CHEM 344 – Molecular Modeling

The Use of Computational Chemistry to Support Experimental Organic Chemistry

Part 1: Molecular Orbital Theory, Hybridization, & Formal Charge

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

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 microwave, IR, UV-Vis, & NMR spectra.
• find transition states and chemical pathways for reactions.
σ-type Molecular Orbitals – H₂

- Two 1s atomic orbitals create two σ molecular orbitals.
- Higher energy orbitals have more nodes than lower energy orbitals.
- Lowest energy orbitals are occupied first in ground state molecules.
- HOMO = Highest energy Occupied Molecular Orbital
- LUMO = Lowest energy Unoccupied Molecular Orbital
- In WebMO red/blue is occupied, yellow/green is unoccupied.
**σ-type Molecular Orbitals – C₂H₆**

- Two ~sp³ atomic hybrid orbitals create two σ molecular orbitals.
- Higher energy orbitals have more nodes than lower energy orbitals.
- Lowest energy orbitals are occupied in ground state molecules.
- **HOMO** = Highest energy Occupied Molecular Orbital
- **LUMO** = Lowest energy Unoccupied Molecular Orbital
- In WebMO red/blue is occupied, yellow/green is unoccupied.

**Ethane, C₂H₆**
**π-type Molecular Orbitals – C₂H₄**

- Two p atomic hybrid orbitals create two π molecular orbitals.

- The presence of a p orbital at each carbon atom implies an sp² hybridization of the atom.

- The ~sp² atomic hybrid orbitals are used to make the σ bonds.

For more on hybridization of carbon atoms:
https://www.chem.wisc.edu/content/343esselman/hybridization
\( \pi \)-type Molecular Orbitals – \( \text{C}_2\text{H}_2 \)

- Four \( p \) atomic hybrid orbitals create four \( \pi \) molecular orbitals, two degenerate \( \pi \) and two degenerate \( \pi^* \) orbitals.
- The presence of two \( p \) orbitals at each carbon atom implies an sp hybridization of the atoms.
**π-type Molecular Orbitals – C₃H₅⁺**

Resonance structures are a simple way to depict π conjugation.
π-type Molecular Orbitals – 1,3-butadiene

Four p atomic orbitals create four π molecular orbitals.

MOs are a more realistic picture of conjugation (orbital overlap) than resonance structures.
π-type Molecular Orbitals – benzene

Six atomic p orbitals create six molecular π orbitals.

π₂ and π₃ are degenerate (equal in energy) and have one node.

π₄* and π₅* are degenerate and have two nodes.

This delocalized π system of three stabilizing molecular orbitals is the source of benzene’s aromatic stability.

For more on aromaticity: https://www.chem.wisc.edu/content/343esselman/aromaticity
Computational chemistry can estimate charges on atoms within molecules by a variety of methods including Natural Population Analysis (NPA) from Natural Bond Orbitals (NBO) calculations.

Electronic Charge Distribution

Dipole moments can be estimated from the geometry and charge distribution. Electrostatic potential maps display the same information in a color gradient. Negative charges are displayed in red, positive charges in blue.
Resonance structures are often drawn to predict charge distribution within a molecule, but this is a sub-optimal method that only predicts the change in charge distribution based upon a substitution.

Electronic Charge Distribution

Benzonitrile

\[
\begin{align*}
\text{C}=\text{N}^- & \quad \text{(aryl)} \\
\text{C}=\text{N}^- & \quad \text{(imine)} \\
\text{C}=\text{N}^- & \quad \text{(amidinic)} \\
\text{C}=\text{N}^- & \quad \text{(aromatic)} \\
\end{align*}
\]

\[
\begin{align*}
\delta^+ \text{C}=\text{N}^- & \quad \text{(aryl)} \\
\delta^+ \text{C}=\text{N}^- & \quad \text{(imine)} \\
\delta^+ \text{C}=\text{N}^- & \quad \text{(amidinic)} \\
\delta^+ \text{C}=\text{N}^- & \quad \text{(aromatic)} \\
\end{align*}
\]
Formal charges, based upon changes in valence electron count upon bonding, are often misleading about the real charge distribution in a molecule. They are strictly for bookkeeping, not actual charge prediction.

