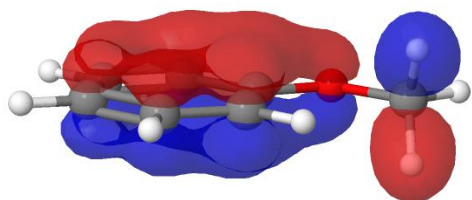
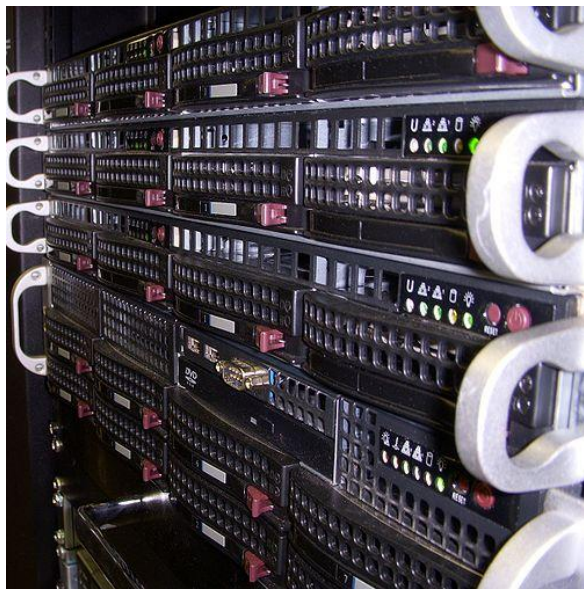
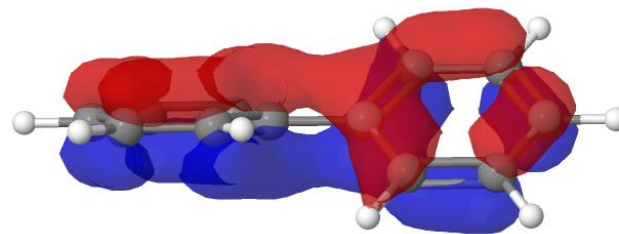
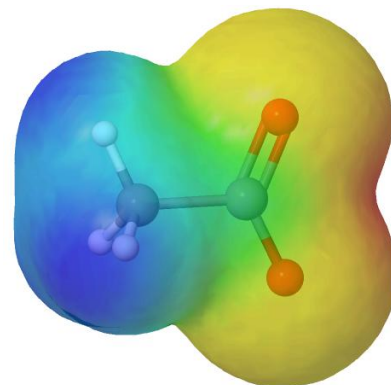
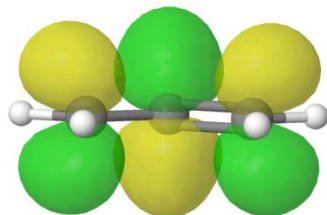


# CHEM 344 – Molecular Modeling

## The Use of Computational Chemistry to Support Experimental Organic Chemistry



Day 1



\* all calculation data obtained from Gaussian09 using B3LYP/6-31G(d) unless otherwise noted.

# Computational Chemistry

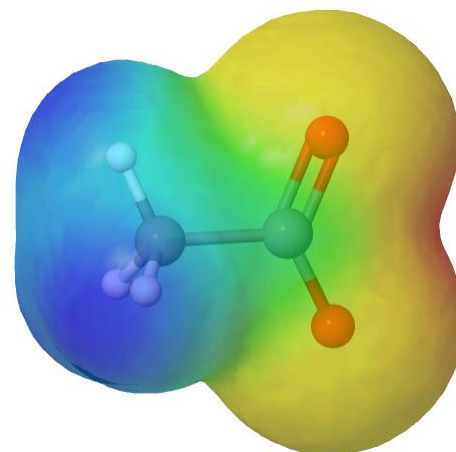
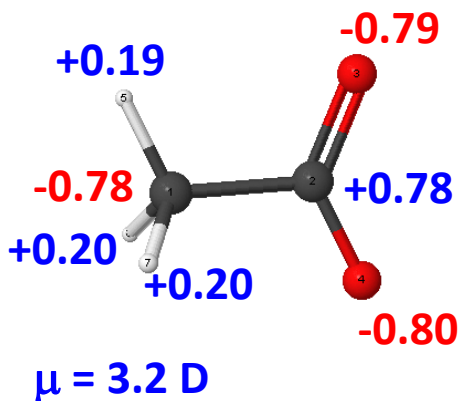
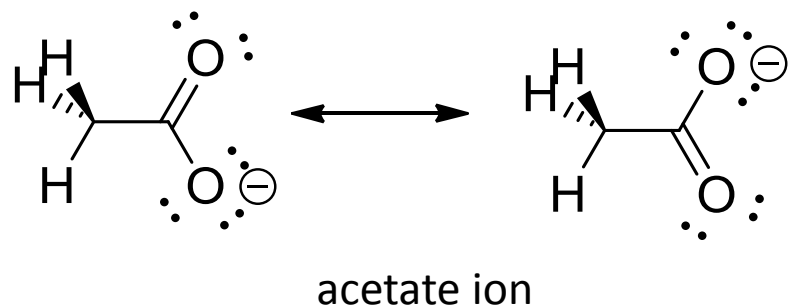
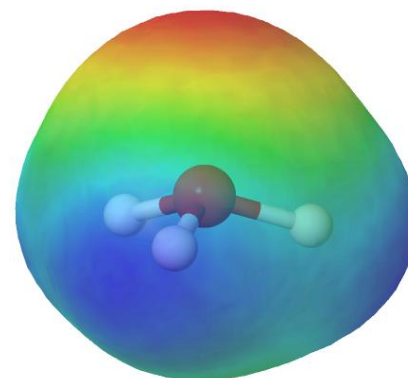
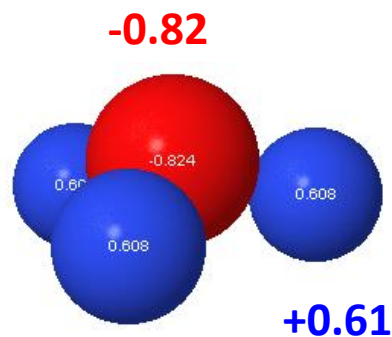
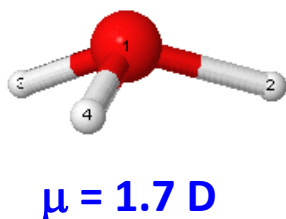
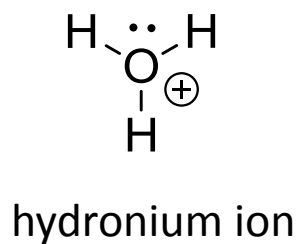
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Organic chemists routinely use computational chemistry to:

- **predict geometries**, physical properties, and relative energies.
- visualize electronic structures (molecular and atomic orbitals).
- predict or explain regio-/stereochemical outcomes of reactions.
- understand stabilizing/destabilizing interactions.
- predict spectra for microwave, IR, UV/Vis, NMR, etc.
- find transition states and chemical pathways for reactions.

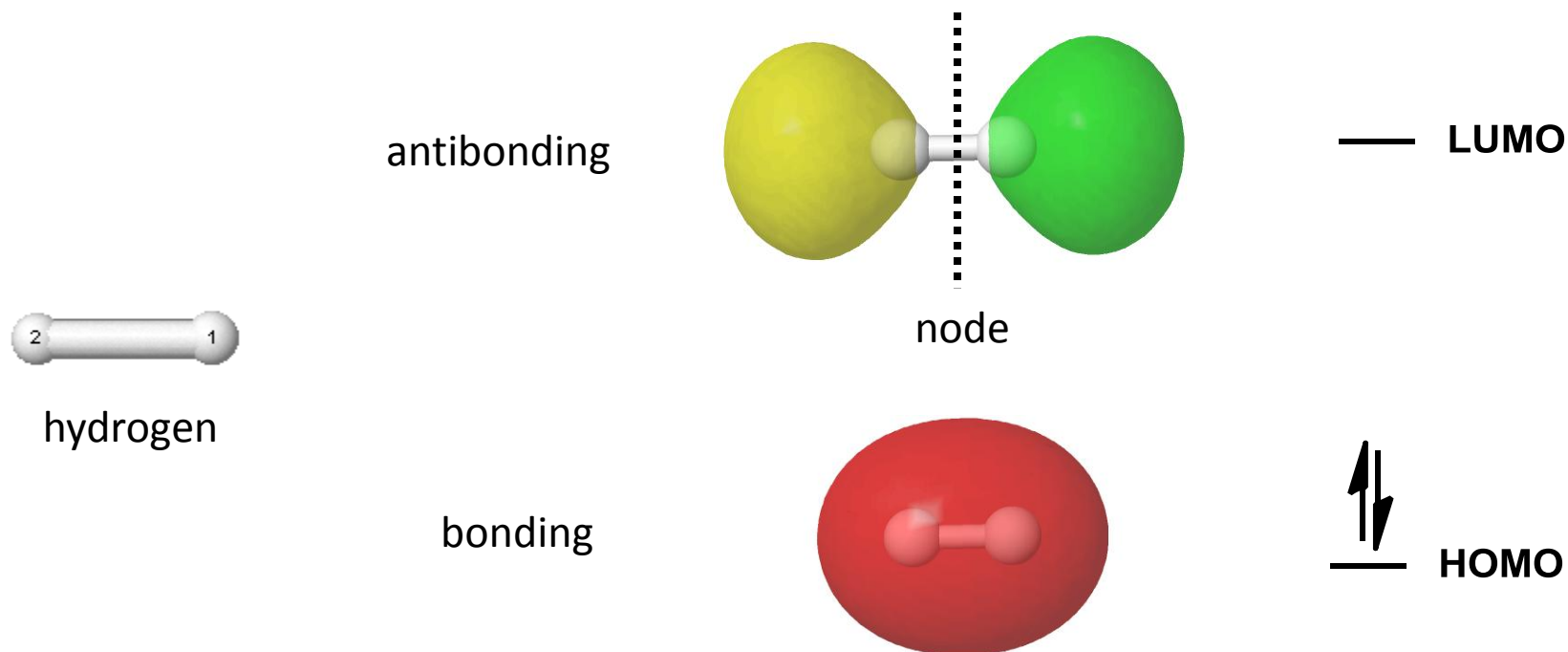
# Molecular Structure & Charge Distribution

