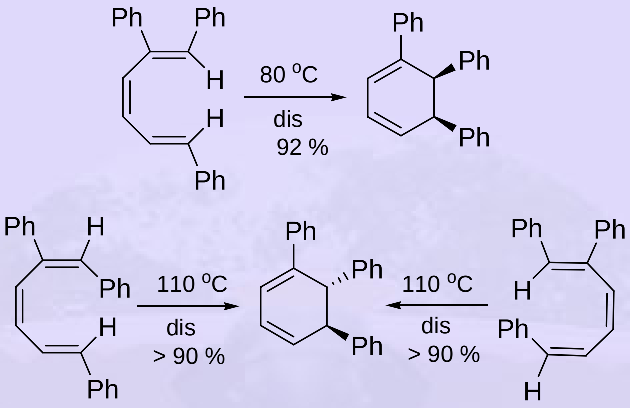
Examples of thermal and photochemical electrocyclic reaction of cyclohexadiene-hexatriene system are abundant in the literature.[] According to the Woodward-Hoffmann rules this six electron system is predicted to undergo disrotatory cyclization under thermal and conrotatory ring closure under photochemical conditions. Isomeric octatrienes conform to the above predictions and undergo stereospecific electrocyclization as shown below.

Stereospecific electrocyclic ring closure of isomeric hexa-1,3-5-trienes.

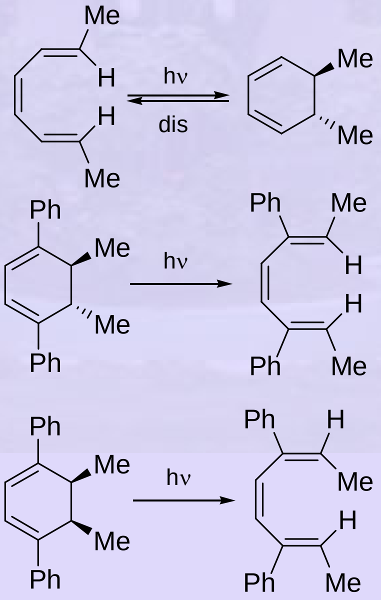


The photochemical reaction proceeds by a conrotatory ring closure / opening mode and in general a photostationary state is reached consisting of an equilibrium mixture of both the hexatriene and cyclohexadiene (shown below).

Stereospecific thermal ring closure of triphenylhexatrienes.



Photochemical electrocyclic ring opening / closure of cyclohexdiene / hexatriene systems



CYCLOADDITION REACTIONS

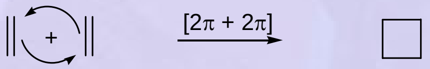
1. Reaction of two components to form a cyclic compound
2. Ring forming reactions
3. Pericyclic type – both components are π systems
4. Intramolecular and intermolecular versions

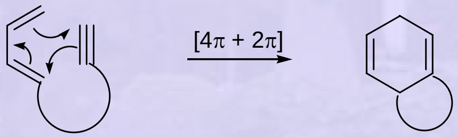
Classification

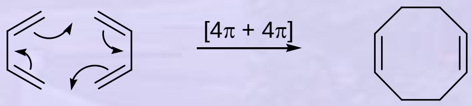
Based on the number of π electrons involved in each component

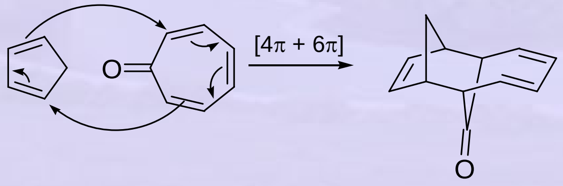
The numbers are written within a square bracket e.g. [2π + 2π], [2π + 4π] etc

