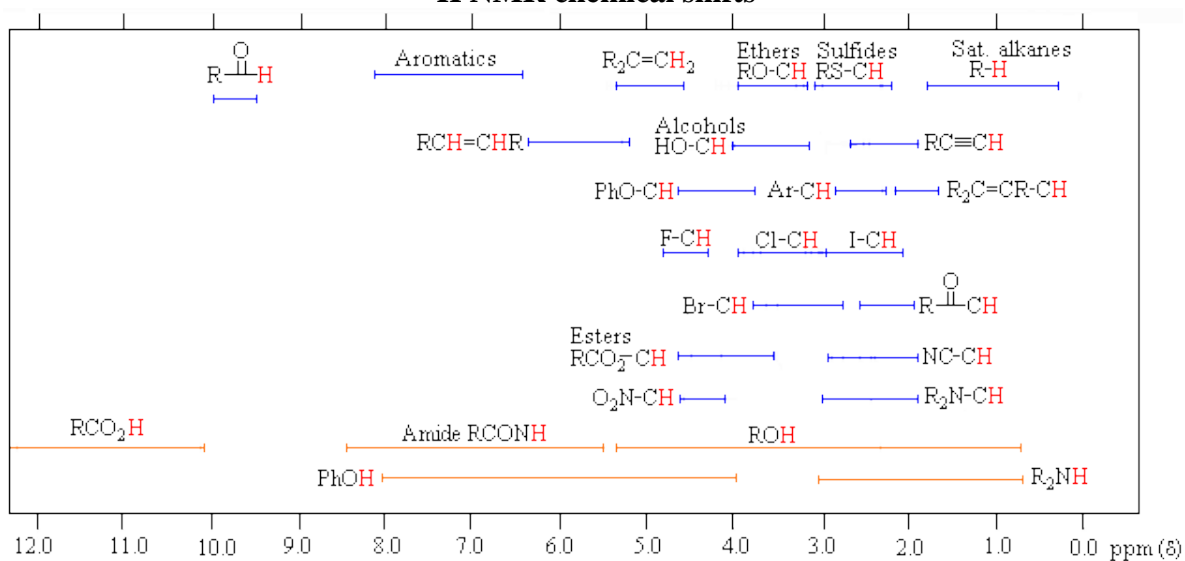




¹H NMR chemical shifts



CHE-334 questions

Part I: 5 of 7 questions (110 pts.)
 Part II: 3 of 5 questions (45 pts.)
 Total exam: 8 of 12 for 155 pts.

CHE-534 questions

Part I: 6 of 7 questions (120 pts.)
 Part II: 3 of 5 questions (45 pts.)
 Total exam: 9 of 12 for 165 pts.

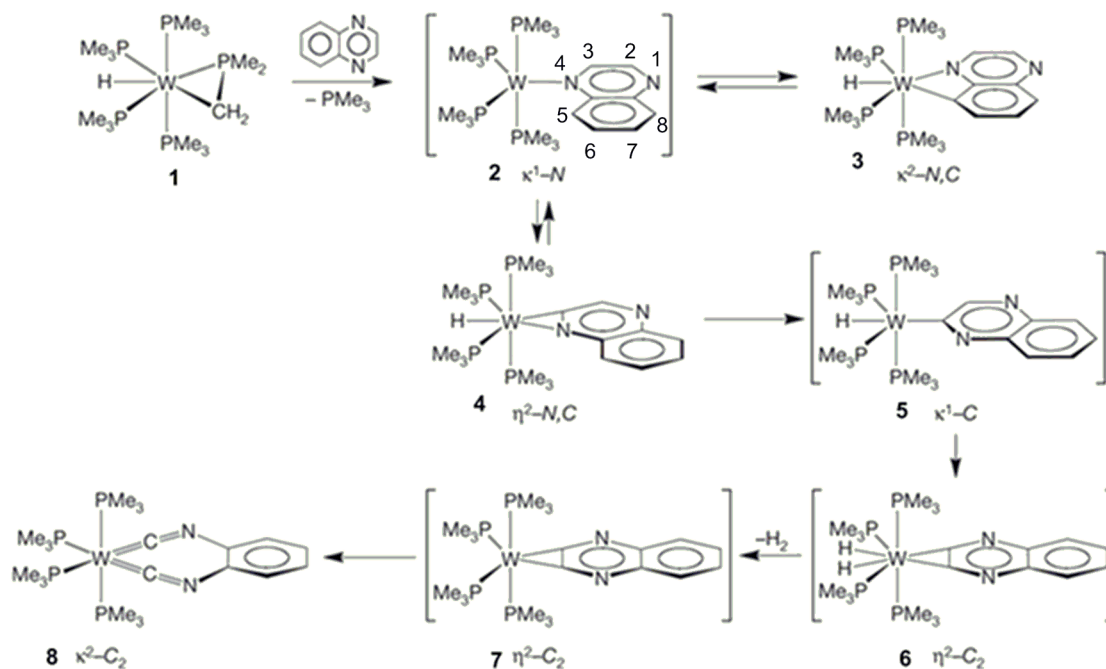
Part I: Questions from Class Presentations

CHE-334: Answer 5 of 7 questions. The first two are worth 25 points and the remaining questions are worth 20 points.

