Pericyclic Reactions
The Woodward Hoffmann Approach

HOMO diene

$_\pi 4_s$

$_\pi 2_s$

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 1
odd ✓
allowed

LUMO dienophile

constructive overlap ✓

6 electrons
no nodes
Hückel
allowed ✓
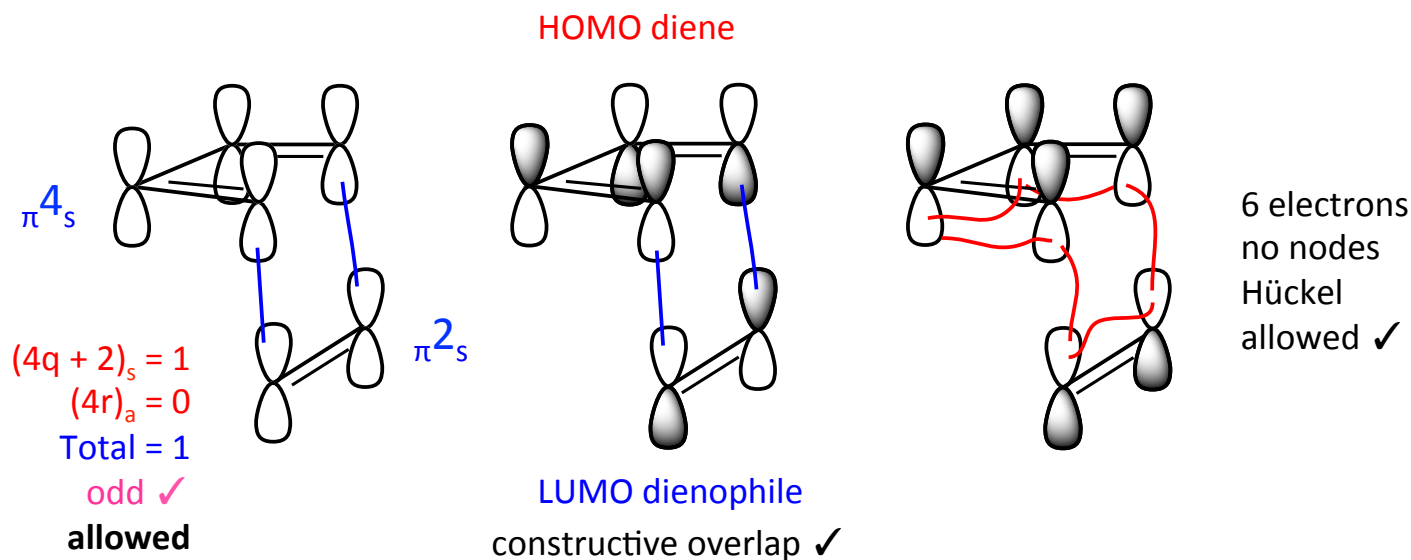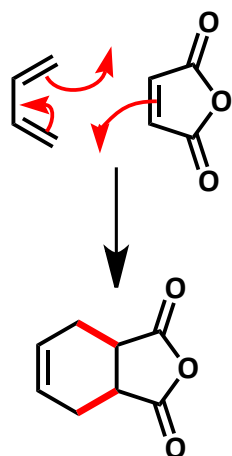
Full handout for 3ʳᵈ year course at http://burton.chem.ox.ac.uk/teaching.html

- *Pericyclic Reactions*, Oxford Chemistry Primer no. 67; Ian Fleming
- *Organic Chemistry* Jonathan Clayden, Nick Greeves, Stuart Warren, Peter Wothers
- *Advanced Organic Chemistry: Reactions, Mechanisms and Structures*; Jerry March
- *Frontier Orbitals and Organic Chemical Reactions*; Ian Fleming
- *Molecular Orbitals & Organic Chemical Reactions*; Ian Fleming
- *Modern Physical Organic Chemistry*; Eric Anslyn and Dennis Docherty

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SBM

Pericyclic Reactions

■ Pericyclic reactions – Reactions in which all first-order changes in bonding relationships take place in concert on a closed curve. *R. B. Woodward and R. Hoffmann 1969*.

i.e. the reactions have cyclic transition states in which all bond-forming and bond-breaking take place in a concerted manner without the formation of an intermediate.

■ Pericyclic reactions involve a transition state with a cyclic array of interacting orbitals; a reorganisation of σ and π-bonds occurs within this cyclic array.

■ Originally termed ' no mechanism reactions' – they could not be explained by standard nucleophile/electrophile mechanisms.
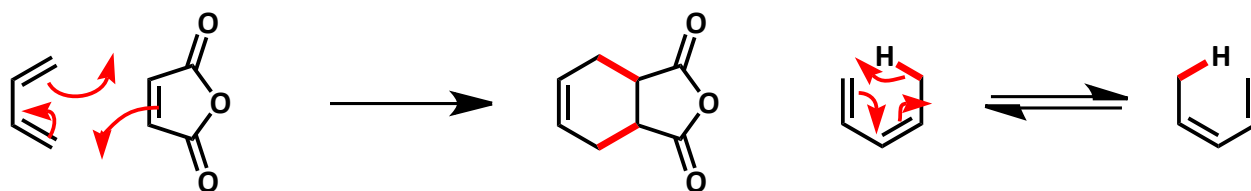
■ No absolute sense in which the electrons flow from one component to another; however, sometimes it is more sensible to push the arrows in only one direction.

■ Here curly arrows are used to show which bonds are being made/broken rather than the direction of flow of electrons.

Four classes.

■ Cycloadditions - **Two components** come together to form two new σ-bonds at the ends of both components and joining them together to form a **ring**. Bimolecular form/break a ring.
Cheletropic reactions are a sub-class of cycloaddition reactions in which the **two σ – bonds** are made or broken to the **same atom**.
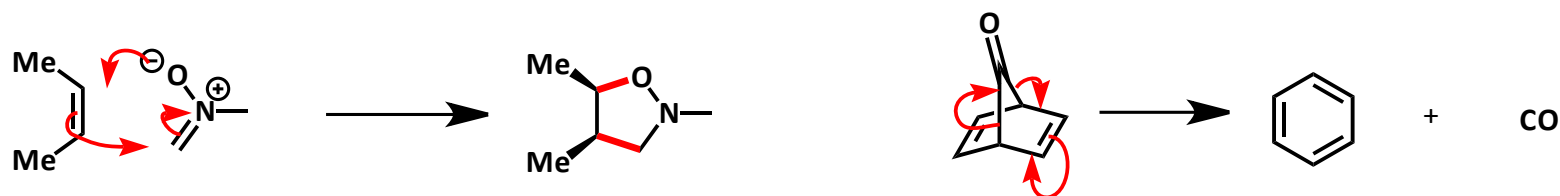

■ Electrocyclic Reactions – **Unimolecular** reactions characterised by the **formation of a ring** from an open chain conjugated system with a σ-bond forming across the ends of the conjugated system. Unimolecular form/break a ring.