From a good geometry, computational chemistry can predict dipole moments and charges on atoms within molecules. (NPA charges from NBO calculations)



# $\sigma$ -type Molecular Orbitals

$\sigma$ -type molecular orbitals have their electron density along the axis of a bond

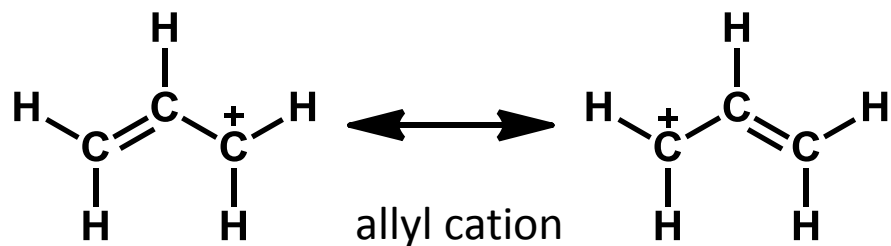


HOMO = Highest Occupied Molecular Orbital

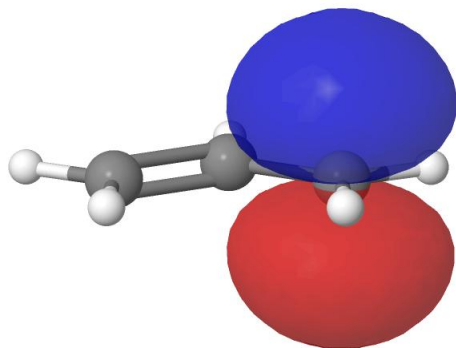
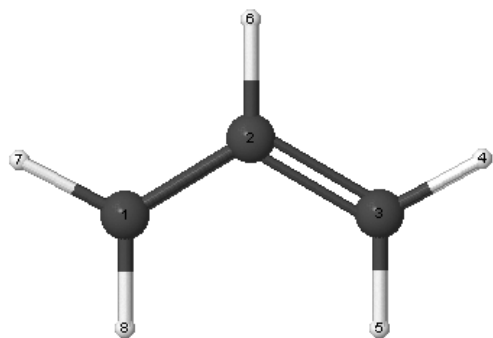
LUMO = Lowest Unoccupied Molecular Orbital

} Frontier Orbitals

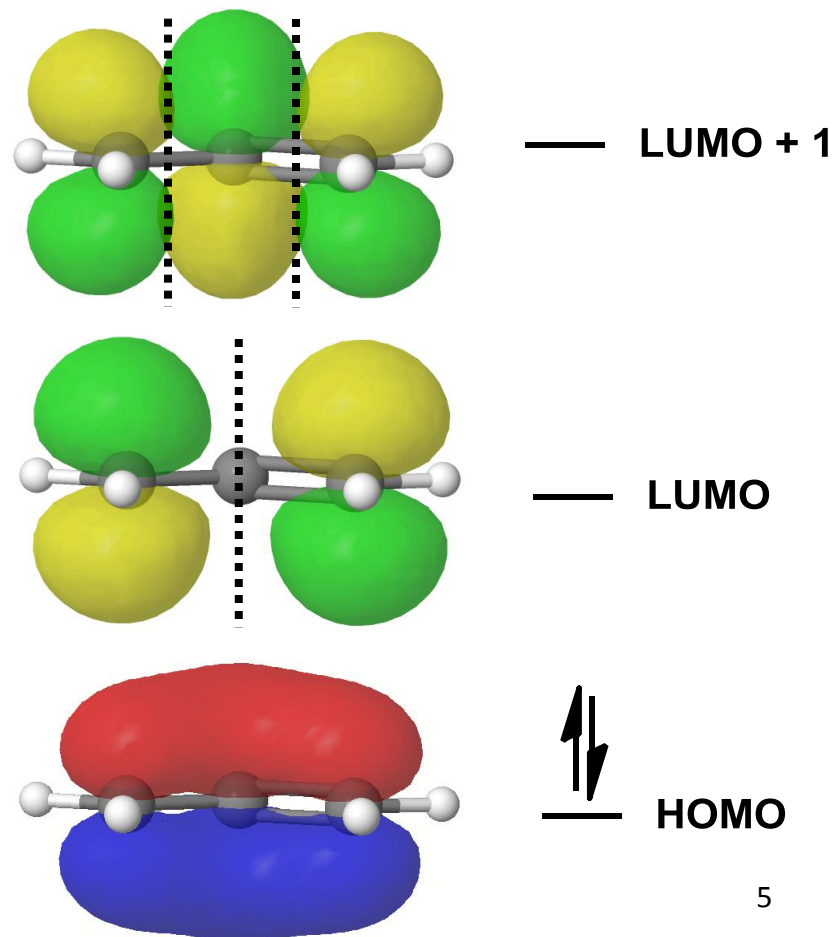
# $\pi$ -type Molecular Orbitals



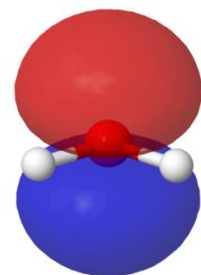
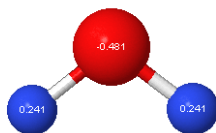
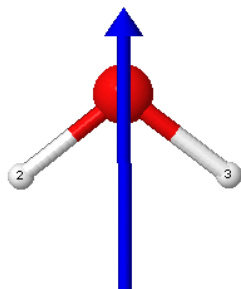
$\pi$ -type molecular orbitals have their electron density in symmetric lobes perpendicular to a molecular plane.



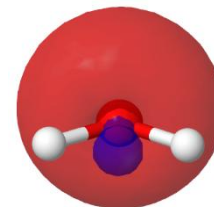
Three p orbitals predicted by NBO



# Optimization and Natural Bond Orbitals of Water





p lone pair

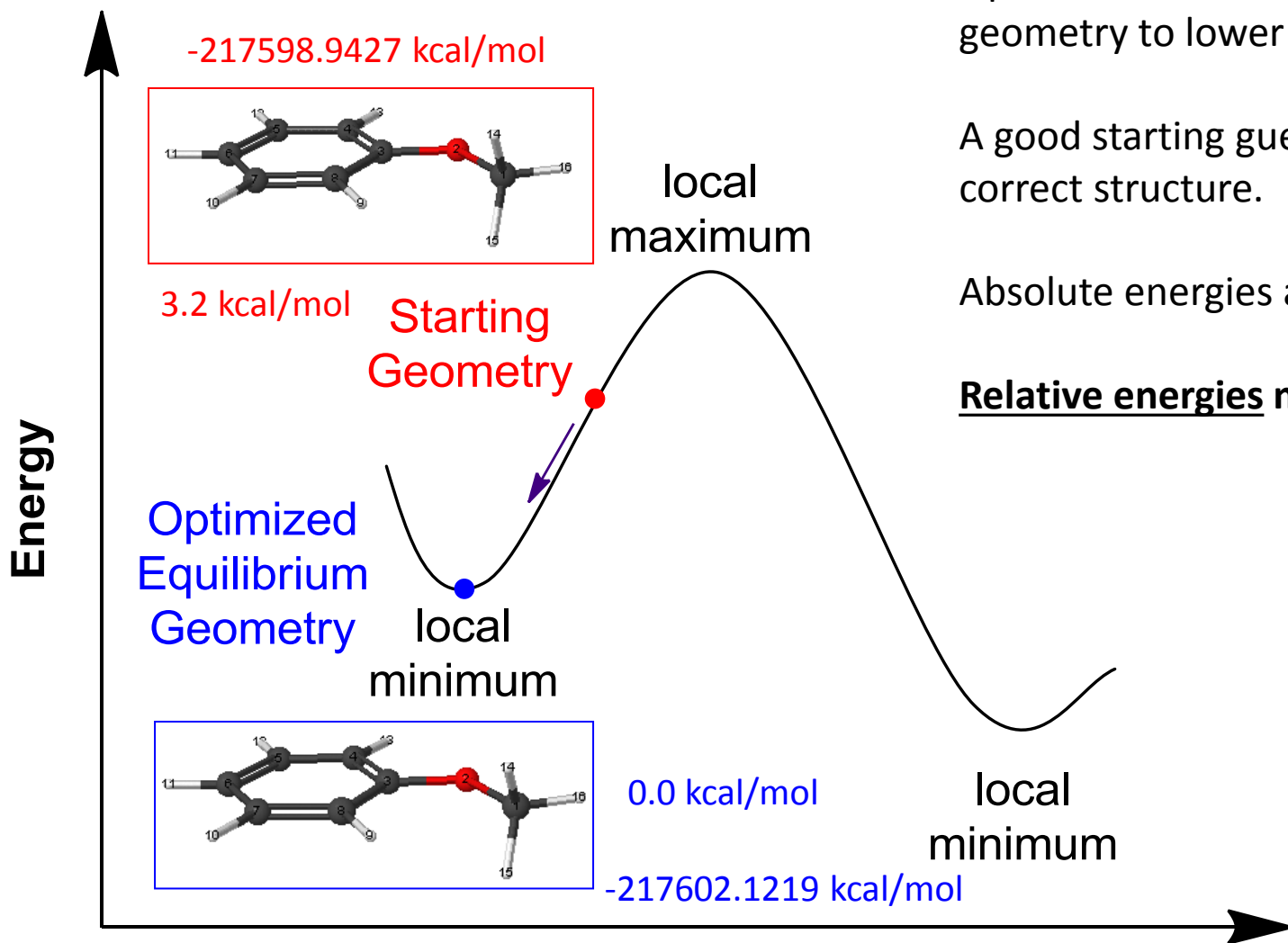


~sp lone pair

VSEPR predicts a tetrahedral electron geometry, which requires two identical lone pairs. This is not the case.