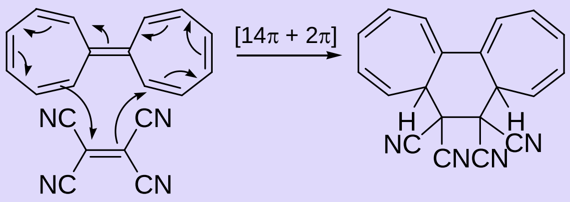
EXAMPLES OF CYCLOADDITION REACTIONS





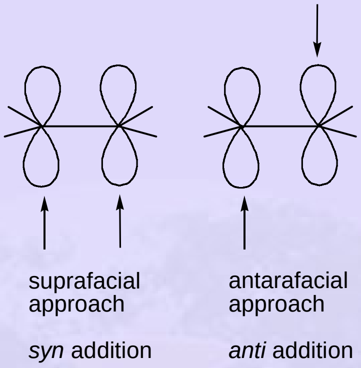






Stereochemistry of cycloaddition reactions

Suprafacial and antarafacial approaches to a π bond

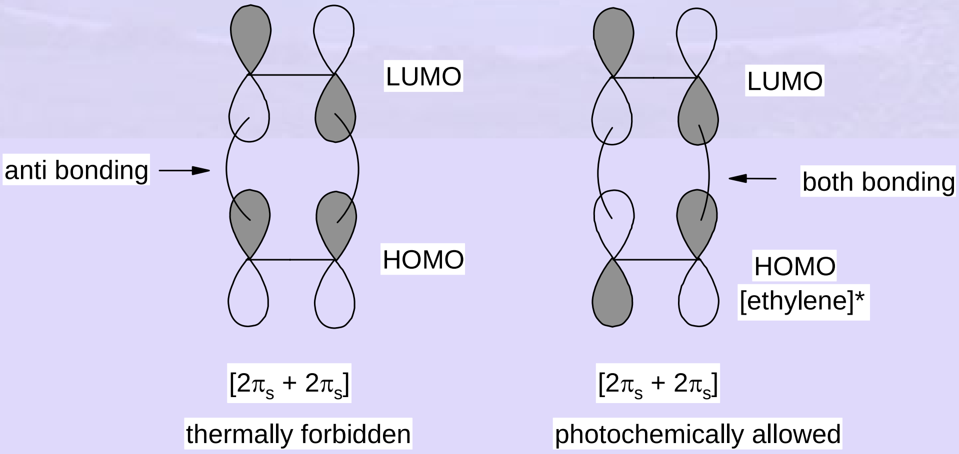


It is necessary to specify with respect to each π component whether the approach is suprafacial or antarafacial

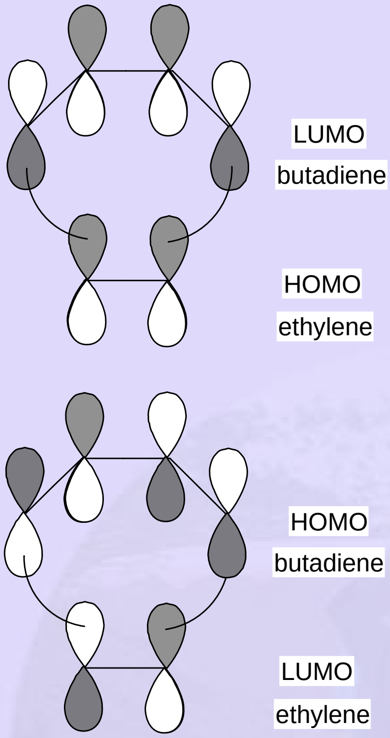
The cycloaddition of ethylene to form cyclobutane is a $[2\pi_s + 2\pi_s]$ process. The thermal Diels-Alder reaction is a $[4\pi_s + 2\pi_s]$ process

Frontier Orbital Method:

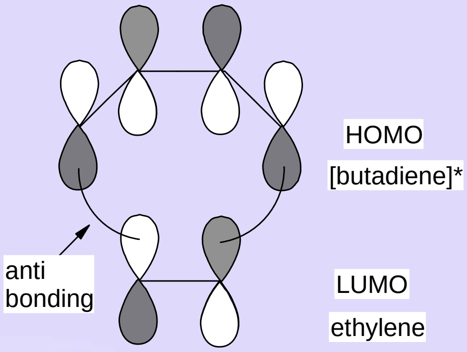
HOMO-LUMO interaction for a $[2\pi_s+2\pi_s]$ cycloaddition.



