

5.53 (Molecular Structure and Reactivity I) Notes

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Week 1

Introduction

1.1 Introduction

9/5:

- Normally, only about 20 kids enroll in this class per year. This year, there are 40.
 - This is a typical class for the first-year grad students in OChem, but Elkin asks what made advanced undergrads and second-year grad students enroll, as well as just so many of us overall.
 - Radosevich told all the inorganic kiddos to take this class!
 - Bioinorganic and Organometallics also aren't being offered because everyone's on sabbatical.
- Oleta Johnson came to sit in on Masha's class! Oleta is Masha's "best friend."
- The lecture now begins (on MIT Time).
- Masha will teach the first half of the course; Alex will teach the second half.
 - TF is Jonathan Edward, an Elkin kiddo.
 - He will hold weekly OH, study sessions, grades problems and exams, etc.
 - Has a mastery of the subject material (took 5.53 last year), and unrivaled "approachability."
 - Reach out to Masha or Alex if we have issues with the subject material, our own journeys in grad school or undergrad, etc. It's easier to fix problems early in the semester!
- Overview of the course.
 - 1st half.
 - Basically physical organic chemistry.
 - A deep dive on structure and reactivity.
 - 2nd half.
 - Basically reaction mechanisms.
 - Kinetics, rate laws, kinetic isotope effects (KIEs), methodology experiments, etc.
 - The tools presented herein are broadly applicable to various fields of chemistry.
- This course will teach us to...
 - Propose *reasonable* mechanisms for organic reactions;
 - Scrutinize mechanisms in the literature;
 - That is, figure out if a proposed mechanism is reasonable or not, evaluate the authors' evidence, and identify follow-up experiments that can be run.
 - Design experiments to distinguish and test proposed mechanisms;
 - Conduct our own mechanistic study.

- Masha gives the metacognition spiel again.
 - Know our strengths and weaknesses (correct these by reviewing undergrad notes and Googling).
- Course logistics.
 - 2 exams.
 - Fully online; they are trusting us to work alone on the honor system.
 - 4 problem sets.
 - Posted 1 week before they are due.
 - Encouraged to work collaboratively, but submit our own work.
 - Jonathan and Masha will reserve a study room in which we can collaborate.
 - 1 mechanistic proposal.
 - Engage the literature!
 - Textbook: Anslyn and Dougherty (2006).
 - The standard textbook for PhysOrg (do readings and practice problems as needed).
 - Jonathan is working on a correspondence of lectures to chapters.
 - Reach out to Masha, Alex, or Jonathan if we have any questions!
 - If you ever miss class, post a new topic on the Canvas discussion board asking for notes (and be generous in uploading your own).
- We now begin the course content.
- **Mechanism:** An accounting of all bond-making and bond-breaking events in a reasonable sequence.
 - Mechanisms don't exist in the physical sense; it is more of a *model* of how things proceed.
- Mechanisms exist in four levels of depth.
 1. Describe electron movement via arrow pushing.

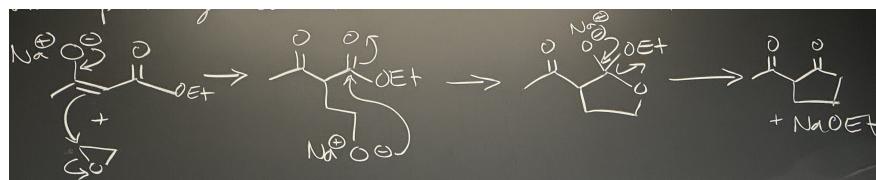


Figure 1.1: Mechanism depth level 1 (arrow pushing).

- Equivalent level: 5.47 & undergrad organic.
- Example: Figure 1.1.
 - In every step that we push arrows, we start at a region of high electron density, we make and break sequential bonds, and we leave the negative charge on an electronegative atom.
 - Once we have completed one step, we can start again from a new region of high electron density, making and breaking bonds, and drawing the product.
 - We repeat this process again and again until we reach the final product.
 - Arrow pushing conserves net neutral charges on molecules.
- Aside: Arrow types.