$AX_2E_2$	Bent			$H_2O, OF_2$
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# Geometry Optimization of Anisole



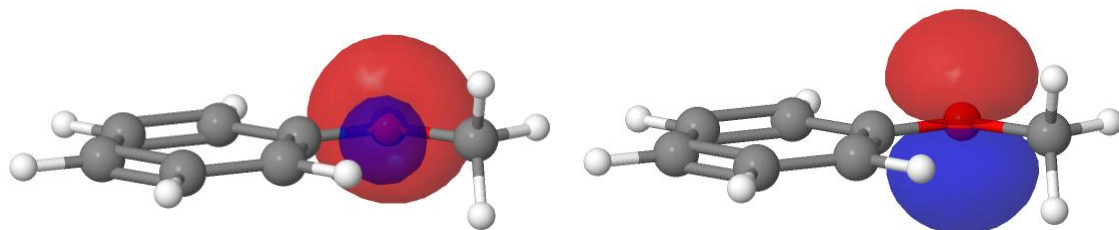
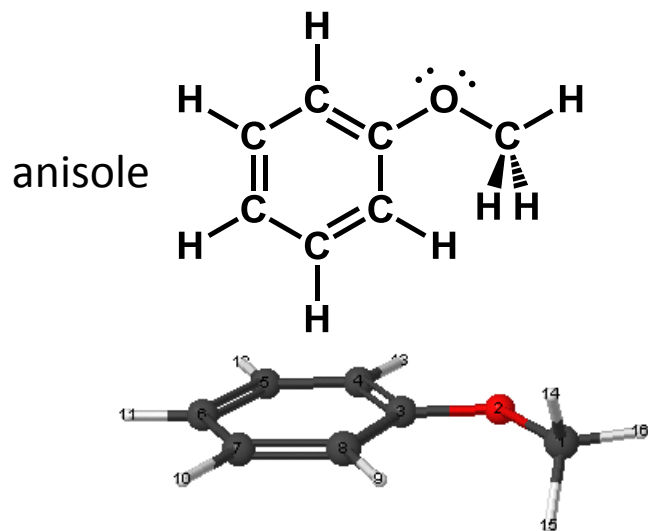
Optimization makes *small* changes in the geometry to lower the energy.

A good starting guess will *likely* lead to a correct structure.

Absolute energies are big and negative.

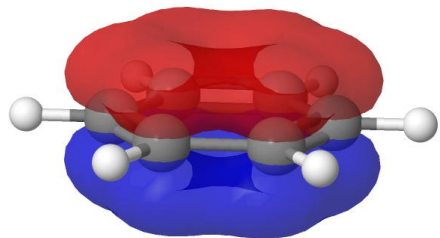
Relative energies make more sense.

# Geometry Optimization of Anisole and Natural Bond Orbitals

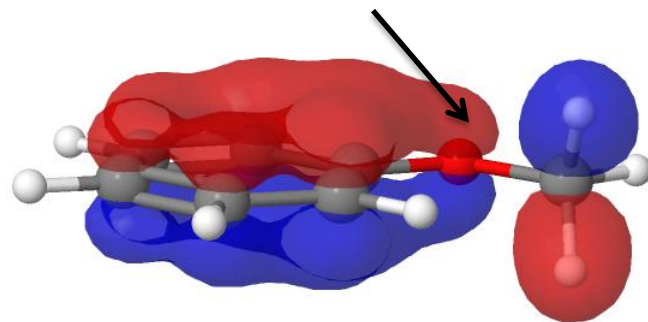


O-atom lone pairs

O-atom p-lone pair conjugated with  $\pi$ -system!



$\pi_1$  MO in benzene

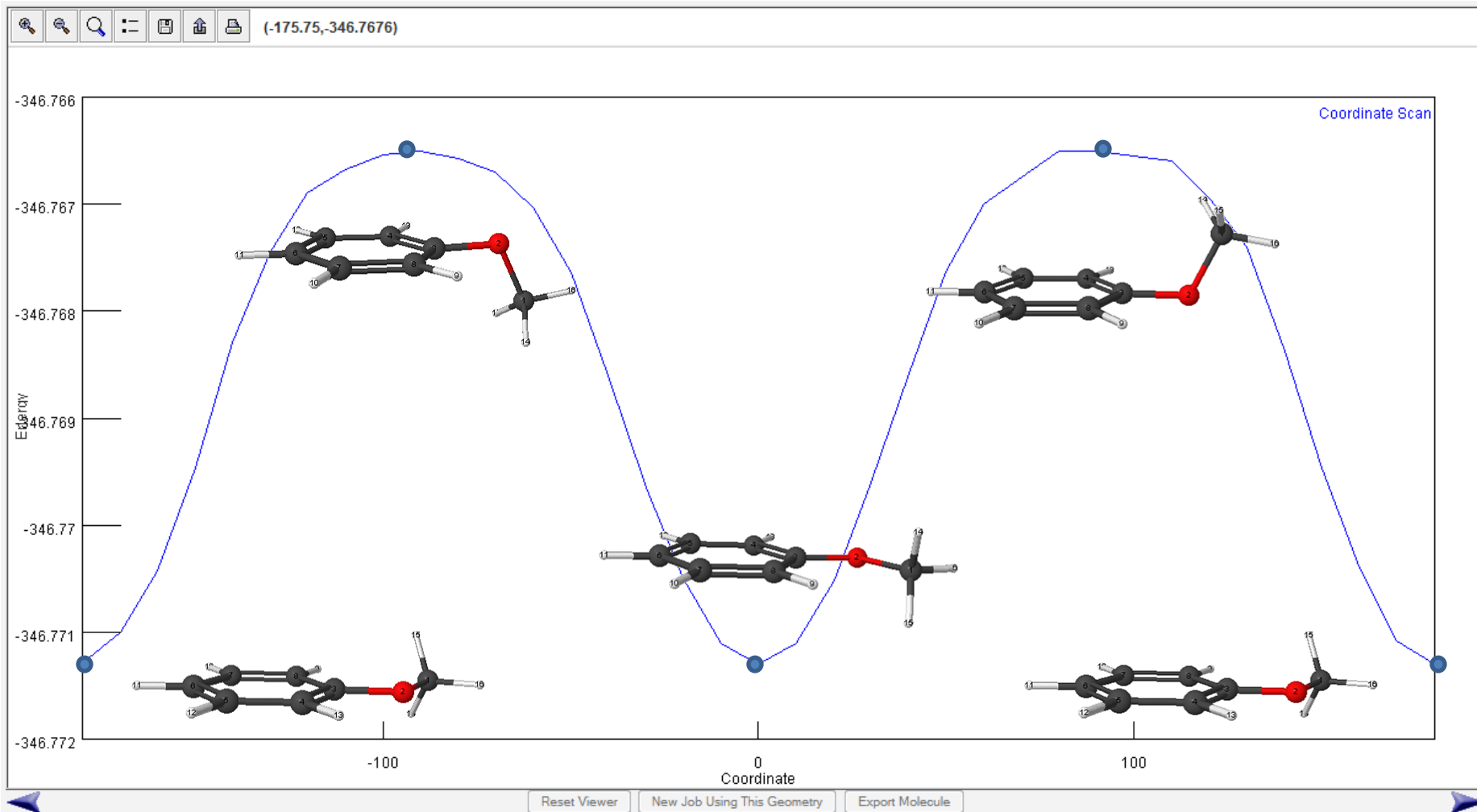


$\pi_1$  MO in anisole

Lone pairs with the same (or similar) symmetry as a  $\pi$  system conjugate.