■ Sigmatropic rearrangements – **Unimolecular isomerisations** which formally involve the overall movement of a σ-bond from one position to another. Unimolecular do not form/break a ring.
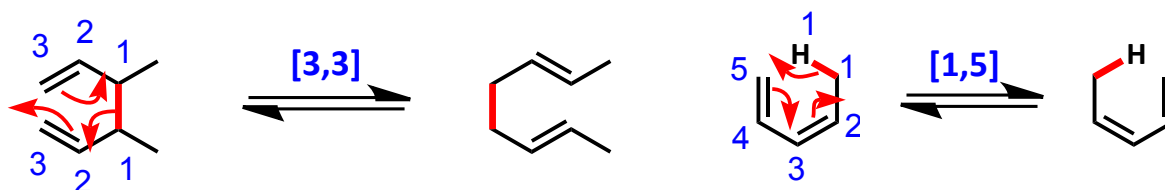
■ Group transfer – appear to be a mix of a sigmatropic rearrangement and a cycloaddition. They are **bimolecular** and so are not sigmatropic rearrangements, and **no ring is formed** so they are not cycloadditions. Biomolecular do not form/break a ring.
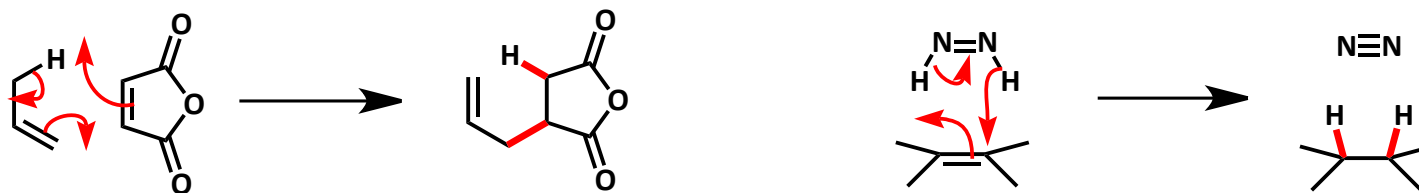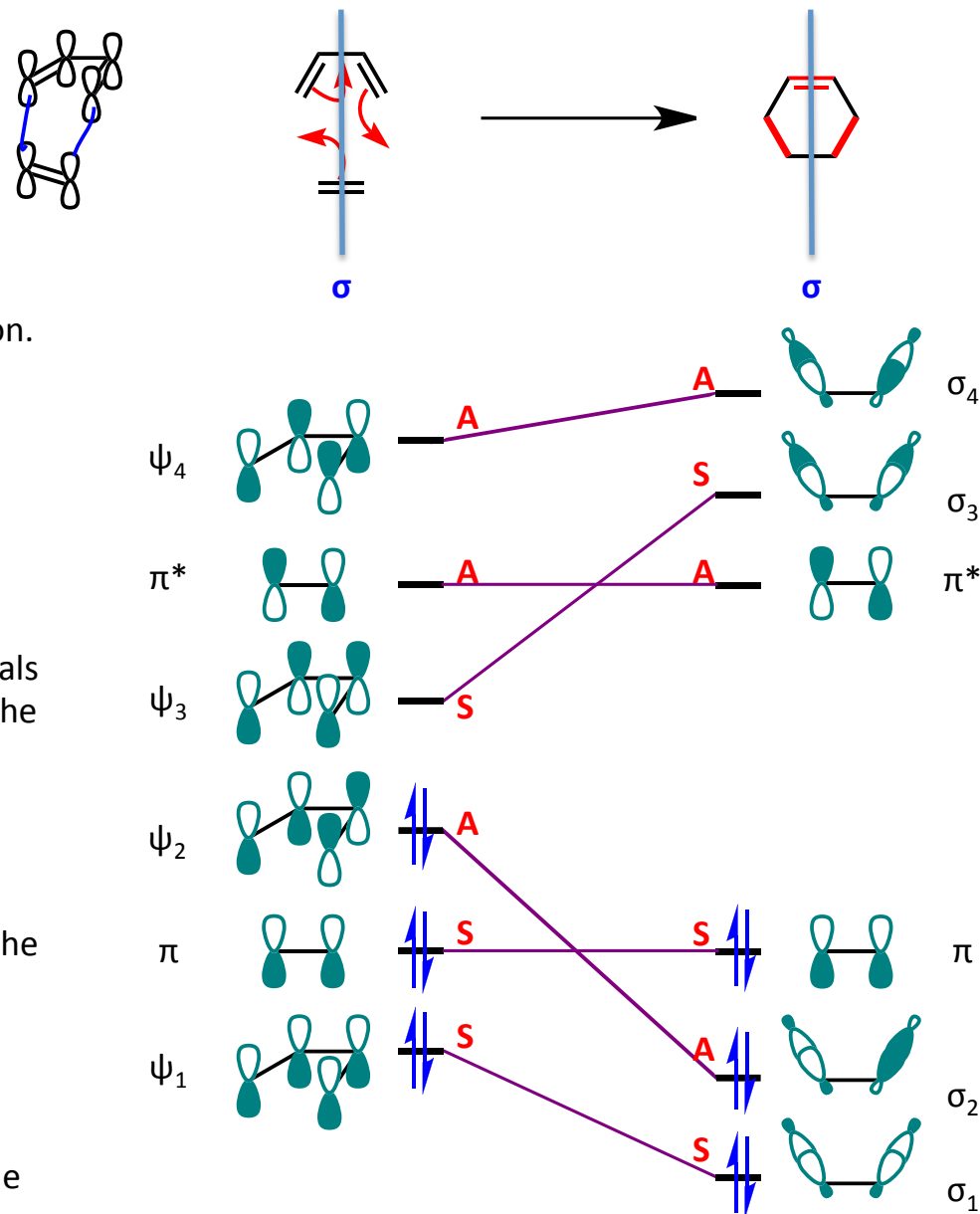

Correlation Diagrams

■ During a pericyclic reaction the orbitals of the starting material are smoothly converted into the orbitals of the product.

■ This means that the symmetry of the orbitals with respect to any symmetry operations of the molecule must be conserved in moving from the starting material(s) to product – this is the 'Conservation of Orbital Symmetry', which is readily depicted in an 'orbital correlation diagram'

- Draw bare bones of reaction.

- Identify orbitals undergoing change.

- Draw sensible approach of substrates.

- Identify symmetry elements maintained during reaction.

- Rank orbitals approximately by energy.

- Classify each orbital with respect to the symmetry element(s) conserved during reaction.

- Construct orbital correlation diagram connecting orbitals of starting materials with those closest in energy and of the same symmetry in the product.

- In the Diels-Alder reaction a plane of symmetry, perpendicular to the molecular planes of both the diene and dienophile and passing through the double bond of the dienophile and the central single bond of the diene.

- In the orbital correlation diagram of the Diels- Alder reaction all interacting bonding orbitals in the diene/dienophile are correlated with new *bonding* orbitals in the product. The reaction is *thermally allowed.*

■ Correlation diagram for electrocyclic reactions

**Me**

Me

Me

Me

Z,E : *E,E* 20,000:1
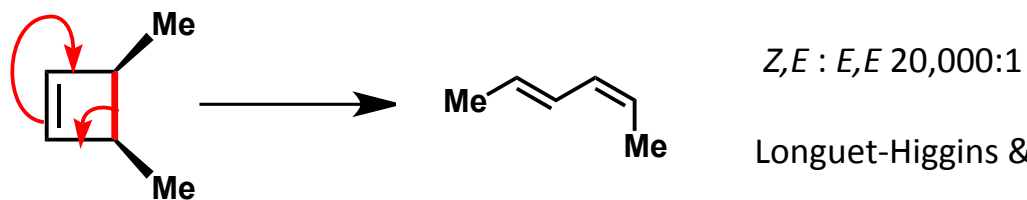
Longuet-Higgins & Abrahamson, *J. Am. Chem. Soc.*, **1965**, *87*, 2045.