**Electronic Charge Distribution**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Formal Charge</th>
<th>Bond Charge (F, O, H, B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydronium ion</td>
<td>-0.82</td>
<td>+0.61 (F = 4.0, O = 3.5, H = 2.1, B = 2.0)</td>
</tr>
<tr>
<td>tetrafluoroborate ion</td>
<td>-0.64</td>
<td>+1.56 (F = 4.0, O = 3.5, H = 2.1, B = 2.0)</td>
</tr>
</tbody>
</table>
Electronic Charge Distribution & Chemical Reactivity

This is an important reaction used to generate the NO$_2^+$ cation used in electrophilic aromatic substitution reactions. The oxygen atom without the formal negative charge is protonated, why?

$$\text{HNO}_3 + \text{H}_2\text{SO}_4 \rightarrow \text{H}_2\text{O} + \text{NO}_2^+ + \text{HSO}_4^-$$
This is the rate-determining step of an electrophilic aromatic substitution reaction. Why is the carbon atom more electrophilic than the formally positive oxygen atom?
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Part 2: Introduction to WebMO/Gaussian09, Optimization and Vibrational Frequency Calculations, NBO calculations, Hybridization, & Coordinate Scans
In an optimization, Gaussian09 makes \textit{small} changes in the geometry to lower the energy. A good starting structure \textit{likely} produce a desired optimized structure.

Absolute energies are large and negative; relative energies are easier to use. The output energies are in Hartrees/particle and must be converted to kcal/mol for use in CHEM 344.

1 Hartree/particle = 627.509 kcal/mol \hspace{1cm} 1 kcal/mol = 4.187 kJ/mol
A vibrational frequency calculation will provide a predicted IR spectrum of the molecule AND confirm that it is an optimized energy minimum on the potential energy surface.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Symmetry</th>
<th>Frequency (cm$^{-1}$)</th>
<th>IR (Raman) Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A1</td>
<td>1713.2813</td>
<td>75.7813</td>
</tr>
<tr>
<td>2</td>
<td>A1</td>
<td>3724.7740</td>
<td>1.6856</td>
</tr>
<tr>
<td>3</td>
<td>B2</td>
<td>3846.9456</td>
<td>19.3847</td>
</tr>
</tbody>
</table>

Reactants, products, intermediates – all energy minima, all real (positive) vibrational modes
Transition states – an energy maximum, 1 imaginary (negative) vibrational mode

http://webbook.nist.gov/cgi/cbook.cgi?ID=C7732185&Type=IR-SPEC&Index=1#IR-SPEC
Molecular and Electronic Structure of Water

An optimized geometry provides the starting point for an NBO calculation which will provide the NPA charges, dipole, electrostatic potential map, MO’s, and NBO’s.

VSEPR predicts a tetrahedral electron geometry and identical lone pair orbitals.

<table>
<thead>
<tr>
<th>Molecule Type</th>
<th>Shape</th>
<th>Electron arrangement</th>
<th>Geometry</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX₂E₂</td>
<td>Bent</td>
<td></td>
<td>H₂O, OF₂</td>
<td></td>
</tr>
</tbody>
</table>


http://pubs.acs.org/doi/pdfplus/10.1021/ed064p124
Molecular and Electronic Structure of Anisole

How well does VSEPR predict the lone pair orbitals for the O-atom in anisole?