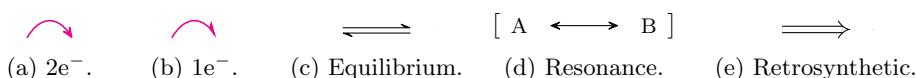


Figure 1.2: Arrow types in arrow pushing.

2. Determine the transition-state structures.

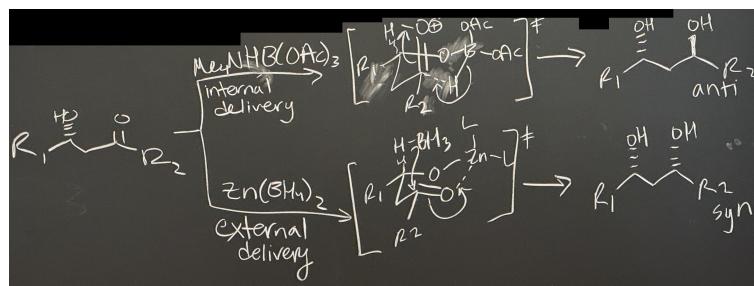
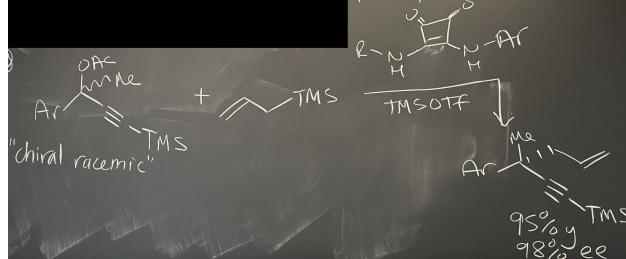


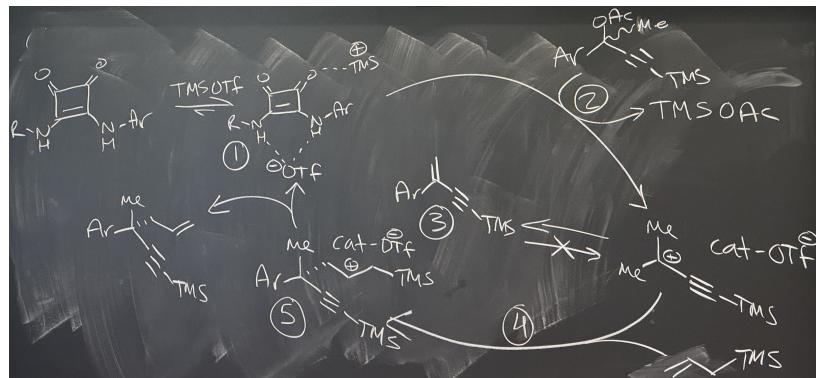
Figure 1.3: Mechanism depth level 2 (transition states).

- Equivalent level: 5.47 & undergrad organic, as well.
- Can't observe these directly — infer from observed selectivities (stereo-, regio-, etc.).
- Example: Figure 1.3.
 - Reacting a β -ketol with two different reducing agents. We can infer the structure of the transition state from the stereochemistry of the product.
 - Internal delivery of tetramethylammonium triacetoxyborohydride yields an *anti*-diol.
 - External delivery of zinc borohydride yields a *syn*-diol.
- Takeaway: We know that in organic chemistry, transition states should have chair-like structures for stability.
- Since we see chair like structures in Figure 1.3, we can infer that these mechanisms are reasonable. Indeed, they have stood for decades!

3. Determine the energy landscape and the full reaction coordinate.



(a) A reaction.



(b) The full reaction coordinate.

Figure 1.4: Mechanism depth level 3 (full reaction coordinate).