# Other Conformational Isomers of Anisole?

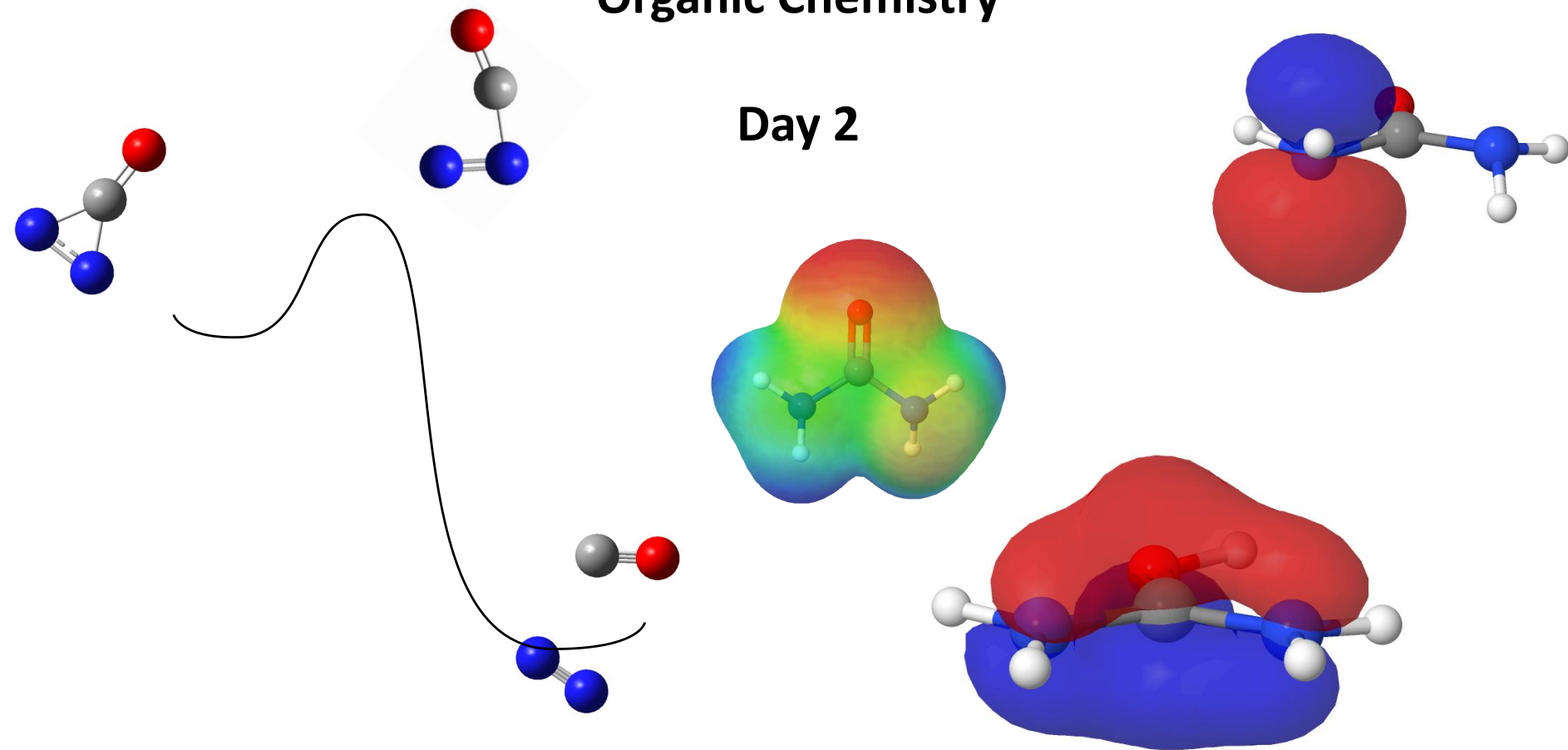


# CHEM 344 – Molecular Modeling

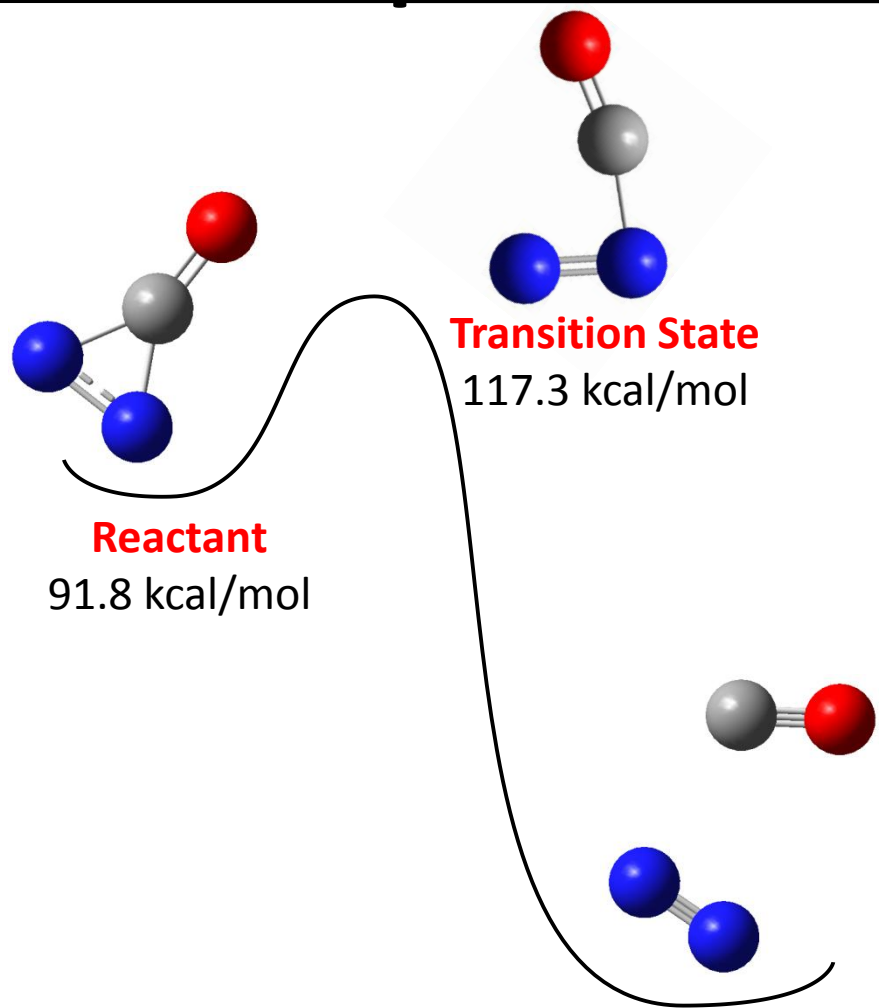
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## The Use of Computational Chemistry to Support Experimental Organic Chemistry

Day 2



# A Potential Energy Surface for the Decomposition of Diazirinone



At the transition state the motion corresponds to a negative or imaginary vibrational mode.

level of theory/basis set  
CCSD(T)/cc-pVTZ with ZPVE

Products  
0.0 kcal/mol

# Geometry Optimization of Urea – when clean-up goes wrong

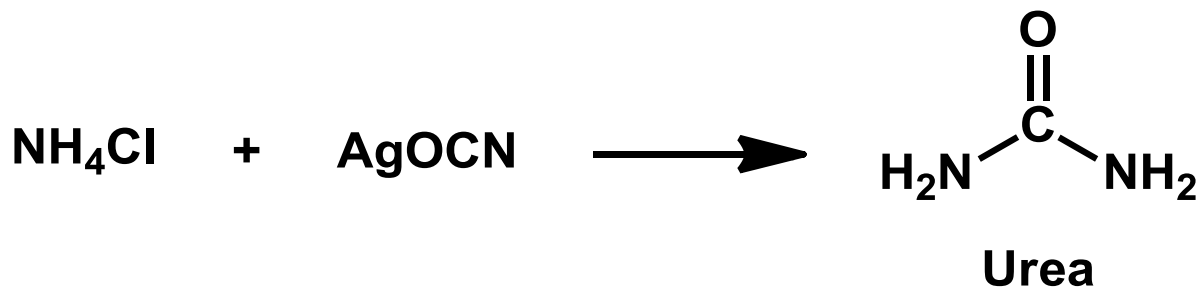
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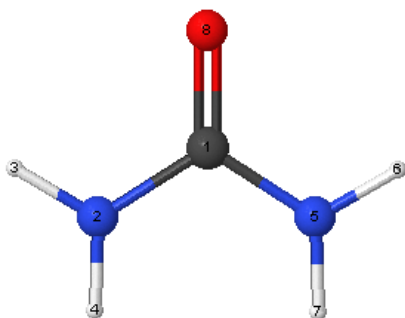
Urea was the first organic molecule to be synthesized from inorganic constituents.

The synthesis of urea helped to dispel the widely-held belief in *vitalism*; the belief that organic molecules which are the molecules of life must possess a “vital force”.

The synthesis was reported in 1828 by Friedrich Wöhler .



# Geometry Optimization of Urea – when clean-up goes wrong



Vibrational Modes

Mode	Symmetry	Frequency (cm <sup>-1</sup> )	IR (Raman) Intensity	Actions
1	A2	-442.9687	0.0000	
2	B1	-329.7550	561.5441	
3	A2	371.3026	0.0000	
4	A1	477.7139	3.4137	

When submitted planar ( $C_{2v}$ )... it has TWO negative vibrational modes.

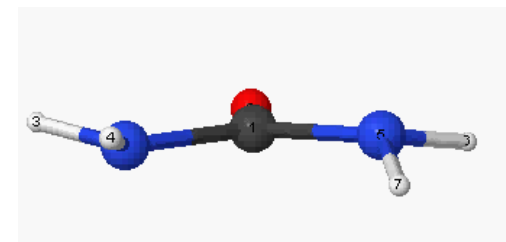
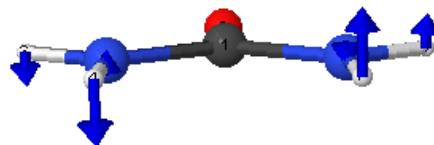
This is not a minimum on the potential energy surface (PES) and therefore is not the correct structure of urea.

**ALWAYS CHECK YOUR WORK!**

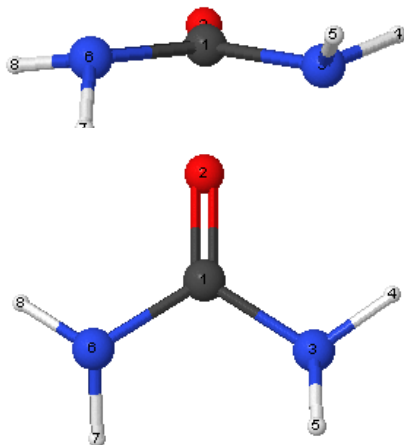
**Garbage in, garbage out.**

# Geometry Optimization of Urea – getting the correct structure

Bad Structure negative vibrational modes will indicate how to get to the correct structure.



Conclusion: urea is not planar.



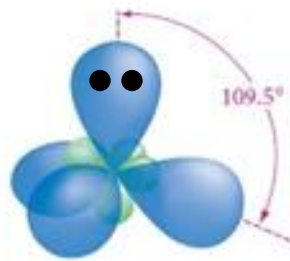
Vibrational Modes					
Mode	Symmetry	Frequency (cm <sup>-1</sup> )	IR (Raman) Intensity	Actions	
1	A	395.3773	70.1787		
2	B	457.1367	70.0816		
3	A	471.8405	2.8197		
4	B	555.1135	110.0660		

When submitted nonplanar (C<sub>2</sub>)... it has ZERO negative vibrational modes.

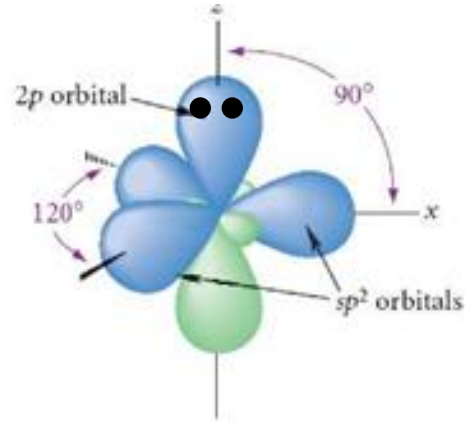
This is the correct structure! **ALWAYS CHECK YOUR WORK!**

# Geometry Optimization of Urea – when clean-up goes wrong

---



4  $sp^3$  orbitals



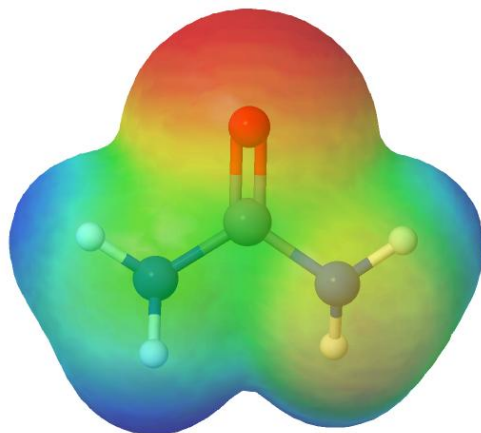
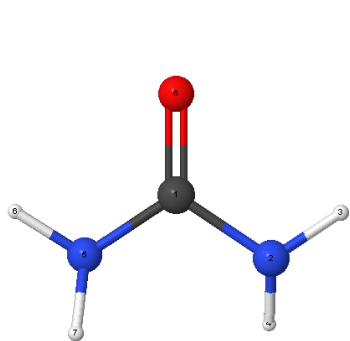
3  $sp^2$  orbitals and 1  $p$  orbital

An  $sp^3$  hybridized nitrogen atom minimizes electron-electron repulsion.