CHE-534: Answer 6 of 7 questions. All questions are worth 20 points.

1. The proposed mechanism for the recent seminal work on C-C bond cleaving of an unstrained aromatic ring is shown below (Aaron Sattler et al. [Nature 2010, 463, 523-526](#)).

Answer 5 of the 6 parts of question 1.



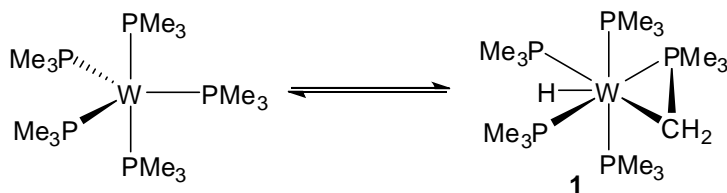
a) The equilibria between **2**, **3** and **4** is a critical entry point to the ultimate goal of reaching complex **8**. In analyzing these two equilibria, **2** to **3** and **2** to **4**, what is the same about these reactions? What makes these processes different? Identify one unifying and one differentiating characteristic. (Do NOT make this more complicated than it is!)

Both equilibria are C-H oxidative addition reactions, but the reactions occur with a different C-H bond of the aromatic (quinoxaline) ring (C-3 C-H in **4**; C-5 C-H in **3**).

b) Some complexes in the mechanism above have a κ² designation while others have a η². What does κ² and η² describe?

κ² is a denticity designation and η² deals with hapticity. Denticity describes the number of atoms from a particular ligand that are coordinated to a metal. These are not consecutive atoms, i.e. atoms that are also bonded to each other. Hapticity deals with the number of consecutive atoms from one ligand that are bonded to a metal.

c) The W reagent, **1**, could also exist as the trigonal bipyramidal structure on the left below. Provide a reason that the structure on the right is favored.



The structure on the left is a d^6 W with five ligands for a total electron count of 16. The structure on the right is a d^4 W with seven ligands for a total electron count of 18. The higher electron count and one that matches the “18 electron rule” probably make the structure on the right more stable or favorable.

For more information see: Hexakis(trimethylphosphine)tungsten(0): synthesis, structure, and reactivity, Daniel Rabinovich, Gerard Parkin, *J. Am. Chem. Soc.*, 1990, 112 (13), pp 5381–5383

As reported in the article, the key novel reaction, the C-C bond cleaving step, occurs with the conversion of **6** to **8**.

d) How did the authors prove experimentally that the transformation of **6** to **7** was important for the formation of **8**?

The authors ran the reaction under an atmosphere of H_2 and that caused a decrease in the yield of **8**. This proved that the release of H_2 in the reductive elimination was a critical step in the formation of **8**.

e) Why might the process to form **7** be important before the W performs the critical C-C bond cleavage to form **8**?

The transformation of **6** to **7** is a reductive elimination and it probably provides the W metal with the necessary electron density to backbond into the C-C bond and eventually cleave it.

f) The authors reported the following experimental information for **8**.

<i>complex 8</i>	^{13}C NMR	IR, CN stretch
	211.4 ppm	1709-1698 cm ⁻¹
<i>normal range for M-CN-R (isocyanide):</i>	151.8-238.7 ppm	2310-1670 cm ⁻¹

What does this say about the bonding relationship between the W-C? Briefly explain.

The relatively high NMR chemical shift and the lower IR stretch suggest that there is considerable backbonding occurring between the W and the C. With more electron donation from the W, the C has a lower bond order with the N and this limits the amount of energy in the C=N bond, thereby lowering the stretching frequency in IR. Likewise a lower C=N bond order limits the shielding of the C from the electrons in N.

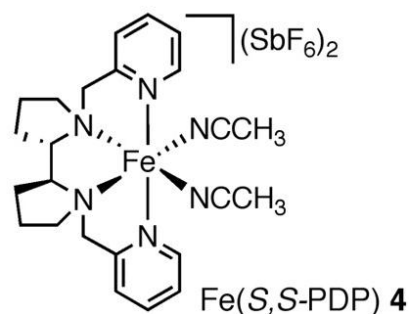
2. The article entitled, “A Predictably Selective Aliphatic C–H Oxidation Reaction for Complex Molecule Synthesis” by M. Christina White et al. (*Science*2007, 318(5851), 783-7) described oxidation reactions with the complex shown below.

a) What is the oxidation state of the Fe?