- Equivalent level: This class!
- This level of analysis enables us to...
 - Rationally design experiments that improve the reaction (i.e., conduct methods development and catalysis);
 - Discover new mechanistic principles.
- Example: Figure 1.4.
 - Figure 1.4a depicts a curious reaction: Propargyl acetate (with racemic chirality) reacts with an allyl silane under a squaramide catalyst and TMSOTf (a Lewis acid).
 - Even though the starting material is racemic, we get an enantioenriched allylated propargyl acetate (95% yield, 98% ee) as a product.
- The mechanism (Figure 1.4b) proceeds in five steps.
 - (1) Activate the catalyst to form an intermediate.
 - (2) Engage the starting material to form a tertiary carbocation.
 - (3) This carbocation can off-cycle to form an elimination product.
 - (4) Preferably, however, we engage our nucleophile (the allyl silane) to get a new cationic adduct, counterbalanced by the catalyst-triflate complex.
 - (5) The adduct goes on to eliminate our product and regenerate the starting intermediate.
- This mechanism originated from a beautiful mechanistic study by this paper's authors. Let's discuss some of their insights.
 - (1) This complex is the **resting state**.
 - Analytical technique(s): Binding experiments between the catalyst and TMSOTf.
 - This is a thermodynamic insight.
 - (2) This step is the **rate-determining step**.
 - Analytical technique(s): The rate law (a kinetic parameter) and **Hammett plots**.
 - (3) This step is an irreversible side reaction.
 - Analytical technique(s): Competition experiments.
 - Since this step is post-RDS in the mechanism, it is quite difficult to study.
 - Takeaway: It is easy to see things between the resting state and RDS, but everything after the RDS is like magic. These steps are very hard — but very important — to probe. Indeed, knowing how and where side reactions originate provides clues on how to stop them!
 - (4) This step is the **stereo-determining step**.
 - Analytical technique(s): The kinetic isotope effect (review this from CHEM 2020!!).^[1]
 - Revealed that stereoinduction was due to noncovalent interaction (NCIs) between the catalyst and intermediate.
 - Usually, your stereo-determining step is your RDS, but not in this regime. It is very hard to optimize a post-RDS, stereo-determining step.
 - (5) This intermediate is stabilized due to hyperconjugation from silicon.
 - Analytical technique(s): β -silicon effects and α -silicon effects.
- We will learn all of the techniques mentioned above in this class.
- Impact of this paper.
 - It's one of the first enantioselective S_N1 reactions.
 - It has a decoupled RDS and stereo-determining step, but gets high ee regardless.
 - This was an unprecedented result, and it changed the way we as chemists think about optimizing entantioselective reactions.
 - Reference: Wendlandt et al. (2018).

¹KIEs should probably be used in our end-of-class mechanistic proposal, will likely be used in our research, and *can* probe post-RDS steps.

4. Computationally determine the entire multidimensional energy surface.

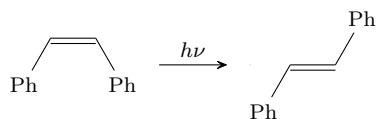


Figure 1.5: Mechanism depth level 4 (full energy manifold).

- Currently only possible for very simple systems.
- Example: Figure 1.5.
 - This is a transformation under light from a *cis*-olefin to a *trans*-olefin.
 - The authors tracked the reaction with femtosecond (10^{-15}) Raman spectroscopy.
 - Reference: Takeuchi et al. (2008).
- Full computational modeling is a pipe dream that would hugely enable our work as chemists.
- **Resting state** (of a catalyst): The state of a catalyst such that if you took an NMR of the reaction mixture at any given time, 95% of the sample would look like this.
- **Rate-determining step.** *Also known as rate-limiting step.*
 - Important because if you can speed it up, you can speed up the whole thing!
- **Rate law:** A measure of how the rate of reaction is influenced by the concentration of different components.
- **Hammett plot:** A mechanistic tool to probe what the rate-determining step is.
- **Stereo-determining step:** The step in a reaction mechanism that sets the stereochemistry of the final product; the ee of this step is the ee of the product.
- Takeaway: Keep in mind these various levels when we're trying to work out a reaction!
- Online tool: Reference Resolver!!
 - Give it the journal, year, and page number, and it brings us to the article.
 - There is a website, but also a browser plugin worth getting.
- Now that we've discussed the kinds of mechanisms, let's talk about what a mechanism can and can't do for us.
- A mechanism *can* tell us...
 - Thermodynamics and equilibria: Identity and structure of the ground state species;
 - Kinetics: Identity and structure of the transition state (TS) structures *relative* to the ground state structures;
 - We can't identify anything about the transition state in absolutes, but we can take educated guesses about intermediates and infer their approximate form.
 - Intermediates: Evidence of reaction intermediates;
 - Example: The tetrahedral intermediate.
 - Such intermediates are often called **metastable**.
 - RDS: Insight into selectivity and RDS's.
- **Metastable** (state): An intermediate energetic state within a dynamical system other than the system's state of least energy. *Also known as unstable equilibrium.*
 - A rectangular prism standing on its end under the force of gravity is metastable.