NBO O-atom lone pairs

<table>
<thead>
<tr>
<th>Orbital</th>
<th>Description</th>
<th>Occupancy</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>LP(1)O2 s(38.74%)p1.58(61.18%)d0.00(0.08%)</td>
<td>1.963755858</td>
<td>1.963755858 -0.538946472 Hartree</td>
</tr>
<tr>
<td>10</td>
<td>LP(2)O2 s(0.00%)p1.00(99.89%)d0.00(0.11%)</td>
<td>1.842971008</td>
<td>1.842971008 -0.300814074 Hartree</td>
</tr>
</tbody>
</table>

π system in anisole
Coordinate or Conformational Scan of Anisole

What happens to the energy of anisole if the O-atom lone pair conjugation is broken?
What about the O-atom lone pairs in furan? If the oxygen atom lone pairs are in symmetric (degenerate) orbitals predicted by VSEPR for a tetrahedral electron geometry, then the oxygen atom lone pair is not conjugated with the two $\pi$ bonds. And, thus, furan would not be aromatic.
What about the O-atom when it has only a single lone pair, in case such as hydronium? If the O-atom lone pair is in a p orbital the molecule should be trigonal planar. If VSEPR predicts this molecule correctly, the molecule should be trigonal pyramidal with a tetrahedral electron geometry.
Geometry Optimization Procedure

1. Draw the molecule in WebMO.
2. Use one of the clean-up tools.
3. Inspect the molecule. Does the predicted structure make chemical sense?
4. Submit an Optimization and Vibrational Frequencies Calculation.
5. Inspect the output molecule. Does the optimized structure still make chemical sense?
6. Confirm that the vibrational modes match the desired species.
7. Consider alternate, lower-energy, conformational isomers.
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Part 3: Potential energy surfaces, transition states, hybridization
Molecular and Electronic Structure of Ammonia

The potential energy surface below depicts the process of nitrogen inversion. Ammonia can convert between two trigonal pyramidal conformational isomers via a planar transition state.

Trigonal planar ($D_{3h}$)

Trigonal pyramidal ($C_{3v}$)

5.5 kcal/mol

The barrier is sufficiently narrow that quantum tunneling readily occurs.
Variation in the Hybridization of Nitrogen Atoms

The nitrogen atom in ammonia is pyramidal while the optimized structure of formamide is planar with a trigonal planar nitrogen.

\[ \text{formamide} \rightarrow \text{ammonia} \]
Molecular and Electronic Structure of Urea

Given the variability of N-atom hybridizations, it is very difficult to know beforehand whether or not a structure should be planar. Urea is a great case-study of this difficulty; even the cleanup tools in WebMO struggle to produce a good input structure.
Molecular and Electronic Structure of Urea

Urea has a non-planar geometry that results in a slightly twisted conjugated $\pi$ system. The nitrogen atom lone pairs are in p-rich (~sp$^8$) orbitals.
In general, a $\Delta E$ of 1.4 kcal/mol translates into an approximate factor of 10 difference in abundance.
Chemical Reactivity – Basicity of Urea

-225.512016 Hartrees
-141510.82 kcal/mol

12.7 kcal/mol

-225.532300 Hartrees
-141523.55 kcal/mol

0.0 kcal/mol
General Guidelines for Computational Data Submission

1. You must cite (on the lab report cover sheet) your computational work used to answer post-lab or pre-lab questions in CHEM 344 by providing the WebMO job number associated with the calculation.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Description</th>
<th>Date</th>
<th>Status</th>
<th>Time</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>229212</td>
<td>C7H8O anisole</td>
<td>Coordinate Scan - Gaussian</td>
<td>1/8/2014 16:02</td>
<td>Running</td>
<td>34:05</td>
<td></td>
</tr>
<tr>
<td>229208</td>
<td>CH4ON2 Urea C2</td>
<td>Optimize + Vib Freq - Gaussian</td>
<td>1/8/2014 14:14</td>
<td>Complete</td>
<td>1:20</td>
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<tr>
<td>229202</td>
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<td>Coordinate Scan - Gaussian</td>
<td>1/8/2014 13:42</td>
<td>Complete</td>
<td>3:56:21</td>
<td></td>
</tr>
</tbody>
</table>

2. You must provide a color-image of each optimized structure or orbital used to answer a post-lab or pre-lab question. Please print multiple pictures per page and cut/paste them into your notebook.

3. Data submitted must be your own work. You are not allowed to use someone else’s data or account. This is considered academic misconduct.
References