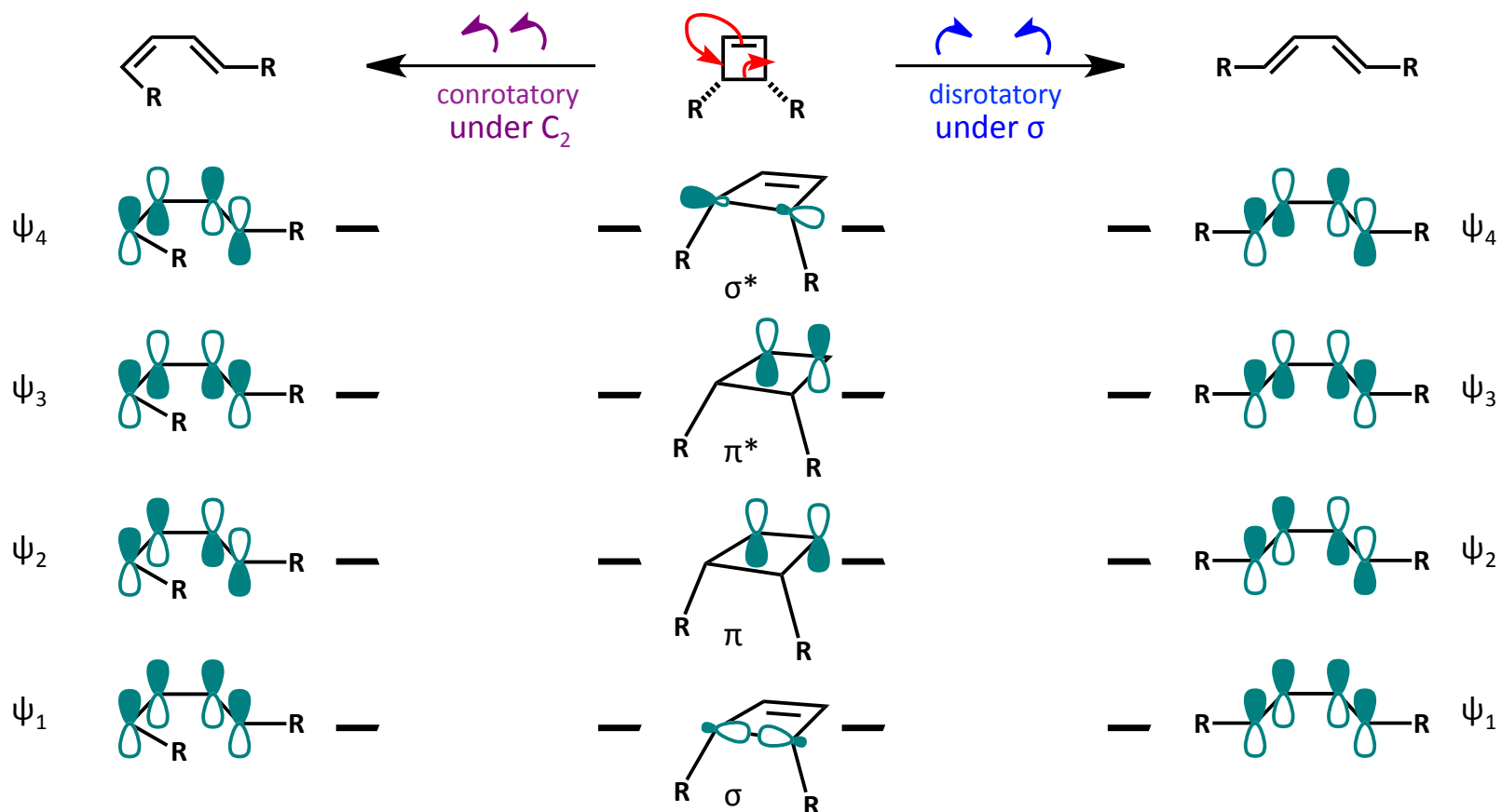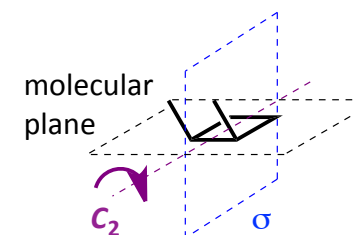■ There are two modes of opening – *conrotatory* or *disrotatory*

■ *Conrotatory – rotation around the axes of the σ-bonds (dotted lines) occurs in the same direction -* throughout this process the molecule retains a C_2-axis which passes through the plane of the molecule and the breaking σ bond.
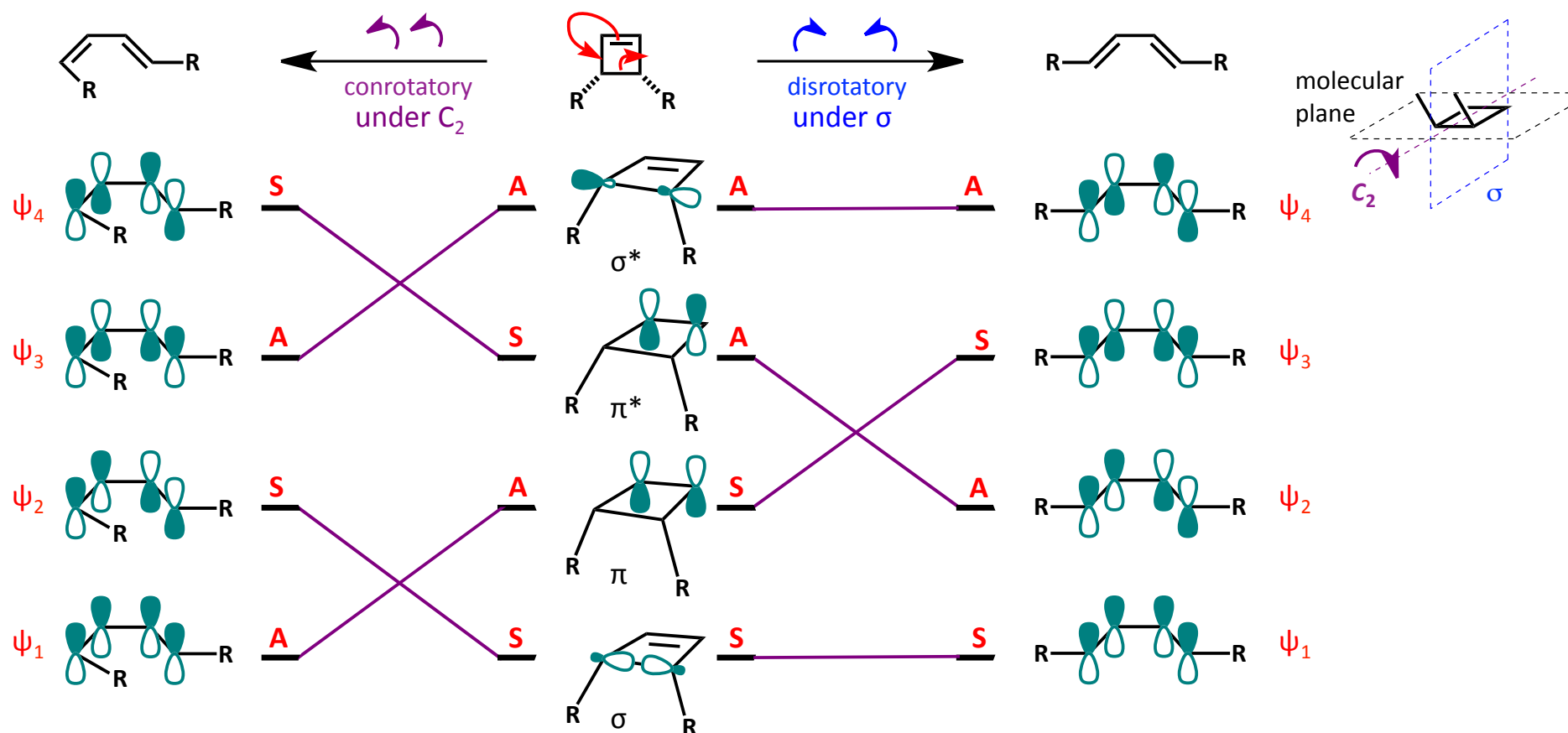
C_2
plan view
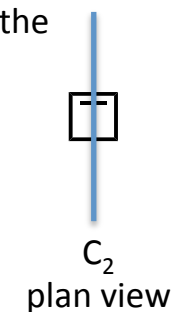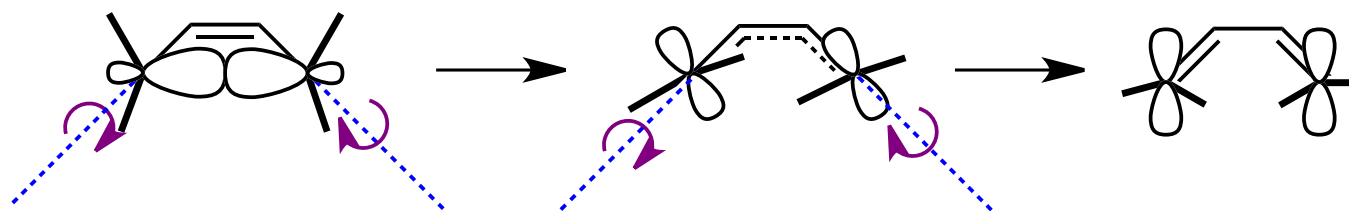
■ *Disrotatory – rotation around the axes of the σ-bonds (dotted lines) occurs in opposite directions –* throughout this process the molecule retains a plane of symmetry which is perpendicular to the plane of the molecule and passes through the breaking σ-bond