- A mechanism *cannot* be proven.
 - Mechanisms are hypotheses or proposals that can only be *disproven* or *supported*.
 - This is because experimental data often fits several possible mechanisms; there might be a hidden secret mechanism that we never thought of.
 - In sum, a mechanism is an interpretation that is consistent with *all* the data.
 - If a mechanism doesn't fit our data (even a little bit), either our mechanism is missing something (maybe a little something) or our experiment is flawed (and we need to rerun it or run something else).
- Best practices.
 - The best mechanisms provide *testable* predictions.
 - If a mechanism doesn't provide testable predictions, it is not a useful model.
 - If it's not useful, it's not grounded in good scientific practice.
 - The best experiments disprove a mechanistic proposal.
 - In practice, we list all possible mechanisms and try to disprove them with experiments.
 - When we submit to a journal, we do not say that our mechanism is proven, but we state our reasoning and our reviewers try to think of other mechanisms that could fit the data.
- Aside: Both Alex and Masha care about how scientists actually do science and how science can be done ethically.
 - They want this to be a practical class that would enable us to go in the lab and run any of these experiments.
- We study mechanisms to...
 - Ensure a safe, robust (reproducible), and scalable process;
 - This is especially important in process chemistry.
 - Human consequences of failing at safety, scale, and/or robustness:
 - Your ammonia plant could explode; it is essential to watch any runaway exotherms in a mechanism and control them!
 - Your drug might not make it to market if its synthesis can't be scaled up.
 - Improve reaction features such as yield, selectivity, and greenness;
 - Expand scope and enable predictability;
 - Think about reactions we run daily, such as the Suzuki coupling. It always works, and it's easily applicable in a wide range of settings *because* we understand the mechanism.
 - Understand systems on a molecular level.
 - Masha takes 30 seconds to preach about how mechanisms are critically important knowledge that will be passed down the generations.
- Aspects of mechanism: Consider the S_N2 reaction, Br⁻ + Me-I → Br-Me + I⁻.



(a) Orbitals.



(b) Energy surface.

$$\frac{d[\text{MeBr}]}{dt} = k[\text{MeI}][\text{Br}^-]$$

(c) Kinetics.

Figure 1.6: Aspects of mechanism.

- Three things we can consider in this mechanism are the orbital interactions, the potential energy surface along the reaction coordinate, and the kinetics.

Week 2

Bonding Models

2.1 Bonding Models 1

- 9/10:
- Lecture 1 recap.
 - Aspects of mechanism.
 - Orbitals, energy surface, and kinetics.
 - Masha redraws Figure 1.6.
 - These are the three main pictures that we'll learn about.
 - Today, we'll focus on orbitals.
 - Today: Bonding models.
 - Reading: Anslyn and Dougherty (2006), Chapter 1!!
 - **Bonding:** How electrons are shared between nuclei.
 - This determines all of molecular structure and reactivity (which is the name of this class, and underpins all of organic chemistry!).
 - From bonding, there arise concepts such as nucleophilicity, electrophilicity, etc.
 - There are several levels of bonding theory / models that we'll talk about today.
 - Caveat: *All* of these models are no more than *approximations* of reality that are useful to us.
 - Lecture outline.
 1. Lewis structures.
 2. VSEPR.
 3. Valence Bond Theory (VBT).
 4. Molecular Orbital Theory.
 5. Qualitative Molecular Orbital Theory (QMOT).
 - Lewis structures.



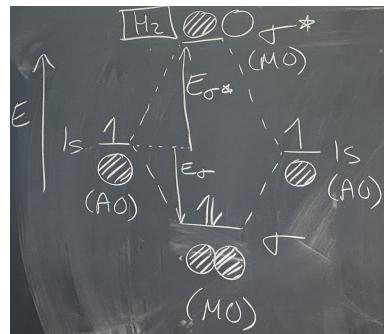
Figure 2.1: Lewis dot structures.