An  $sp^2$  hybridized nitrogen atom maximizes the ability to overlap with an adjacent  $\pi$  system.

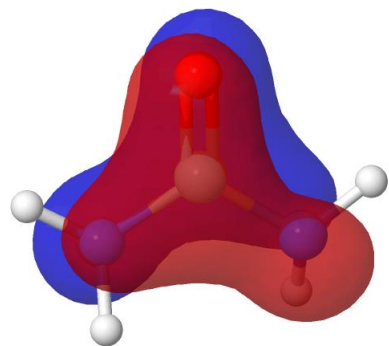
Many nitrogen atoms exist somewhere between these two extremes.

# Geometry Optimization & Natural Bond Orbitals of Urea

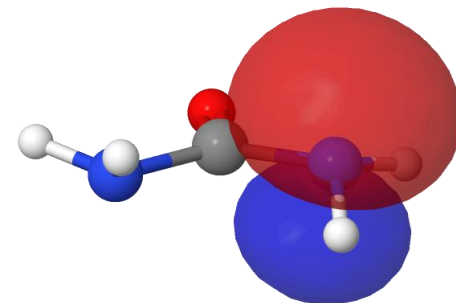
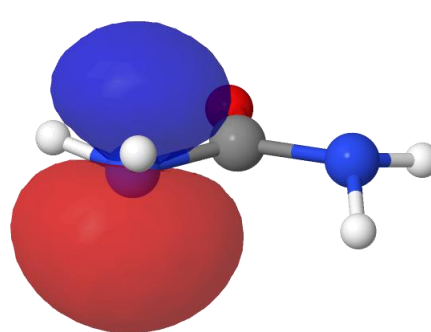


Urea has a conjugated  $\pi$  system which is responsible for its increased planarity.

Slightly twisted  $\pi$  system, but good conjugation.



HOMO - 4



Natural Hybrid Orbitals

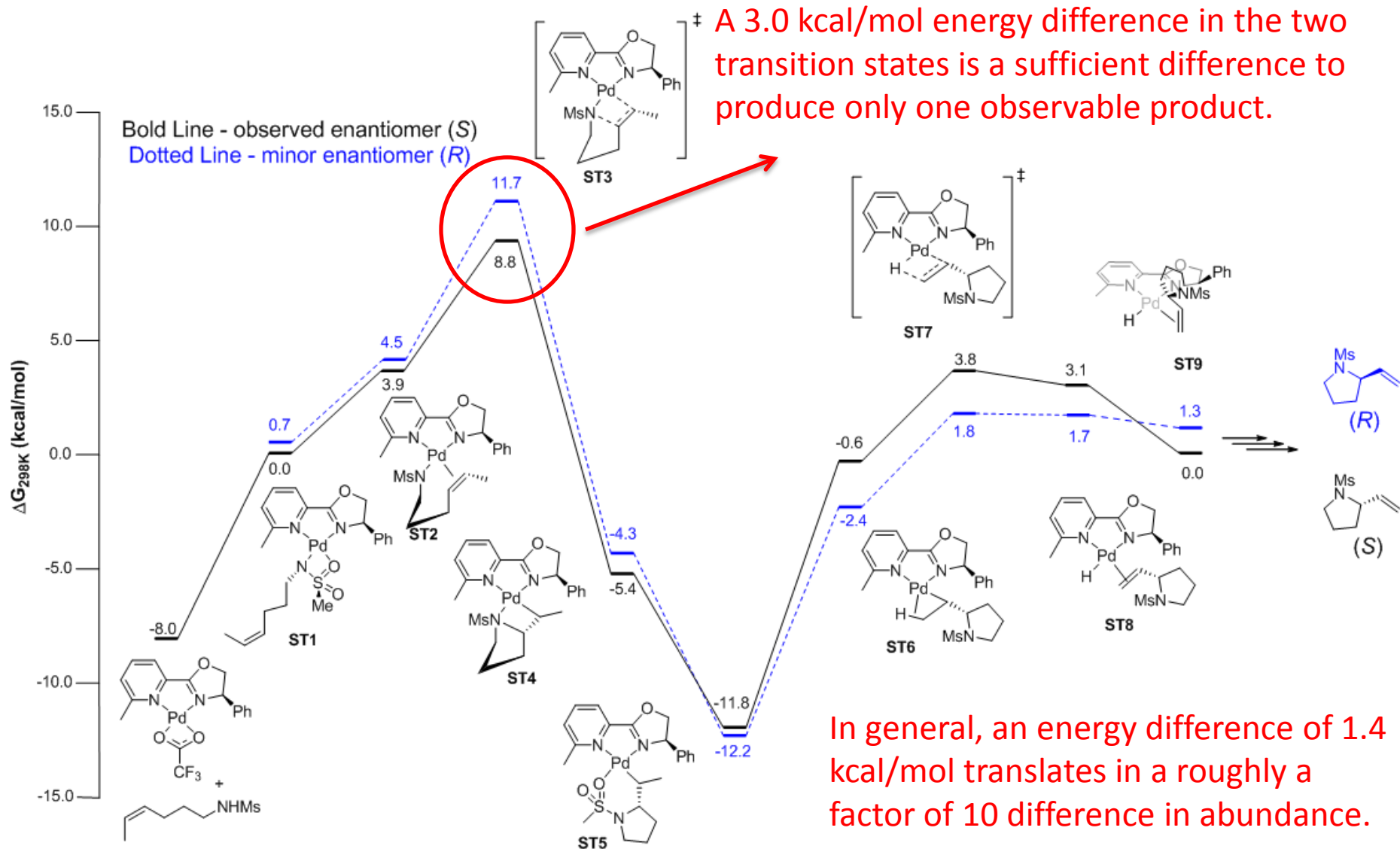
O-lone pairs p and  $\sim sp$

N-lone pairs not  $sp^3$ , but  $\sim sp^9$

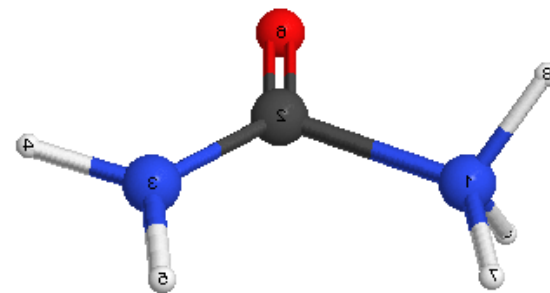
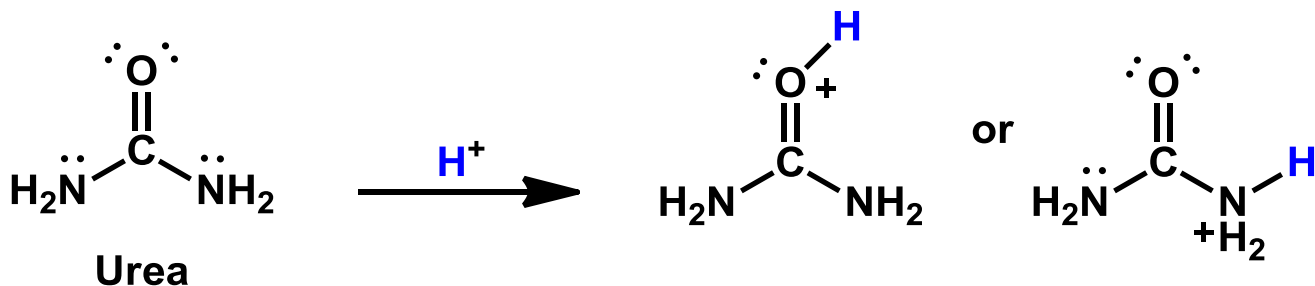
Display Range		21	- 24	/ 68	
Orbital	Description	Occupancy	Energy	Actions	
21	LP(1)O2 s(59.44%)p0.68(40.51%)d0.00(0.05%)	1.975348831	-0.659850538 Hartree		
22	LP(2)O2 s(0.00%)p1.00(99.79%)d0.00(0.21%)	1.848747053	-0.226456252 Hartree		
23	LP(1)N3 s(10.77%)p8.28(89.17%)d0.01(0.07%)	1.832070455	-0.295371587 Hartree		
24	LP(1)N6 s(10.77%)p8.28(89.17%)d0.01(0.07%)	1.832070455	-0.295371587 Hartree		



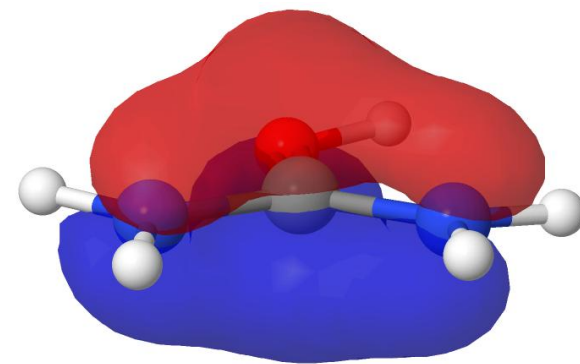
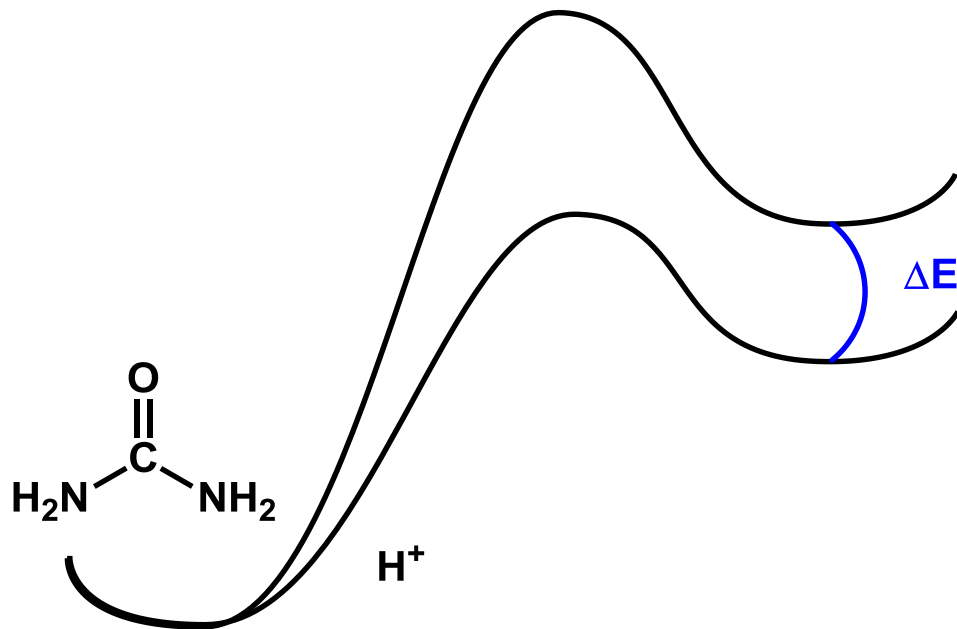
# Potential Energy Surface



# Basicity of Urea – Which atom is most basic, oxygen or nitrogen?



12.1 kcal/mol



0.0 kcal/mol

Breaking  $\pi$ -conjugation greatly increases the relative energy and results in a huge difference in the basicity (many factors of ten) between the nitrogen and oxygen atoms.