σ
plan view
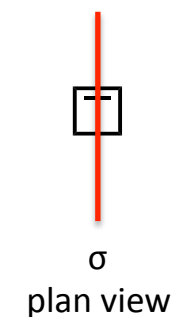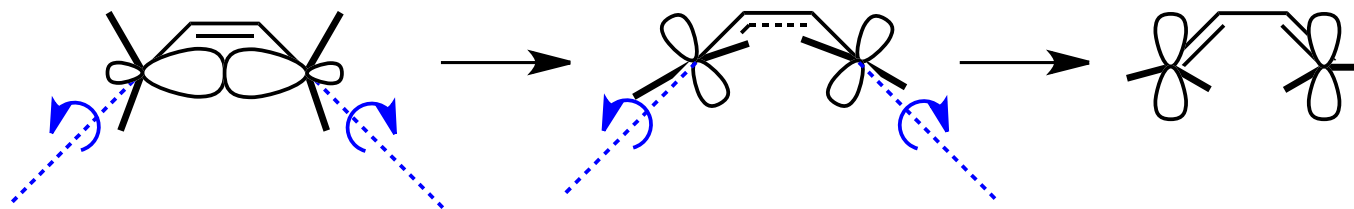
- Correlation diagram for electrocyclic reactions.
- Identify orbitals undergoing change (curly arrows) – σ and π.
- The orbitals undergoing change are either symmetric or antisymmetric with respect to the symmetry elements preserved during the reaction.
- Rank orbitals approximately by energy.
- Label orbitals as 'S' or 'A'.
- Construct orbital correlation diagram connecting orbitals of starting materials with those closest in energy and of the same symmetry in the product.

molecular plane

C_2 σ

conrotatory under C_2

disrotatory under σ

ψ_4

σ*

ψ_4

ψ_3

π*

ψ_3

ψ_2

π

ψ_2

ψ_1

σ

ψ_1

■ In the conrotatory mode, all ground state bonding orbitals in cyclobutene ($\sigma^2\pi^2$) correlate with ground state bonding orbitals in butadiene ($\psi_1^2\psi_2^2$) – the conrotatory opening of butadiene is **thermally** allowed (favoured).

■ In the disrotatory mode, the ground state bonding orbitals in cyclobutene ($\sigma^2\pi^2$) correlate with a doubly excited state of butadiene ($\psi_1^2\psi_3^2$) – the disrotatory opening of butadiene is **thermally** forbidden (disfavoured).

■ The **photochemical** ring closure of butadiene to give cyclobutene is disrotatory. The 1st excited sate of butadiene is $\psi_1^2\psi_2^1\psi_3^1$ which correlates smoothly with the 1st excited sate of cyclobutene ($\sigma^2\pi^1\pi^{*1}$); under conrotatory ring closure $\psi_1^2\psi_2^1\psi_3^1$ correlates with a much high energy state in cyclobutene ($\sigma^1\pi^2\sigma^{*1}$).
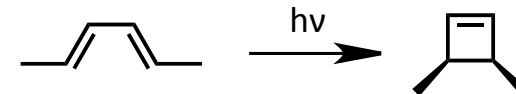
■ Correlation diagrams can be distilled into a simple rule for predicting which pericyclic reactions are "allowed".

The Woodward-Hoffmann Rules:

A ground state pericyclic reaction is symmetry allowed when the total number of $(4q + 2)_s$ and $(4r)_a$ components is odd (q and r must be integers).

A pericyclic change in the first electronically excited state (i.e. a photochemical reaction) is symmetry-allowed when the total number of $(4q + 2)_s$ and $(4r)_a$ components is even.

■ We will use the Diels-Alder reaction to exemplify the application of the Woodward-Hoffmann rules.

■ Draw a 'curly arrow' mechanism to identify the components.

■ For the Diels-Alder reaction these are 4π (diene) and 2π (dienophile).

■ Draw a convincing 3-D orbital diagram to show the overlap of the components.

■ Label the components as supra or antarafacial.

■ Sum the components according to the Woodward-Hoffmann rule.

■ Draw a 'curly arrow' mechanism – this generally allows identification of the components.

■ For the Diels-Alder reaction these are 4π (diene) and 2π (dienophile),
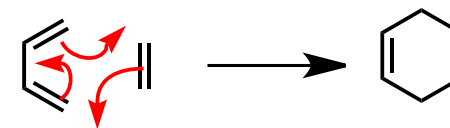
■ Draw a convincing 3-D orbital diagram to show the overlap of the components.
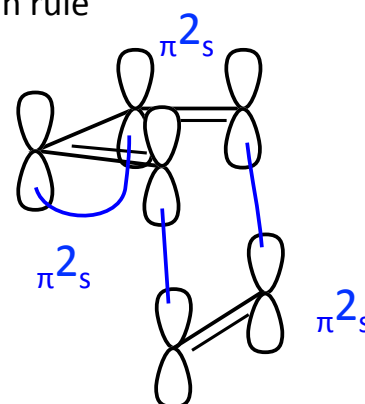
■ Label the components as supra or antarafacial. Here the diene is being used in a suprafacial manner – the two new bonds are being formed on the same face of the diene.
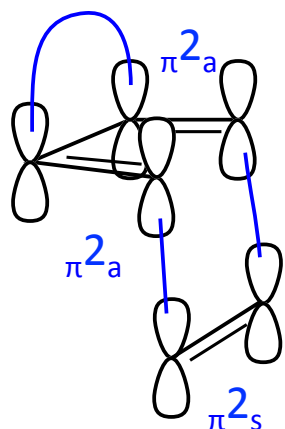The alkene is also being used in a suprafacial manner being used in a suprafacial manner

■ Sum the components according to the Woodward-Hoffmann rule
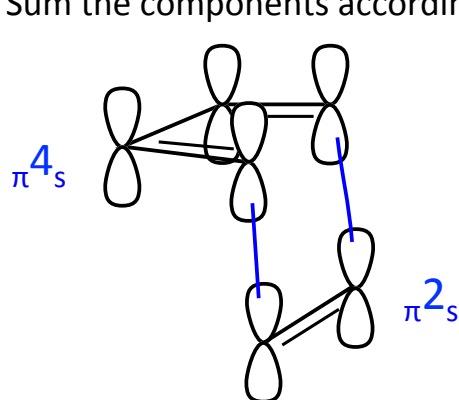
$_\pi 4_s$ $_\pi 2_s$

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 1
odd ✓
allowed

$_\pi 2_s$ $_\pi 2_s$ $_\pi 2_s$

$(4q + 2)_s = 3$
$(4r)_a = 0$
Total = 3
odd ✓
allowed

$_\pi 2_a$ $_\pi 2_a$ $_\pi 2_s$

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 1
odd ✓
allowed

$_\pi 2_a$ $_\pi 2_s$ $_\pi 2_s$

H ————— H
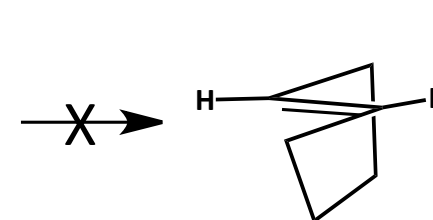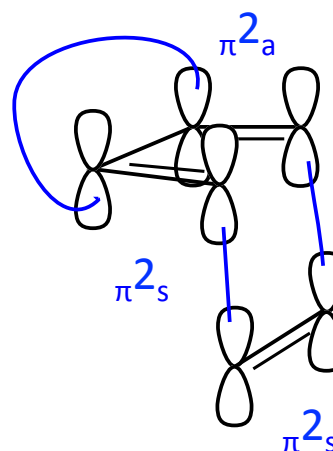
$(4q + 2)_s = 2$
$(4r)_a = 0$
Total = 2
even ✗
forbidden

■ Generally simplest to maximise suprafacial components and not subdivide conjugated systems.

[2 + 2] cycloadditions

■ Draw a 'curly arrow' mechanism to identify the components – 2π, 2π

■ Draw a convincing 3-D orbital diagram to show the overlap of the components

■ Label the components as supra or antarafacial.