- Developed in 1916 by G. N. Lewis.
 - He was nominated 48 times, but never won the Nobel Prize because some people on the review committee didn't like his "interesting personality."
- In this model, we use dots to — on paper — indicate where electrons are in bonds.
- From these **Lewis dot structures**, people developed the "stick structures" that we still use today.
- Lewis structures are very useful in identifying the number of bonds and lone pairs.
- Valence Shell Electron Pair Repulsion (VSEPR).
 - Developed 1939-1957.
 - Key finding: Electrons in bonds repel each other, so you maximize the distance between bonds.
 - This let us go beyond Lewis structures into things like explaining tetrahedral carbon (and its 109.5° bond angles).
 - Issues develop when we try to rationalize other molecules.
 - For example, isobutane has 110.6° Me–C–Me bond angles. The VSEPR purists will cite "sterics."
 - As another example, NH₃ has 107 H–N–H bond angle. The VSEPR purists will cite "lone pair is big."
 - Really, these were just excuses by the VSEPR purists for a bad model, and what we really needed was a new model.
- Valence Bond Theory (VBT).
 - Developed by Linus Pauling, with his seminal paper in 1931.
 - For this work and some other stuff, he won the Nobel Prize in Chemistry in 1954.
 - To be historically accurate, Pauling built off the work of Heitler and London (1926).
 - However, Pauling was the person to both put everybody else's work all together and be visible enough to take the credit.
 - Additional takeaway from Pauling's biography: Don't make your whole life about your work. For example, Pauling was shunned by many of his colleagues after he got into nuclear proliferation, but now we say he was so brave. He even won the Nobel Peace Prize!
 - Takeaway on Pauling vs. Lewis: It pays to not be a jerk. Lewis died via cyanide poisoning (may have been an accident, but was probably suicide).
 - This is a quantum mechanical (QM) description of Lewis structures.
 - Central tenet: Each atom contributes 1 valence electron in a QM-derived atomic orbital (AO).
 - Shows that electrons are delocalized between atoms, and where two electrons overlap and localize is a chemical bond.
 - In other words, electrons are not restricted to tight orbitals.
 - Many concepts arise within VBT until the advent of MO theory.
- VBT was key for many conceptual innovations, such as **hybridization**, **electronegativity**, and **resonance**.
- **Hybridization:** The mixing of orbitals on the same atom to make new orbitals.
 - Specifically, we can take a linear combination of AO waveforms (or AOs).
 - More directional orbitals give you better overlap and therefore stronger bonds.
 - Example: A linear combination $s + p_y + p_x + p_z$ yields four sp^3 -hybridized orbitals. That's four orbitals with uneven lobes. We can draw all of these on top of each other, and from *there*, we get the tetrahedral carbon.

- We always like new models that agree with old models; this is called a **sanity check**.
- We can also calculate something called the **hybridization index**.
- **Hybridization index:** The number i in the following formula, expressed as a function of the experimentally determined bond angle θ . *Denoted by i . Given by*

$$1 + i \cos \theta = 0$$
- Example: NH_3 has a hybridization index of 3.4.
- Example: H_2O has a hybridization index of 4! That's why it has the tiny bond angle. The remaining s -character is localized on the oxygen, and that's why we say that oxygen is electron dense and nucleophilic.
 - Would this similarly predict that H_2O has longer bonds than NH_3 ??
- **Electronegativity:** The power of an atom to attract electrons to itself.
 - There are different scales for this. We probably used the **Pauling scale**, but there is also a **Mulliken scale**.
 - More electronegative atoms have lower energy orbitals.
 - This is summarized via the **inductive effect**.
- **Inductive effect:** The withdrawing of electron density through σ -bonds.
 - Example: ACN . We think about nitrogen having a partial negative charge and carbon having a partial positive charge. This results in a dipole.
 - Takeaway: Dipoles arise from electronegativity in VBT!
- **Resonance:** The superposition of several Lewis structures.
 - Example: Consider an α, β -unsaturated ketone. Its resonance structure is a zwitterionic intermediate, and a second resonance structure is a different zwitterion. We have three resonance forms, so that predicts more stable than something with less resonance structures. It also identifies our positive and negative reactive sites.
 - Resonance usually happens through π -networks, but it *can* happen through σ -networks.
 - Takeaway: Delocalization of electron density leads to stability.
 - Know your rules for drawing good resonance structures.
 - We only move bonds, not atoms (no nuclear motion).
 - Prefer to have the least separation of charge.
 - Put the more negative charge on the more electronegative atoms.
- Limitations of VBT.
 - Over time, some key experimental findings emerged that VBT couldn't explain. These results motivated people to develop a new model to explain these rare cases.
 - Nowadays, exceptions to VBT are not so rare.
 - Remember: If a model can't explain certain cases, it's not a useful model.
 - Maxim: Not predictive = not useful.
- Here's a list of the limitations of VBT.
 - Doesn't account for unusual stability/instability (e.g., aromaticity and antiaromaticity).
 - No antibonding orbitals (i.e., no explanation of interactions between molecules).
 - When a nucleophile attacks a ketone, the interaction is with the antibonding orbital of the ketone. Forming a new bond involves populating an antibonding orbital.
 - Thursday is all about aromaticity, and modern ways to conceptualize it.