# Chapter 5 Goals

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- Students have read all of chapter 5 and are familiar with key computational concepts and procedures.
- Students should be able complete all of the calculations necessary in chapter 5 using WebMO/Gaussian09.
- Students should be able to use computational chemistry to help understand organic chemistry and explain chemical phenomena.
- Students should feel comfortable completing calculations independently and have a clear understanding of where/how to get help.

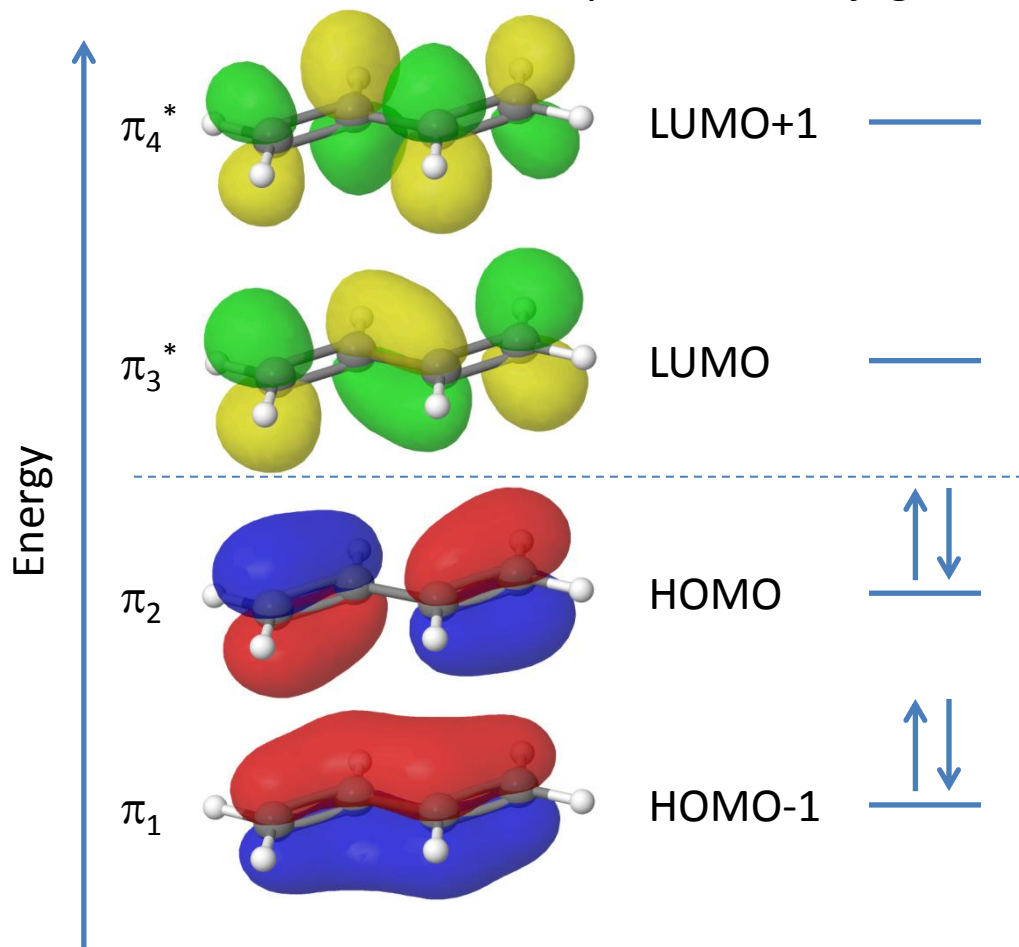
# References

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- 1) WebMO, Revision 12.0. <http://webmo.net/> 2012.
- 2) Gaussian 09, Revision B.1, Frisch et al. Gaussian, Inc., Wallingford CT, 2009.
- 3) Shaffer, C. J.; Esselman, B. J.; McMahon, R. J.; Stanton, J. F.; Woods, R. C. Attempted Isolation and Characterization of Diazirinone (N<sub>2</sub>CO). *J. Org. Chem.* **2010**, 75(6), 1815-1821.
- 4) McDonald, R. I.; White, P. B.; Tam, C.; Weinstein, A. B.; Stahl, S. S. *Org. Lett.* **2011**, 13, 2830-2833.

# 1,3-butadiene – Electronic Structure

Recall the  $\pi$  systems of conjugated dienes like 1,3-butadiene.

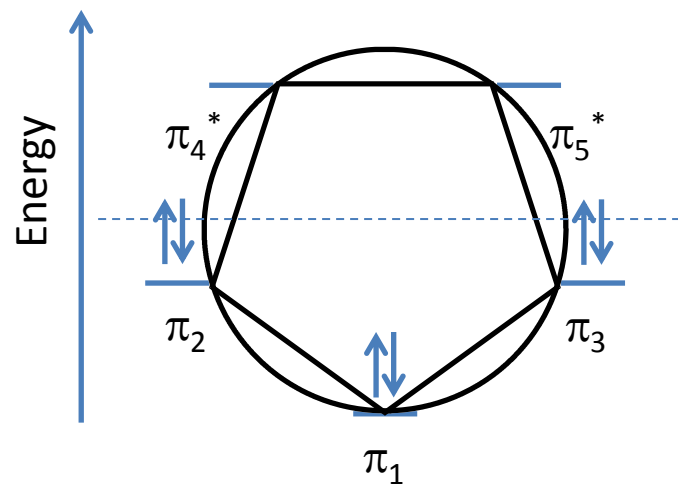
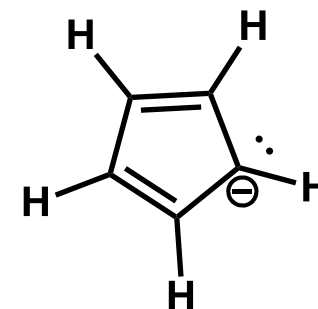
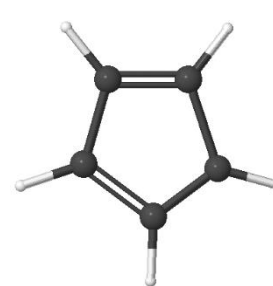
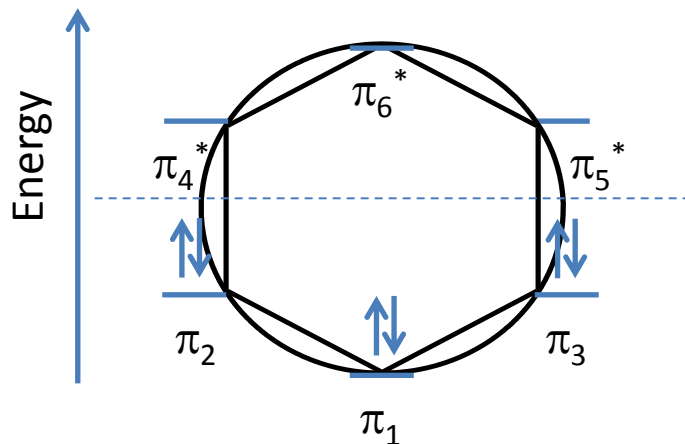
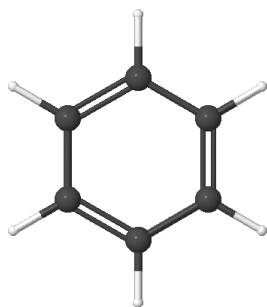


- Four p atomic orbitals create four  $\pi$  molecular orbitals.
- As the energy of the orbital increases so does the number of nodes.
- Lowest energy orbitals are filled first.
- HOMO = Highest energy Occupied Molecular Orbital
- LUMO = Lowest energy Unoccupied Molecular Orbital
- In WebMO **red/blue** is occupied, **yellow/green** is unoccupied.