■ Sum the components according to the Woodward-Hoffmann rule
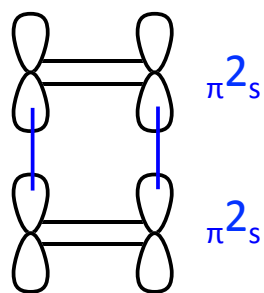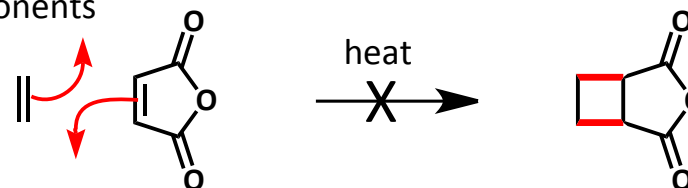
$\pi 2_s$ $(4q + 2)_s = 2$
              $(4r)_a = 0$
$\pi 2_s$ Total = 2
              even ✗
              forbidden
              (thermally)

              $(4q + 2)_s = 2$
              $(4r)_a = 0$
              Total = 2
              even ✓
              allowed –
              photochemically

$\pi 2_s$

$\pi 2_a$

$\pi 2_a$

$\pi 2_s$
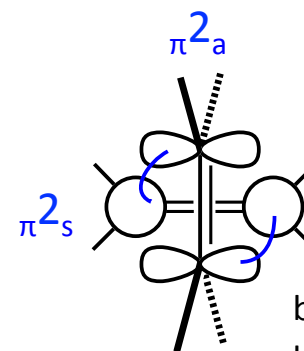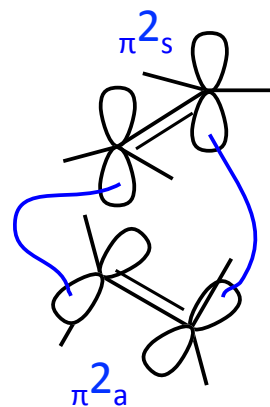
$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 1
odd ✓
allowed
(thermally)

but geometrically
unreasonable,
therefore does not
occur

■ Woodward-Hoffmann rule gives you the symmetry allowed orbital overlap but *you* have to decide whether the overlap *you* have drawn is geometrically reasonable.
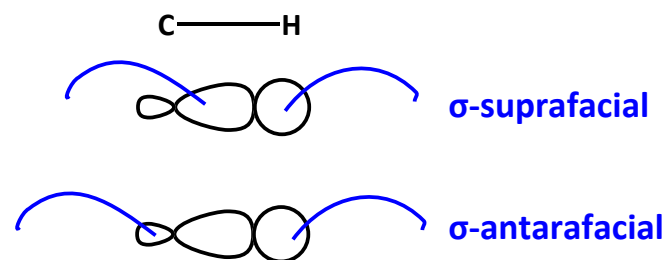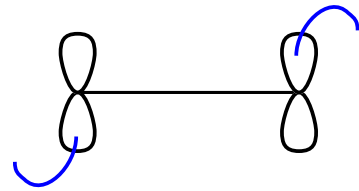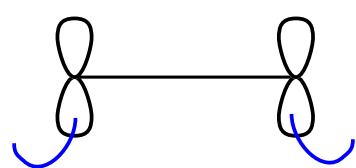
Nomenclature for suprafacial and antarafacial components.

■ Suprafacial and antarafacial refer to modes of bond formation that are respectively on the same face or on opposite faces of a molecular component.
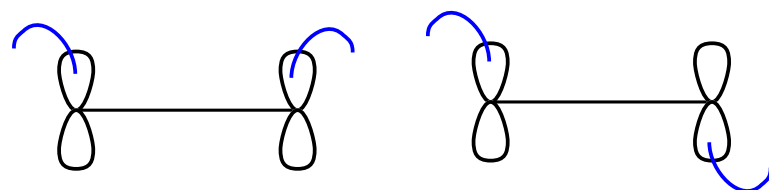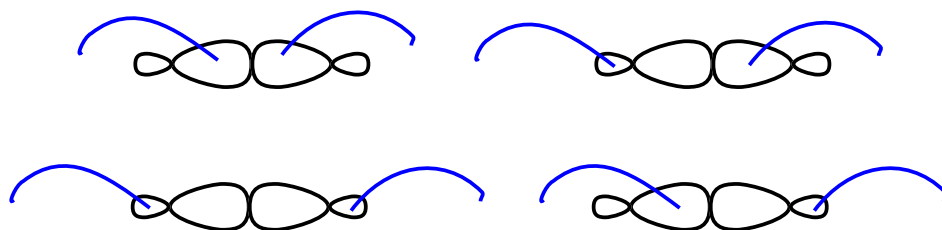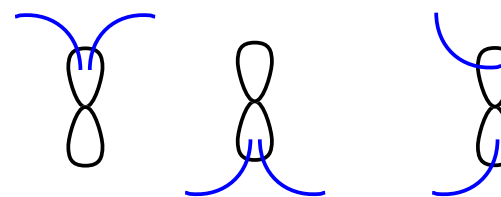

π-suprafacial   **π-antarafacial**

σ-suprafacial

σ-antarafacial

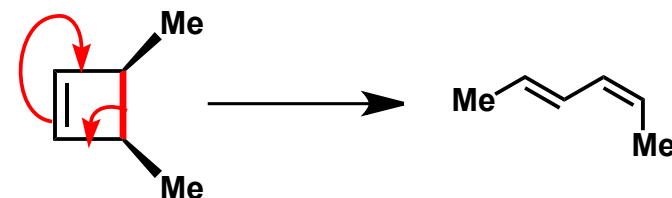**σ-suprafacial**   **σ-antarafacial**   **ω-suprafacial**   **ω-antarafacial**

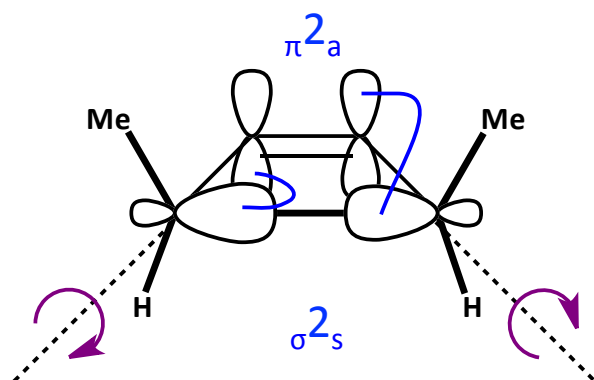Woodward-Hoffmann approach for thermal electrocyclic reactions

■ Draw a 'curly arrow' mechanism to identify the components – these are 2π (alkene) and 2σ (single bond)
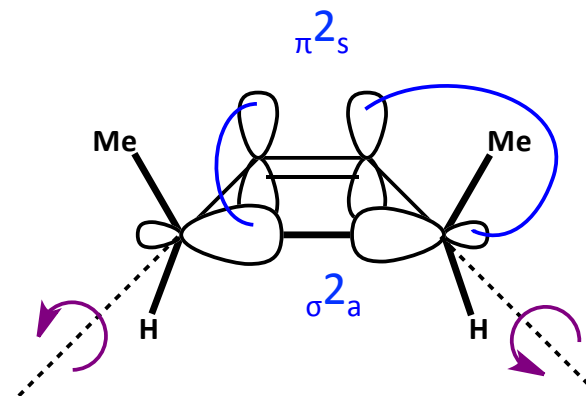

■ Draw a convincing 3-D orbital diagram to show the overlap of the components

■ Label the components as supra or antarafacial.

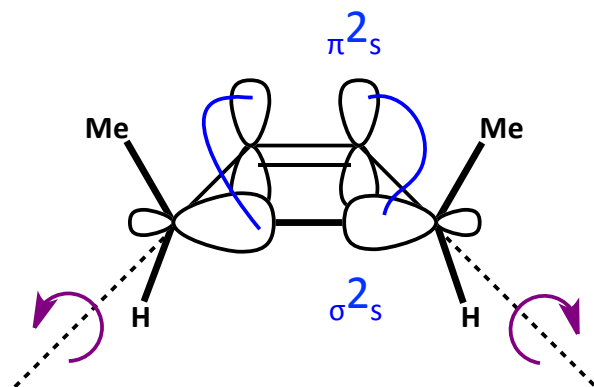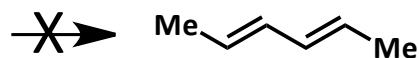■ Sum the components according to the Woodward-Hoffmann rule.

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 1
odd ✓
**allowed
(conrotatory)**

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 1
odd ✓
**allowed
(conrotatory)**

$(4q + 2)_s = 2$
$(4r)_a = 0$
Total = 2
even ✗
**forbidden
disrotatory**

■ Thermal ring opening of cyclobutene is *conrotatory*. Thermal *disrotatory* opening is symmetry forbidden.

Woodward-Hoffmann approach for sigmatropic rearrangements

■Draw a 'curly arrow' mechanism to identify the components – 2π, 2σ, 2π

■ Draw a convincing 3-D orbital diagram to show the overlap of the components

■ Label the components as supra or antarafacial.

■ Sum the components according to the Woodward-Hoffmann rule.