HOMO-LUMO interaction for a $[4\pi_s+2\pi_s]$ cycloaddition

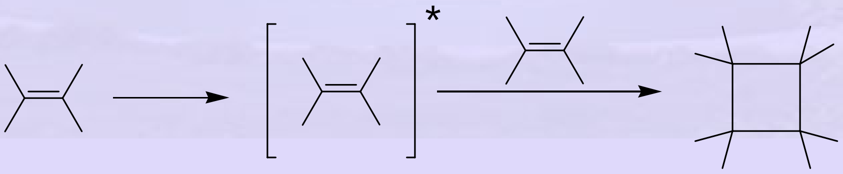


$[4\pi_s + 2\pi_s]$
thermally allowed



$[4\pi_s + 2\pi_s]$
photochemically forbidden

Concerted $[2\pi+2\pi]$ cycloaddition reactions of alkenes



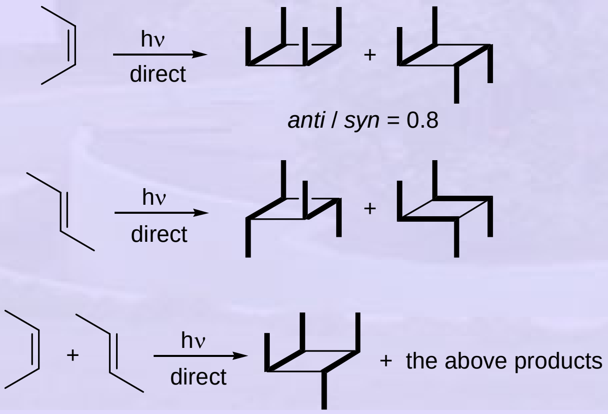
1. Convenient way to form cyclobutanes
2. Reaction occurs from singlet excited π-π* state
3. Triplet sensitizer is required to form T1 state
4. Acyclic alkenes undergo competing cis-trans isomerization

5. Reaction is generally suprafacial-suprafacial additon and hence highly stereospecific

Photochemical [2π + 2π] Cycloadditions:

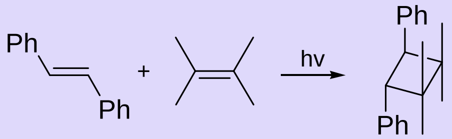
The concerted photochemical [2π + 2π] cycloaddition reaction is suprafacial on both of the π systems. The dimerization of *cis*- and *trans*-2-butene have been reported to take place in a highly stereospecific manner. The structure of the four possible isomers are given in Scheme below. The original 2-butene fragment in the product is shown by thick lines. Only two isomers namely the *cis-syn-cis* (*syn)* and the *cis-anti-cis* (*anti)* isomer are formed when pure *cis* 2-butene was photolysed in the liquid state. Similarly when pure *trans*-2-butene was photolysed it gave only *trans-anti-trans* and *cis-anti-cis* isomers. The fourth isomer, namely *cis-anti-trans*, was formed only when a mixture of *cis*- and *trans*-2-butene was photolysed. This experiment clearly points to the fact that the reaction is highly stereospecific and suprafacial in each of the reacting partners.

Photochemical cycloaddition reactions of *cis*- and *trans*-2-butene.



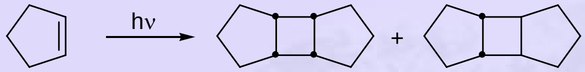
Chapman has reported an efficient photochemical cross addition of *trans*-stilbene with tetramethylethylene with high quantum yield (Φ = 1.0) and high stereospecificity. The inverse dependence of the rate of cycloaddition with temperature provided evidence for an *exciplex* formation.

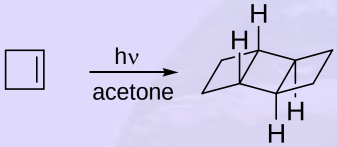
Photochemical cross addition of *trans*-stilbene and tetramethylethylene

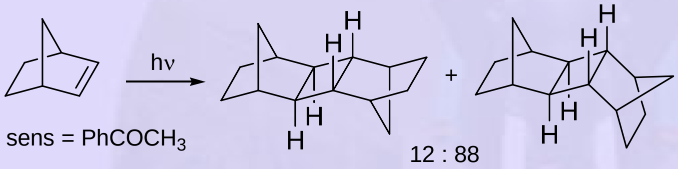


Via exciplex, Φ = 1.0

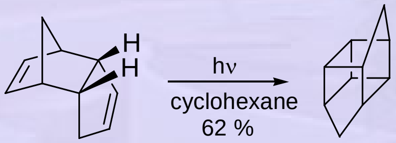
[2π+2π] Photocycloadditions of cyclic alkenes

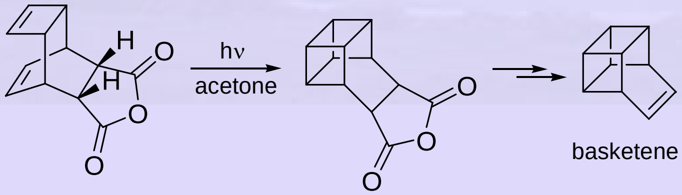


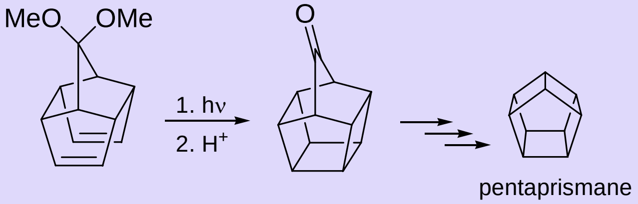




Synthesis of cage structures by photochemical cycloaddition





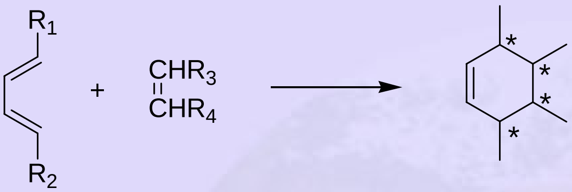


Diels-Alder Reaction:

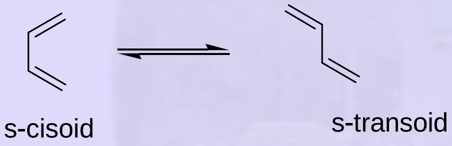
Thermal cycloaddition between a cisoid conjugated diene and a dienophile, usually a olefin or an acetylene

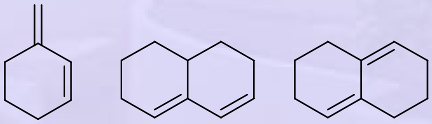
Six membered ring is formed

It is a concerted [$4\pi_s + 2\pi_s$] addition

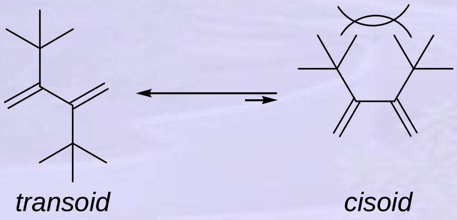


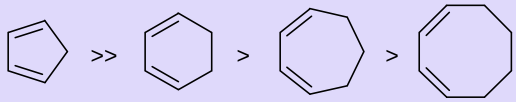
Diels-Alder Diene





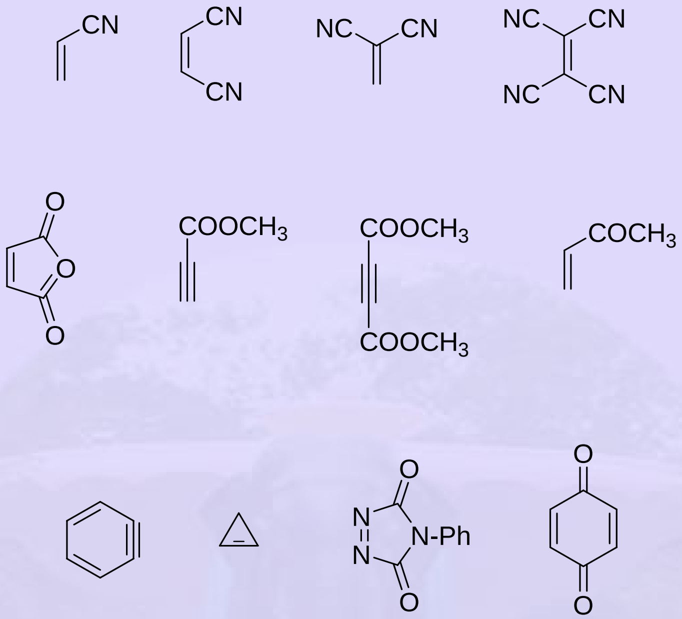
conjugated *transoid* dienes



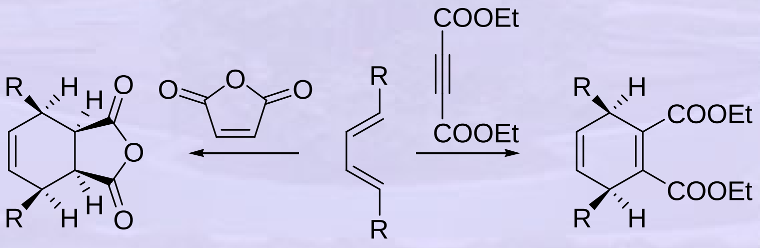


Order of reactivity of cyclic conjugated dienes

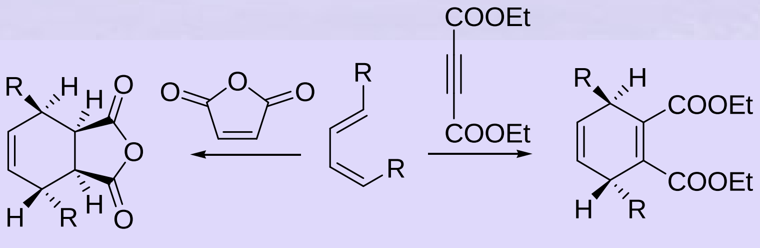
Dienophiles:



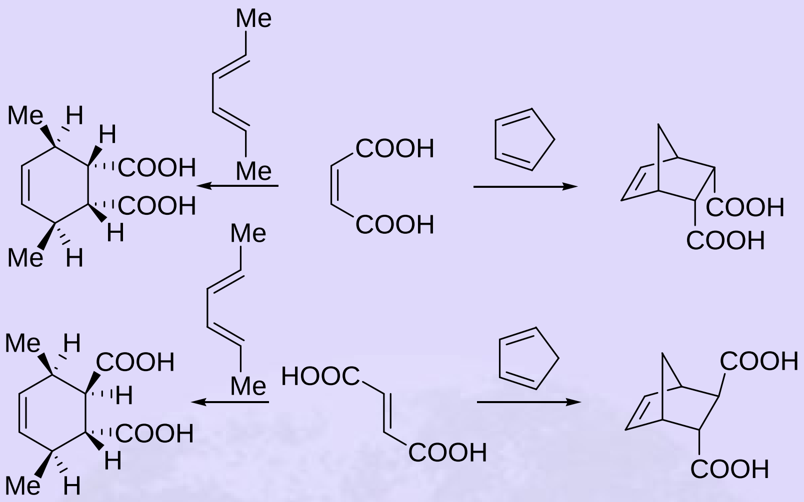
The "*cis*" rule :



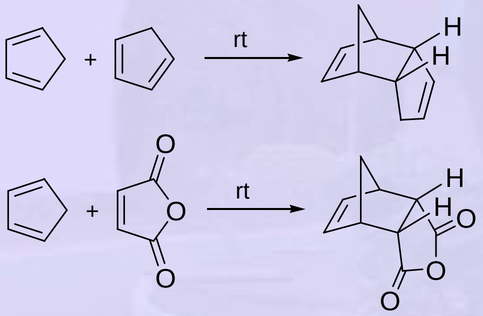
R = Me, Ph

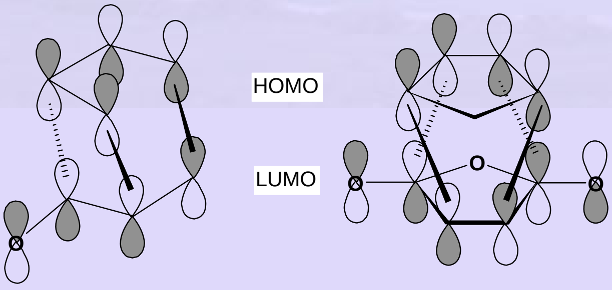


R = Me, Ph

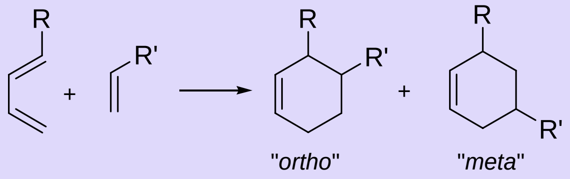


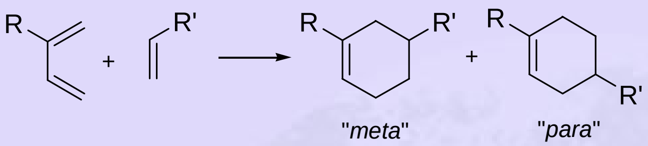
Alder's "endo" rule (secondary orbital interactions):





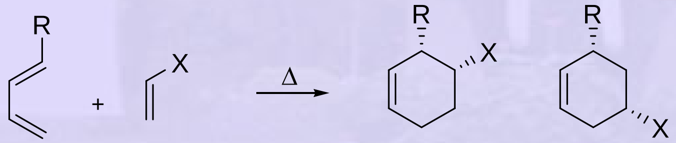
Regioselectivity in Diels-Alder reaction:



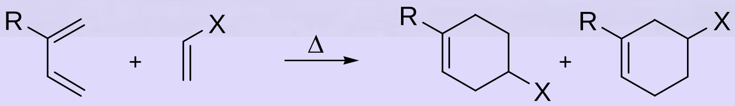


Diels-Alder reactions are highly ortho/para selective.

The regioselectivity in Diels-Alder reactions is exemplified below



R	X	ortho		meta
Me	COOMe	89	:	11
OAc	COOMe	100	:	0
OMe	COOMe	100	:	0
OMe	CN	100	:	0
OMe	CHO	100	:	0



R	X	*para*	:	*meta*
Me	COOMe	80	:	20
Me	CHO	100	:	0
OMe	COMe	100	:	0
OMe	CHO	100	:	0