# Frost Circles for Hydrocarbons

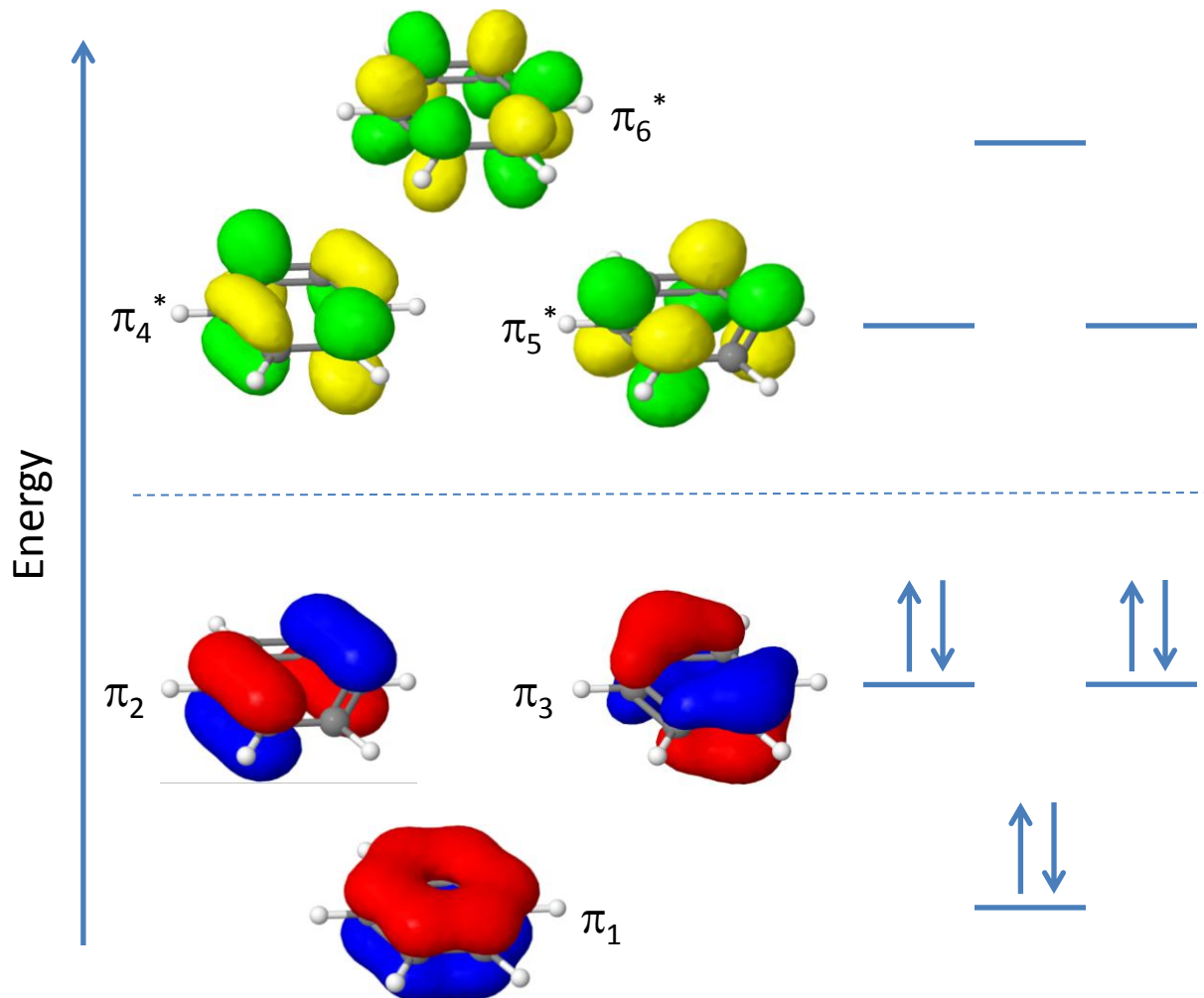
The energy distribution of cyclic conjugated systems can be predicted by Frost circles, which help to explain the Hückel rule. (Works well for monocyclic hydrocarbon molecules.)

- Place a polygon, in the shape of the molecule, vertex down on a circle.
- Place an orbital at each intersection of the polygon and circle.
- Fill in the electrons as usual.
- If all the electrons are paired and at a lower energy, the species is likely aromatic.



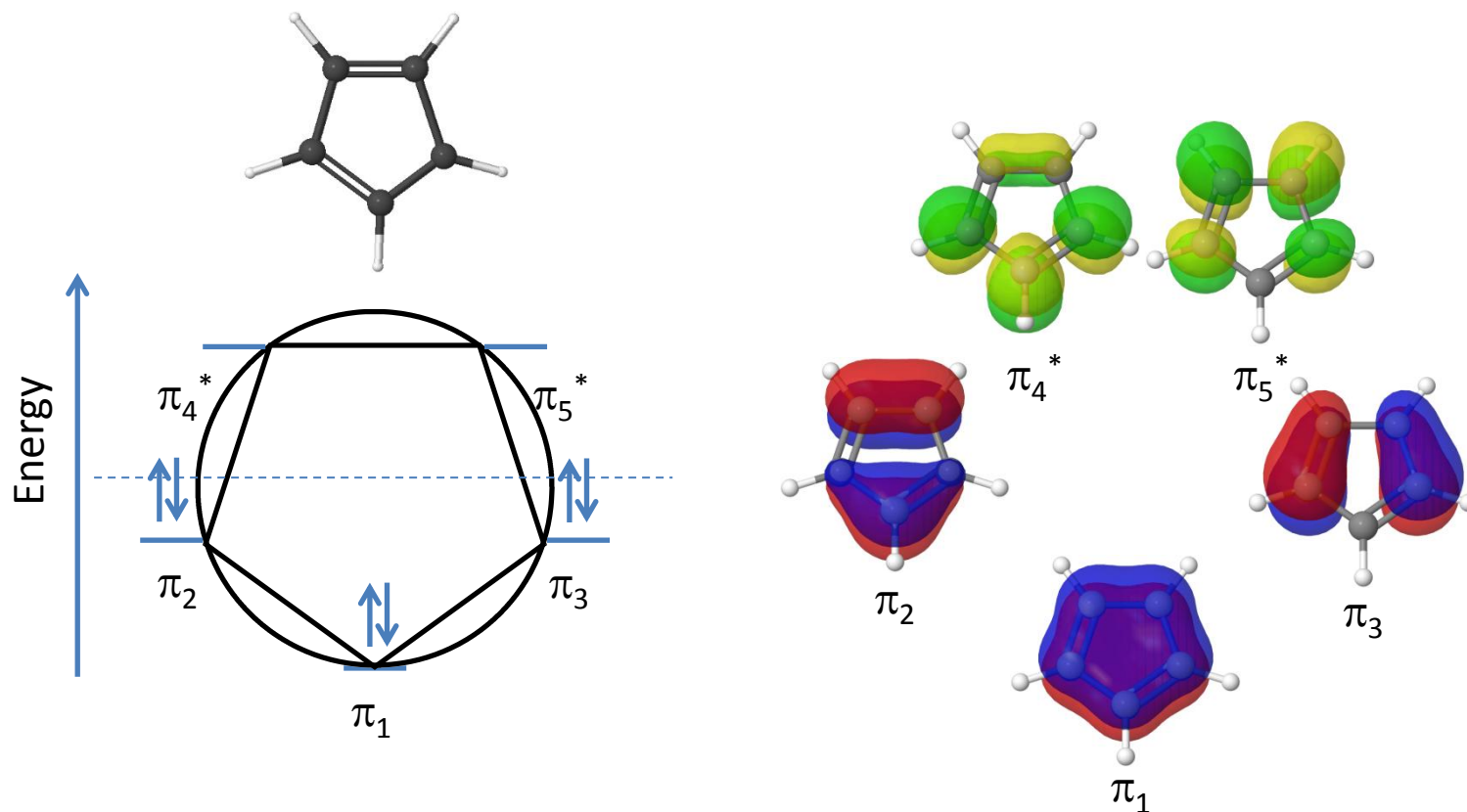
# Benzene – Electronic Structure

Cyclic Conjugated systems, like benzene, are slightly more complicated.



- Six atomic p orbitals create six molecular  $\pi$  orbitals.
- $\pi_2$  and  $\pi_3$  are degenerate (equal in energy) and have a node.
- $\pi_4^*$  and  $\pi_5^*$  are degenerate and have two nodes.
- This delocalized  $\pi$  system of three largely stabilizing molecular orbitals is the source of benzene's stability.

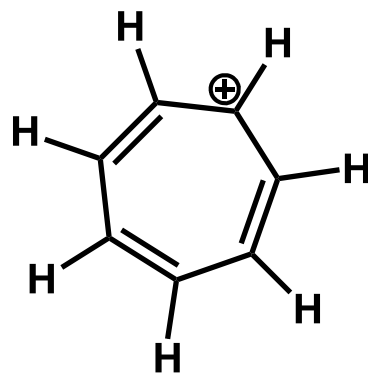
# Cyclopentadienyl Anion – Electronic Structure



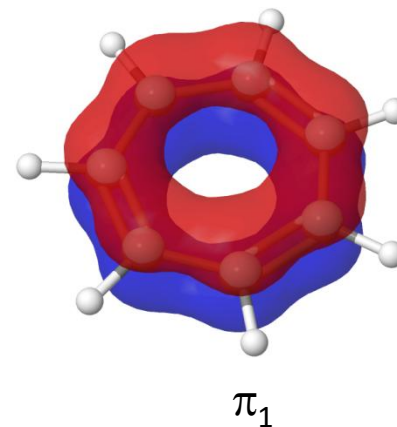
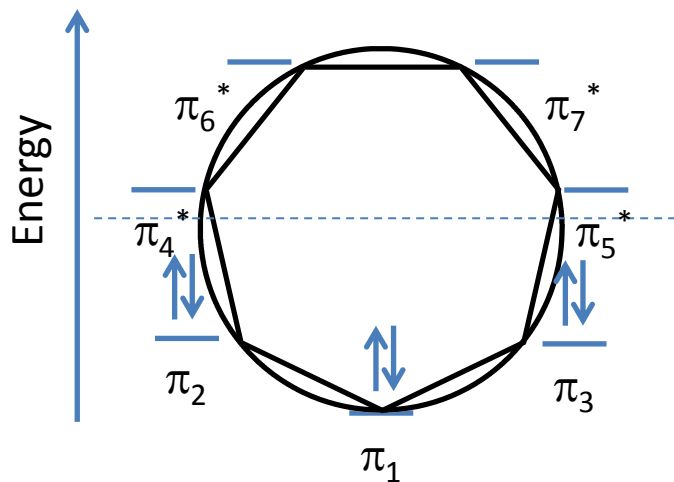
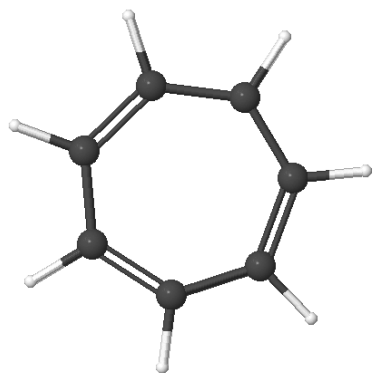