$\sigma 2_s$

$\pi 2_s$

$\pi 2_s$

Me

Me

$(4q + 2)_s = 3$
$(4r)_a = 0$
Total = 3
odd ✓
allowed

$\pi 2_s$

$\sigma 2_s$

Me

$\pi 2_s$

Me

$\sigma 2_s$

$\pi 2_s$

$\pi 2_s$

Me

Me

$(4q + 2)_s = 3$
$(4r)_a = 0$
Total = 3
odd ✓
allowed
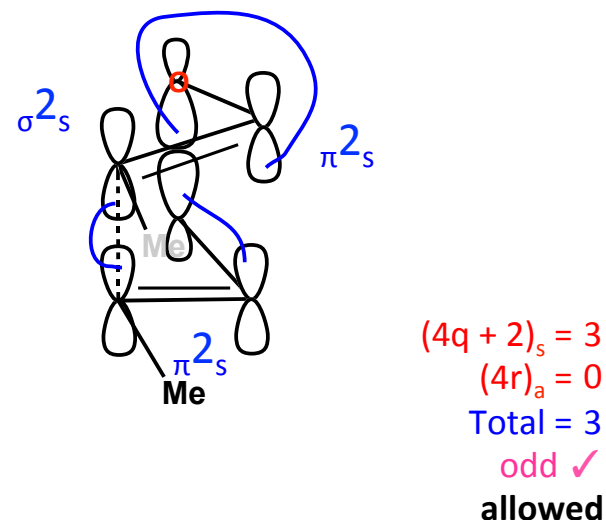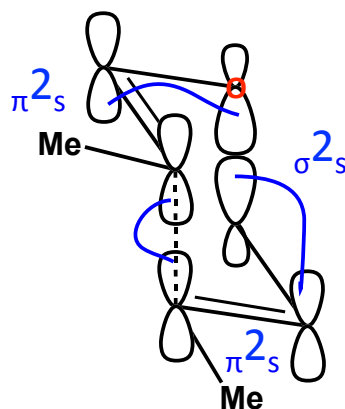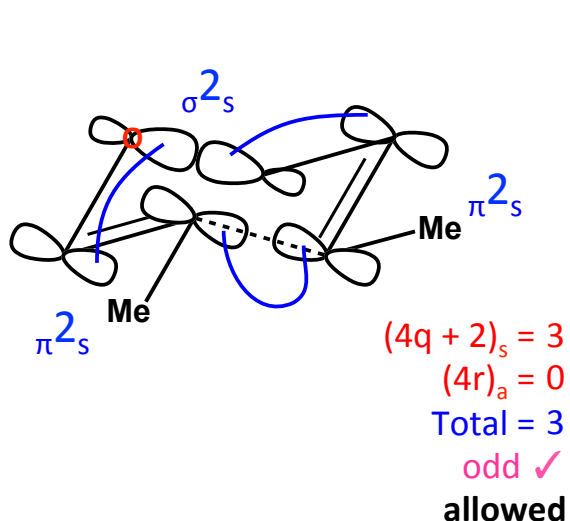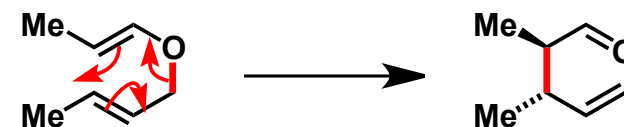
■ Claisen rearrangement *via* chair TS is allowed.   ■ Claisen rearrangement *via* boat TS is allowed.

■ Woodward-Hoffmann rule does not tell us that the chair TS is lower in energy than the boat TS. You need to use your chemical knowledge/intuition to decide that a chair is generally lower in energy than the corresponding boat and that it is generally more favourable to have equatorial substituents than axial substituents on a chair.

Woodward-Hoffmann approach for sigmatropic rearrangements and group transfer

■ Draw a 'curly arrow' mechanism to identify the components

■ Draw a convincing 3-D orbital diagram to show the overlap of the components

■ Label the components as supra or antarafacial.

■ Sum the components according to the Woodward-Hoffmann rule.

$(4q + 2)_s = 3$
$(4r)_a = 0$
Total = 3
odd ✓
allowed

$(4q + 2)_s = 3$
$(4r)_a = 0$
Total = 3
odd ✓
allowed
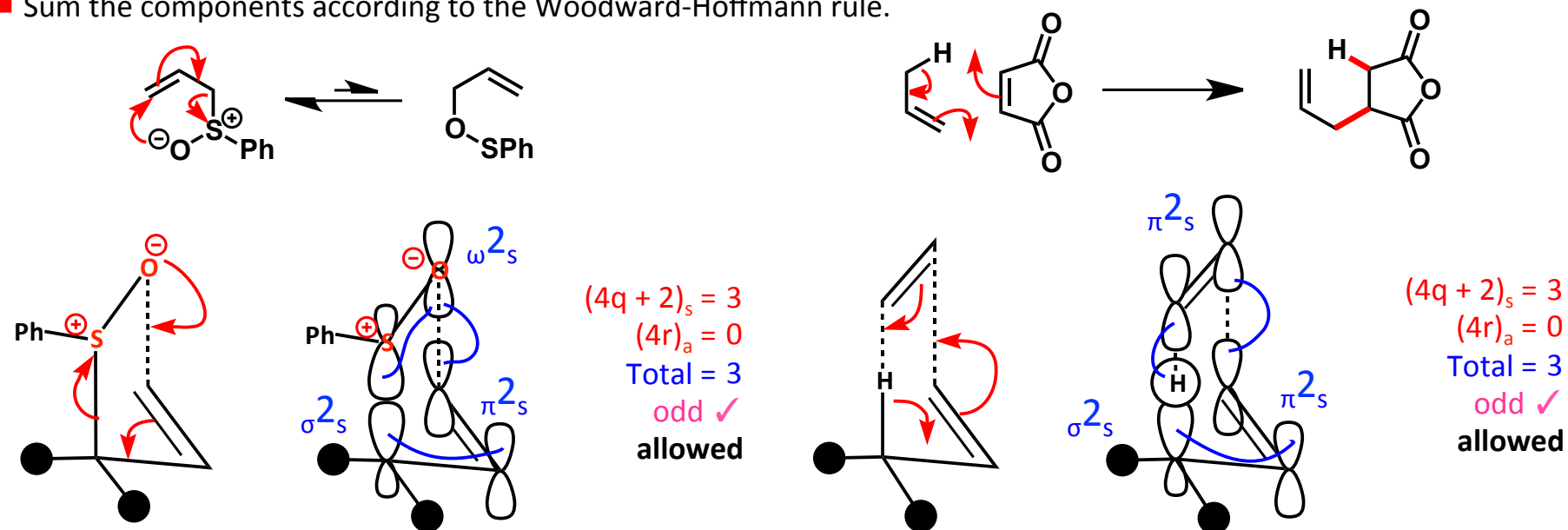
■ [2,3]-sigmatropic rearrangement *via* envelope TS.   ■ ene-reaction (group transfer) *via* envelope TS.