- This leads to the mother of all bonding models, Molecular Orbital Theory.
 - Central tenet: Molecular orbitals (e.g., σ , σ^* , π , π^*) arise from linear combinations of atomic orbitals (in Orgo, this is s & p ; we won't consider d -orbital effects so much).
 - We consider the electronic structure of the whole molecule, not just atoms or bonds.
 - We focus on key molecular orbitals such as the HOMO and LUMO.
 - We also get **group orbitals**: Leads into QMOT, which is MOs for prototypical groups.
- MO theory leads to MO diagrams.

Figure 2.2: MO diagram for H_2 .

- Two atomic orbitals interact to fill two molecular orbitals.
- We fill the bonding orbital with all the electrons that come in (in this case, 2).
- The energy of stabilization is E_σ .
- The destabilization energy is E_{σ^*} .
- Read Anslyn and Dougherty (2006) for more rules.
- Notes.
 - $|E_{\sigma^*}| > |E_\sigma|$. Thus, if the antibonding orbitals get populated, the molecule breaks. This is because of nuclear repulsion.
 - The σ -bond is more stable than the $1s$ orbitals by themselves. This is why the H–H bond forms. This kind of analysis allows us to predict whether or not a bond will form.
- Question for us to consider: Why doesn't He–He form?
 - Because its antibonding MOs would be populated.
- Example MO diagram: Ethylene.

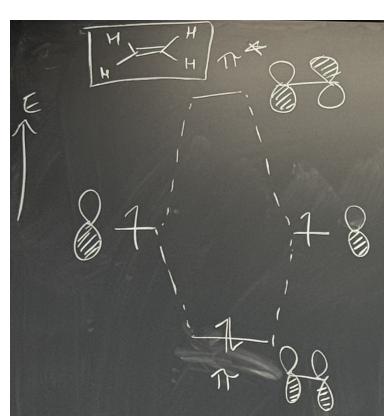
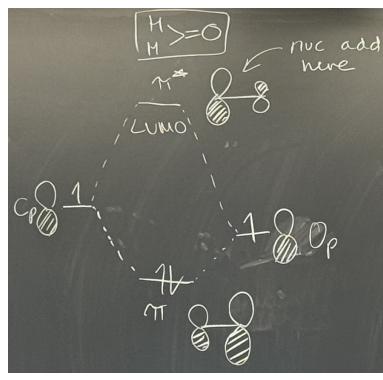


Figure 2.3: MO diagram for ethylene.