# Aromatic Ions

tropylium cation  
 $C_7H_7^+$



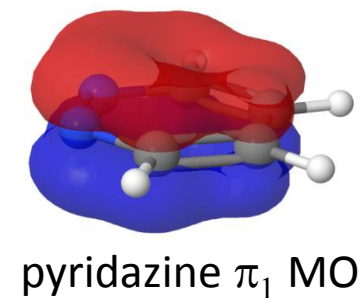
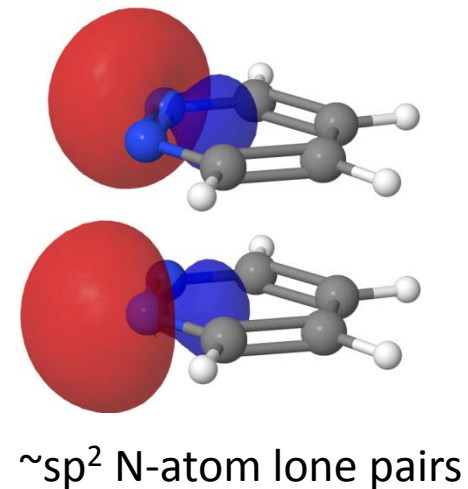
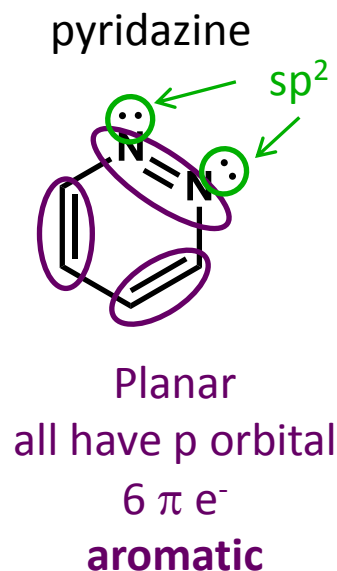
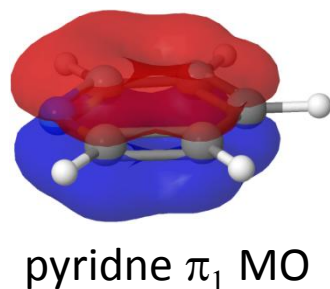
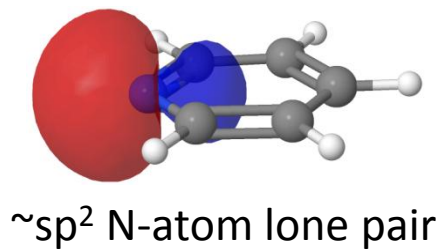
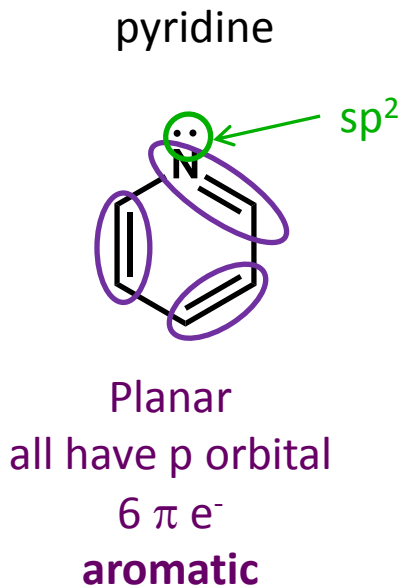
planar  
all have p orbital  
 $6 \pi e^-$   
aromatic



# Aromatic Heterocycles

## Aromatic molecules

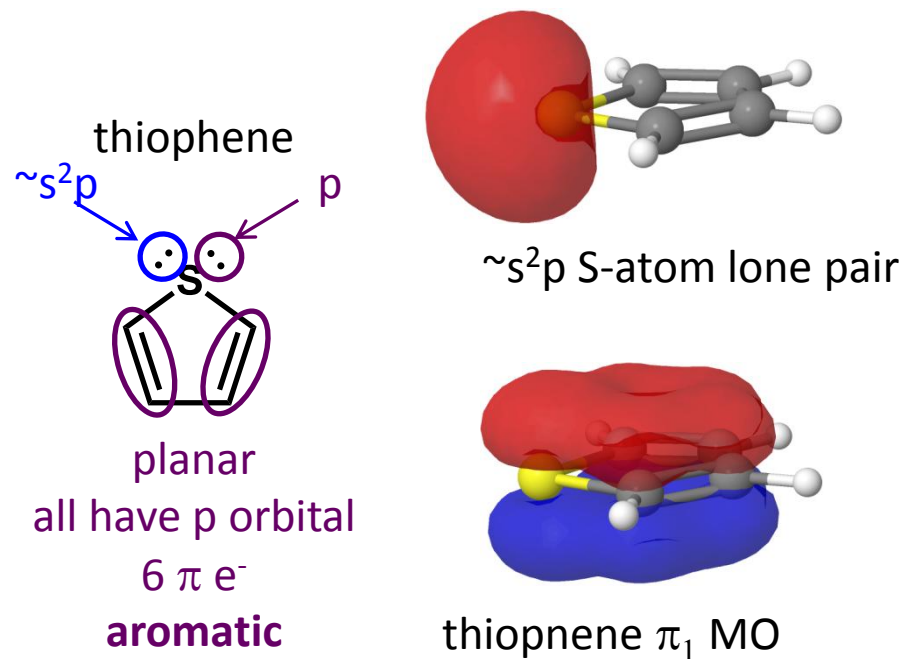
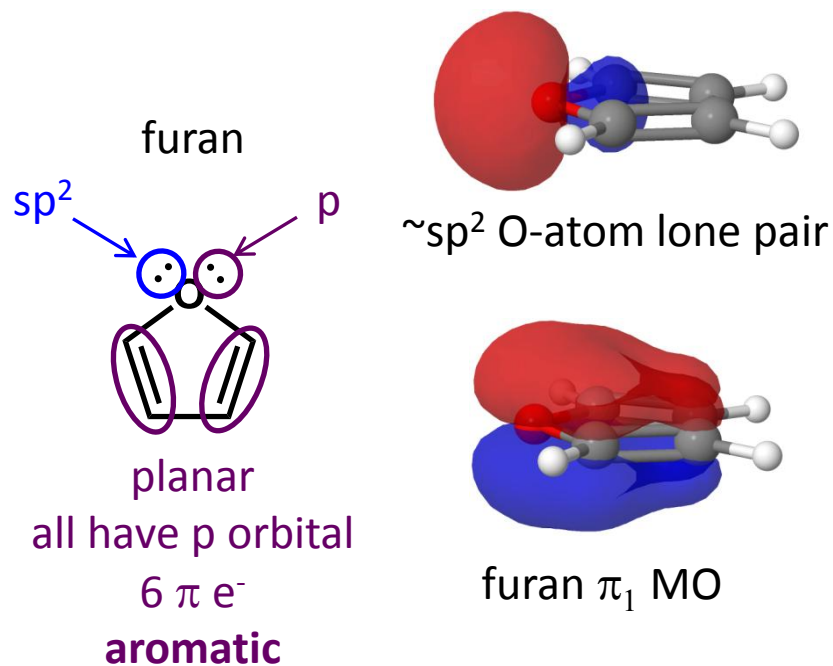
- have enhanced stability, lowered reactivity compared to alkenes
- are planar and cyclic or polycyclic
- have a p orbital at every atom in the ring
- have a diatropic ring current (Chapter 13 & 16)
- have  $4n+2$   $\pi$  electrons (Hückel's Rule)



# Aromatic Heterocycles

## Aromatic molecules

- have enhanced stability, lowered reactivity compared to alkenes
- are planar and cyclic or polycyclic
- have a p orbital at every atom in the ring
- have a diatropic ring current (Chapter 13 & 16)
- have  $4n+2$   $\pi$  electrons (Hückel's Rule)



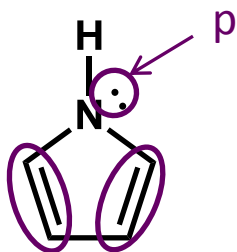
# Aromatic Heterocycles

## Aromatic molecules

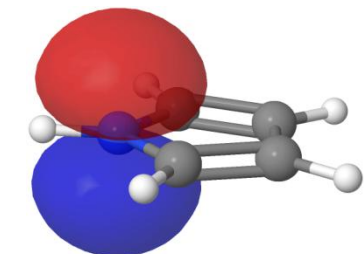
- have enhanced stability, lowered reactivity compared to alkenes
- are planar and cyclic or polycyclic
- have a p orbital at every atom in the ring
- have a diatropic ring current (Chapter 13 & 16)
- have  $4n+2 \pi$  electrons (Hückel's Rule)

pyrrole

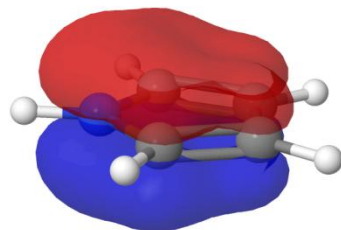
$sp^2$  N-atom



planar  
all have p orbital  
 $6 \pi e^-$   
**aromatic**

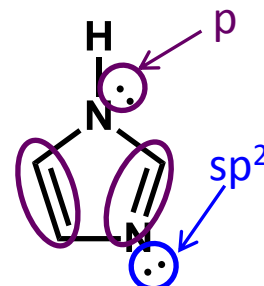


p N-atom lone pair  
before bonding

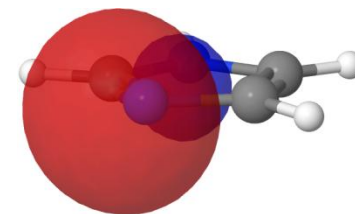


pyrrole  $\pi$  system

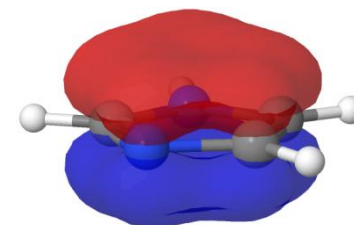
imidazole



planar  
all have p orbital  
 $6 \pi e^-$   
**aromatic**



$\sim sp^2$  N-atom lone pair



Imidazole  $\pi$  system

# Cyclobutadiene – Potential Energy Surface – Triplet Aromaticity