For thermal cycloadditions and group transfers:
■ If the total number of electrons is (4n + 2) both components can be used in a suprafacial manner.
■ If the total number of electrons is (4n) one of the components is suprafacial and the other antarafacial.
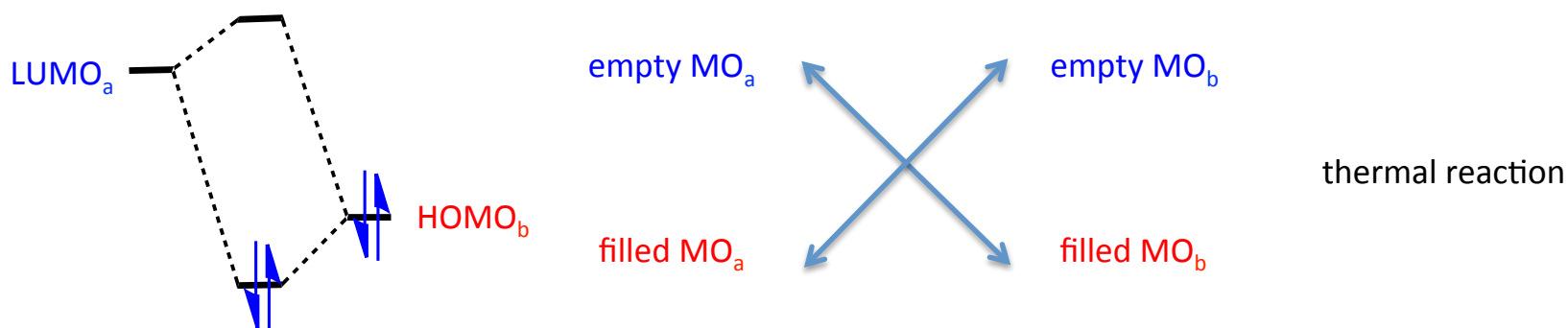For electrocyclic reactions:
■ Thermal electrocyclic processes will be *conrotatory* if the total number of electrons is 4n and *disrotatory* if the total number of electrons is (4n +2).
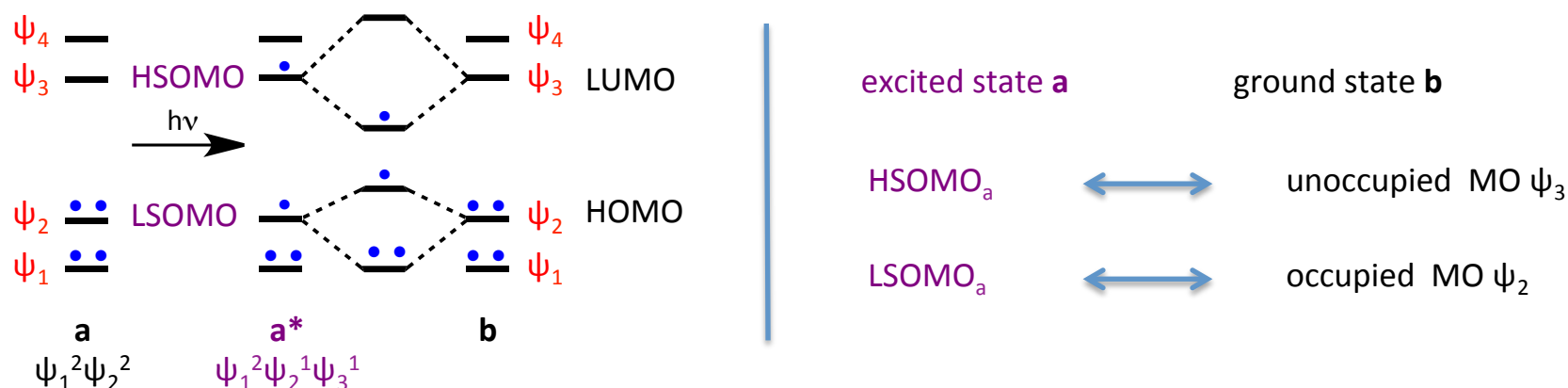
■ Frontier Molecular Orbital approach – revision

'As two molecules approach each other, three major forces operate:

(i)   The occupied orbitals of one repel the occupied orbitals of the other.

(ii)   Any positive charge on one attracts any negative charge on the other (and repels any positive)

(iii)   The occupied orbitals (especially the HOMOs) of each interact with the unoccupied orbitals (especially the LUMOs) of the other, causing an attraction between the molecules.'   (from Fleming, Molecular Orbitals and Organic Chemical Reactions)

Frontier Molecular Orbital considers the interaction of the Highest Occupied Molecular Orbital (HOMO) and the Lowest Unoccupied Molecular Orbital (LUMO) to be of overriding importance.
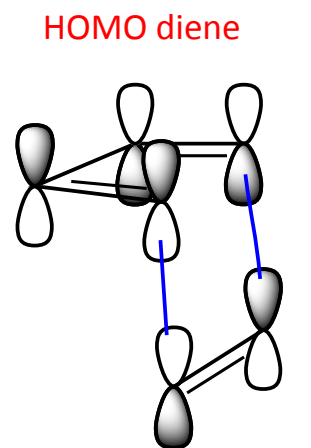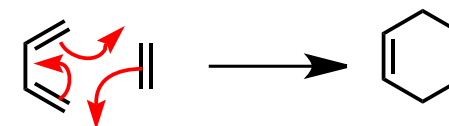
$LUMO_a$

$HOMO_b$

empty MO_a empty MO_b

filled MO_a filled MO_b

thermal reaction

■ For *photochemical* reactions one molecule is in the excited state

ψ_4

ψ_3 HSOMO ψ_3 LUMO

$h\nu$

ψ_2 LSOMO ψ_2 HOMO

ψ_1 ψ_1

a   a*   b

$\psi_1{}^2\psi_2{}^2$ $\psi_1{}^2\psi_2{}^1\psi_3{}^1$

excited state **a**   ground state **b**

$HSOMO_a$ ⟷   unoccupied MO ψ_3

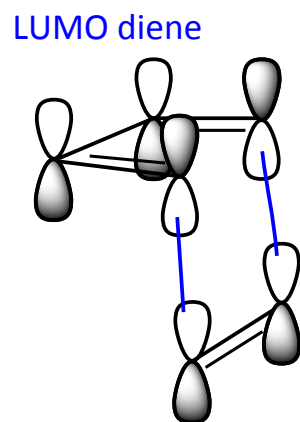$LSOMO_a$ ⟷   occupied MO ψ_2

The FMO approach

■ To apply the FMO method one has to assign a single HOMO and a single LUMO to the reaction components and see how they interact.

■ The FMO approach is simple to apply to reactions with two components (e.g. cycloadditions, electrocyclic ring opening) but its application to sigmatropic rearrangements and group transfer reactions is somewhat contrived.

■ Draw a 'curly arrow' mechanism to identify the components

■ Assign a single HOMO and a single LUMO to the reaction

■ Draw a convincing 3-D orbital diagram to show the overlap of the components

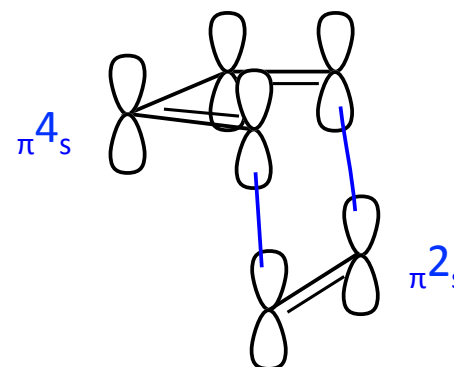■ Check to see if there is constructive overlap between the orbitals

HOMO diene   LUMO diene

$_\pi 4_s$

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 1
odd ✓
allowed

$_\pi 2_s$

LUMO dienophile   HOMO dienophile

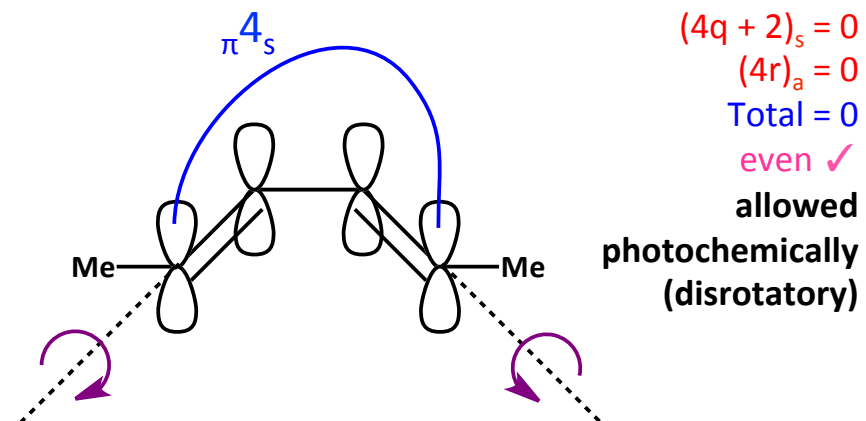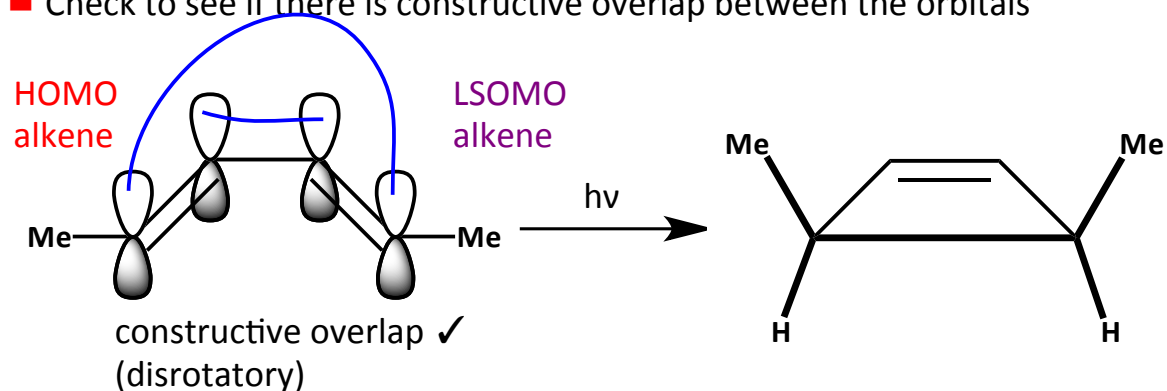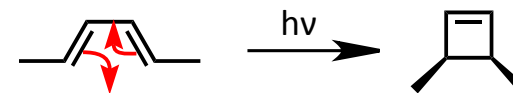constructive overlap ✓   constructive overlap ✓