- Looking specifically at the π -bond formation.
 - This is why we form a stable π -bond.
 - Example MO diagram: Formaldehyde.
- 
- The diagram illustrates the molecular orbital (MO) formation in formaldehyde (H₂O). At the top left, the Lewis structure H₂O is shown with two hydrogen atoms (H) and one oxygen atom (O). A horizontal arrow labeled 'm' points from the oxygen towards the carbon atom. Below the molecule, several atomic orbitals (AOs) are depicted as pairs of overlapping circles. On the left, a carbon p-orbital (C_p) is shown with one lobe filled with diagonal lines. On the right, an oxygen p-orbital (O_p) is shown with two lobes, both filled with diagonal lines. A dashed line labeled 'LUMO' connects the C_p orbital to the lower-energy O_p orbital. In the center, a carbon s-orbital (C_s) is shown with a single lobe filled with diagonal lines. To the right, a hydrogen s-orbital (H_s) is shown with a single lobe filled with diagonal lines. A dashed line labeled 'nuc add here' points to the oxygen atom. At the bottom, a pi bonding orbital (π) is shown with two horizontal pairs of overlapping circles, one pair above the carbon atom and one pair below it, both filled with diagonal lines.
- Figure 2.4: MO diagram for formaldehyde.
- We mix a C_p AO and a (lower energy) O_p AO.
 - These orbitals interact less well than those in ethylene due to their difference in energy.
 - We benefit from constructive phasing, but the lobes are much bigger on oxygen.
 - In the antibonding orbital, the lobes are much bigger on carbon.
 - Principles revealed by this MO diagram.
 - Closer energy AOs give stronger mixing, resulting in lower energy MOs. Lower energy MOs are more stabilizing.
 - More electronegative atoms have lower energy atomic orbitals.
 - The π -orbital is asymmetric because its energetically more similar to O_p than C_p.
 - In other words, it's going to look more like the O_p orbital.
 - One more way of stating this is that the coefficient of oxygen in the LCAO is bigger.
 - We know that the LUMO (frontier orbital) interacts with nucleophiles. The lobe of the LUMO is bigger on carbon, hence why we react there.
 - Qualitative MO theory (QMOT).
 - All about forming group orbitals for common functional groups or motifs.
 - Essentially, we may not need to calculate MOs for the whole molecule to find out how every carbonyl reacts; we can trust that carbonyl group orbitals are decently conserved.
 - There are a bunch of rules for how to form a QMOT diagram.
 - See Table 1.7 in Anslyn and Dougherty (2006) for building QMOT diagrams.
 - This is the basis of **Walsh diagrams**.
 - We can build group MOs from linear combinations of *s* & *p* AOs.
 - **Walsh diagram:** A representation of an MO diagram as a function of geometric distortions.
 - This matters because geometry affects orbital overlap, which can be destabilizing or stabilizing.

- Example QMOT diagram: CH_3 .

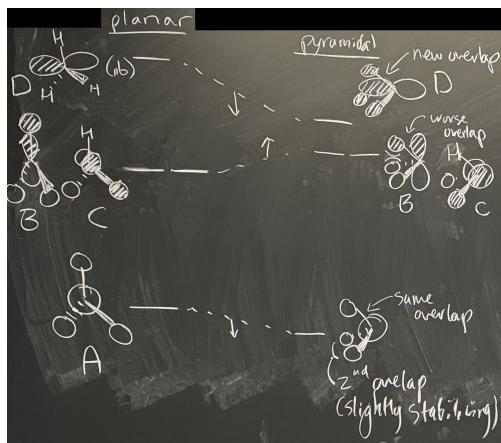


Figure 2.5: QMOT diagram for CH_3 .

- Key question: What geometry of CH_3 is favorable?
- Masha defines axes.
- Undetermined yet if this is a radical, cation, or anion. We'll get there!
- We look at a planar set of orbitals first.
 - A.** All phases in sync, all s orbitals.
 - B.** Phases align top to bottom with the p_x orbital of carbon.
 - C.** Phases align in and out of the board with the p_y orbital of carbon.
 - D.** Nonbonding; just the p_z orbital.
- There are also **E**, **F**, and **G** orbitals that are energetically above these, but we won't draw them for now (because we won't fill them with electrons in the carbocation, carbanion, or carbon radical).
 - The **E**, **F**, and **G** orbitals will have the opposite phasing of the lower orbitals!
- We now draw an analogous, pyramidal set of orbitals.
 - A.** Overlap is *slightly* more favorable because we have a secondary orbital interaction between the hydrogens now. The C–H overlap stays the same.
 - B.** Worse overlap. We're losing a **primary** interaction instead of gaining a **secondary** one, so the energy of **B** actually goes up *more* than **A** went down. We also get some destabilizing secondary interaction between the H orbitals.
 - C.** Just like **B**, we get worse primary overlap, and new interfering secondary overlap.
 - D.** Gets stabilized the *most* significantly! This is because we've taken something with no bonding interactions and *created* bonding interactions between the p -orbital and the hydrogens.
- Relationship between QMOT and Walsh diagrams: A Walsh diagram is a QMOT diagram with everything connected.
- Now how do we fill electrons?
 - Consider the CH_3^+ cation: We have 6 electrons, so we populate the planar orbitals because it's more stable overall.
 - Consider the CH_3^- anion: We have 8 electrons, so we populate the pyramidal orbitals because *they're* more stable overall.
- This rigorous prediction of conformation is the benefit of this model.
- We can also use this model for other isostructural molecules.