The FMO approach

■ Draw a 'curly arrow' mechanism to identify the components

■ Assign a single HOMO and a single LUMO to the reaction

■ Draw a convincing 3-D orbital diagram to show the overlap of the components

■ Check to see if there is constructive overlap between the orbitals

LUMO alkene

HOMO sigma   constructive overlap

LUMO alkene

HOMO sigma   constructive overlap ✓

HOMO alkene

LUMO sigma
constructive overlap ✓

$\pi 2_s$

$\sigma 2_a$

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 3
odd ✓
allowed
(conrotatory)

■ The preference of one conrotatory (or disrotatory) mode is termed *torqueoselectivity* (more later).
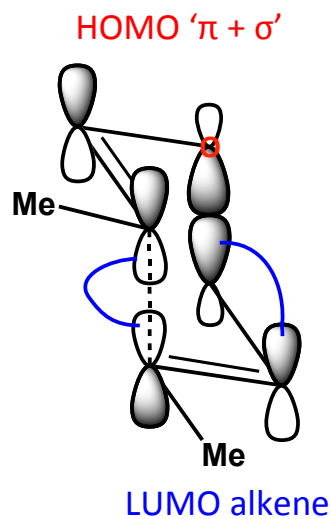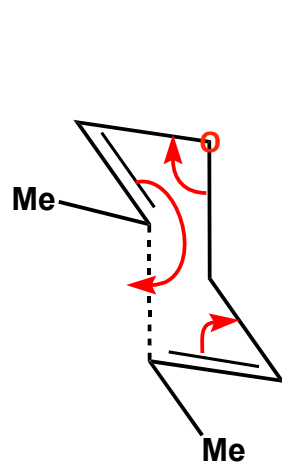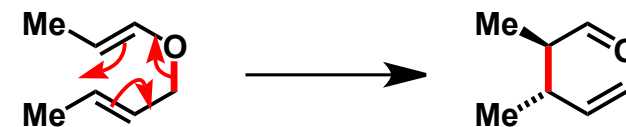
The FMO approach

■ Draw a 'curly arrow' mechanism to identify the components

■ Assign a single **HSOMO** and a single LUMO to the reaction, (or a single **LSOMO** and HOMO) – note a **HSOMO** has the same phases as the 'LUMO' and a **LSOMO** has the same phases as the HOMO)

■ Draw a convincing 3-D orbital diagram to show the overlap of the components

■ Check to see if there is constructive overlap between the orbitals

HOMO
alkene

LSOMO
alkene

Me   Me

constructive overlap ✓
(disrotatory)

hv

Me   Me

H   H

$_\pi 4_s$

$(4q + 2)_s = 0$
$(4r)_a = 0$
Total = 0
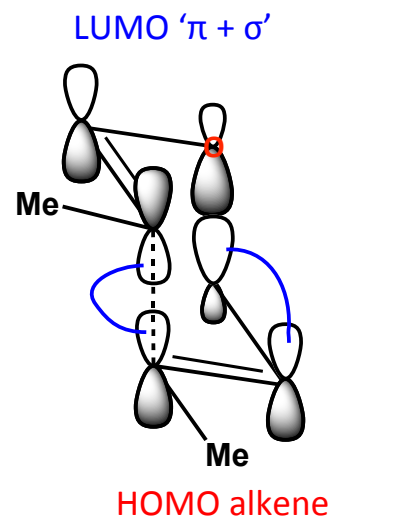even ✓
**allowed
photochemically
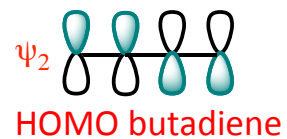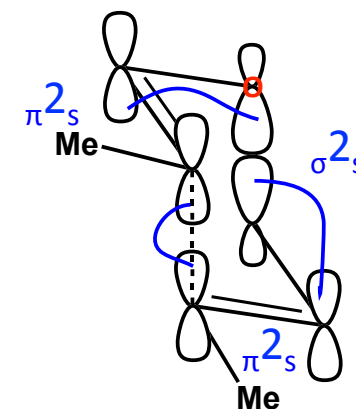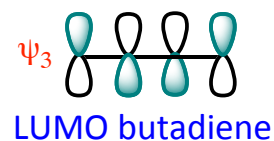(disrotatory)**

Me   Me

The FMO approach

- Draw a 'curly arrow' mechanism to identify the components

- Assign a single HOMO and a single LUMO to the reaction

- Draw a convincing 3-D orbital diagram to show the overlap of the components

- Check to see if there is constructive overlap between the orbitals

HOMO 'π + σ'

LUMO 'π + σ'

LUMO alkene

HOMO alkene

$\pi 2_s$

$\sigma 2_s$

$\pi 2_s$

constructive overlap ✓

constructive overlap ✓

$(4q + 2)_s = 1$
$(4r)_a = 0$
Total = 3
odd ✓
allowed

ψ_2

ψ_3

HOMO butadiene

LUMO butadiene

The FMO approach

- Draw a 'curly arrow' mechanism to identify the components

- Assign a single HOMO and a single LUMO to the reaction

- Draw a convincing 3-D orbital diagram to show the overlap of the components

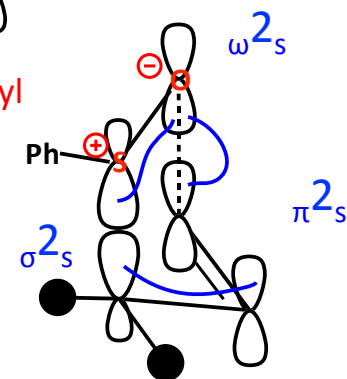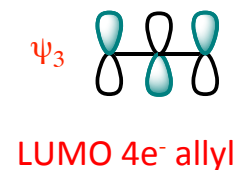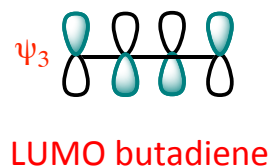- Check to see if there is constructive overlap between the orbitals

HOMO ω

LUMO, σ + ω

Ph

HOMO alkene

LUMO, alkene + σ

constructive overlap ✓

constructive overlap ✓

ψ_3

LUMO butadiene

ψ_3

LUMO 4e⁻ allyl

$_\omega 2_s$

$_\pi 2_s$

$_\sigma 2_s$

$(4q + 2)_s = 3$

$(4r)_a = 0$

Total = 3

odd ✓

allowed

■ Pericyclic reaction summary:

■ Four classes:
    Cycloadditions (chelotropic reactions); Electrocyclic reactions; Sigmatropic rearrangements; Group transfer.

■ Woodward-Hoffmann rules:

A ground state pericyclic reaction is symmetry allowed when the total number of $(4q + 2)_s$ and $(4r)_a$ components is odd (q and r must be integers).

A pericyclic change in the first electronically excited state (i.e. a photochemical reaction) is symmetry-allowed when the total number of $(4q + 2)_s$ and $(4r)_a$ components is even.

For thermal cycloadditions and group transfers:
■ If the total number of electrons is (4n + 2) both components can be used in a suprafacial manner.
■ If the total number of electrons is (4n) one of the components is suprafacial and the other antarafacial.
For electrocyclic reactions:
■ Thermal electrocyclic processes will be *conrotatory* if the total number of electrons is 4n and *disrotatory* if the total number of electrons is (4n +2).

R. B. Woodward · R. Hoffmann

The Conservation
of Orbital Symmetry

Verlag Chemie
Academic Press

12. Violations

There are none!

Nor can violations be expected of so fundamental a principle of maximum bonding. All the more is it then important to give consideration to some reactions which might appear on casual inspection to contravene orbital symmetry conservation.