- Examples.
 - NH₃: 8 electrons, pyramidal.
 - BH₃: 6 electrons, planar.
 - ·CH₃: 7 electrons, *slightly* planar.
 - But this is a special case only for ·CH₃; any other radical is pyramidal.
- Primary (orbital interaction): An interaction between orbitals on adjacent atoms in a molecule.
- Secondary (orbital interaction): An interaction between orbitals on atoms that are separated by one other atom in a molecule.
- What is quantitative about QMOT?
 - There is a lot more depth in Anslyn and Dougherty (2006). You can calculate the actual potential energy surface and figure out these conformations exactly.
- Example QMOT diagram: CH₂.

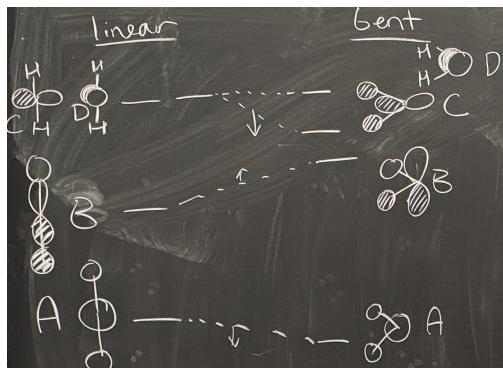


Figure 2.6: QMOT diagram for CH₂.

- Two geometries: Linear and bent.
- Linear.
 - A. Linear chain of *s*-orbitals with matching phases.
 - B. Linear chain of matching phases orbitals, with *p_x* on carbon.
 - C. One of the other *p*-orbitals, with no phasing.
 - D. The last remaining *p*-orbital, again with no phasing.
- Bent.
 - A. Goes down slightly. We kept primary, and added secondary.
 - B. Losing primary overlap and gaining a destabilizing secondary interaction; higher *E* like before.
 - C. Adding *significant* constructive interference. Biggest effect again!
 - D. Staying the same; no bonding interactions to begin or end with. We don't consider secondary interactions when there's no density at all there.
- Example species.
- H₂O: 8 electrons, bent.
 - Note that this model predicts that H₂O has nondegenerate lone pairs, which has been experimentally verified!
 - Bulk water acts as if it has degenerate lone pairs. We can read Anslyn and Dougherty (2006) about this, but otherwise, it's outside the scope of the class.

- CH₂ (a **carbene**): 6 electrons, a mix of linear and bent!
 - We'll return to carbenes in a few weeks.
 - We'll define **triplet** (2 electrons in different orbitals) and **singlet** (2 electrons in same orbital) carbenes later.
 - Triplet is 136°, and singlet is 105°, so the triplet is more linear and the singlet is more bent! The triplet has reactivity more characteristic of the linear orbital picture, and the singlet has reactivity more characteristic of the bent orbital picture.
 - The triplet is more favored by 9 kcal/mol
- Last page of notes: QMOT for formaldehyde by combining carbene with an oxygen atom. Masha will post on Canvas.
- Masha reiterates the textbook!!

References

- Anslyn, E. V., & Dougherty, D. A. (2006). *Modern physical organic chemistry*. University Science Books.
- Takeuchi, S., Ruhman, S., Tsuneda, T., Chiba, M., Taketsugu, T., & Tahara, T. (2008). Spectroscopic tracking of structural evolution in ultrafast stilbene photoisomerization. *Science*, 322(5904), 1073–1077. <https://doi.org/10.1126/science.1160902>
- Wendlandt, A. E., Vangal, P., & Jacobsen, E. N. (2018). Quaternary stereocentres via an enantioconvergent catalytic S_N1 reaction. *Nature*, 556, 447–451. <https://doi.org/10.1038/s41586-018-0042-1>