Fe^{+2}

b) Identify the X and L type ligands on the complex.

All ligands are L type, including the pyridine N's, the pyrrolidine N's and the acetonitrile N's.



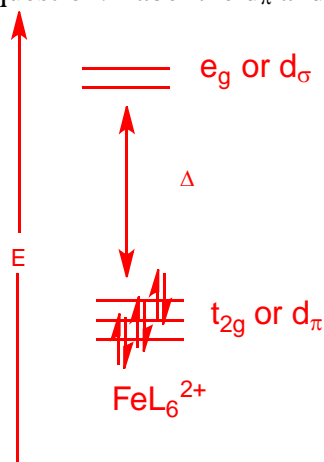
c) What is the total electron count of the Fe in **4**?

18 e^- 's ($d^6 + 6 \times 2 \text{ e}^-$ ligands)

d) What is the coordination number and molecular geometry of the Fe in **4**?

6, octahedral.

e) Draw the electronic orbital diagram for the Fe d orbitals. Include the correct number of electrons based on your answer to part a of this question. Label the d_π and d_σ orbital groups.



f) Although the mechanism of the oxidation processes catalyzed by **4** was unknown, if the substrate and/or oxidant did interact directly with the iron, i.e. inner sphere reactions, what would be the mechanism of ligand substitution and what ligand(s) would be most likely to substitute? Why would this ligand be most likely to leave?

Since **4** is an 18 e^- complex, it would most likely react by a dissociative mechanism. The acetonitrile ligands (CH_3CN) would be the ligand most likely to leave. Since all the other N ligands are part of a tetradentate ligand, they would not be easily replaced since the chelate effect would keep them bound to the iron.

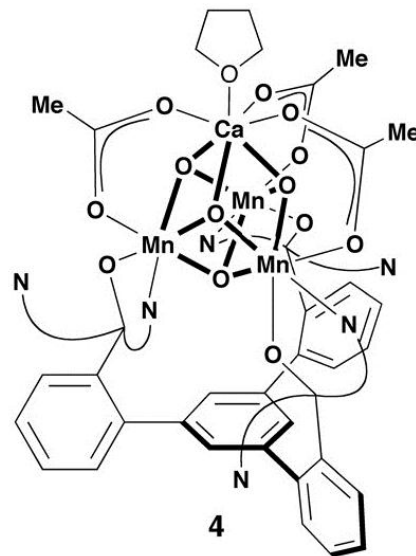
3. The authors of the recent article entitled, "A Synthetic Model of the Mn_3Ca Subsite of the Oxygen-Evolving Complex in Photosystem II" (Theodor Agapie et al. [Science](#) **2011**, *333*(6043), 733-736), detailed the synthesis of the metal cluster complex **4**. Answer 5 of the 6 parts in question 3.

a) The presenters of the article in class showed a method for calculating the approximate formal charge on each Mn in the cluster. Determine the charge by showing that calculation.

X-type ligand analysis:

four oxo (-2) ligands	= -8
three alkoxy (-1) ligands	= -3
<u>three acetate (-1) ligands</u>	<u>= -3</u>
total negative charges	= -14

Ca is +2, so there is a charge of -12 remaining for the three Mn atoms. Therefore each Mn must have an approximate formal charge of +4.



b) What analytical tool did the researchers use to determine the oxidation state of the Mn atoms in the metal cluster? How did they use this tool to determine the oxidation state?

The researchers used X-ray crystallography to determine the Mn atom oxidation state. In particular, they looked at the bond length of the Mn-O bonds and found that these bonds were short and close to the average for a Mn⁺⁴ oxidation state.

c) Why do oxo or alkoxy ligands work well to stabilize high oxidation state metals?

Oxo or alkoxy ligands are π basic ligands so they can donate more electron density to particularly electron deficient metals through their two lone pairs of electrons.

d) What was the effect of adding Ca⁺² to the Mn cluster?

The Ca⁺² is not redox active, so it structurally stabilized the cubane metal cluster, but was not capable of engaging in any electron transfer reactions. This allowed the three Mn atoms in the cluster to attain a high +4 oxidation state and not be prone to redox side reactions.

e) In the context of the photosystem II oxygen-evolving complex and its catalytic process that converts 2 H₂O to O₂ and 4H⁺'s, why is it necessary to have high oxidation state Mn?

The reaction that converts H₂O to O₂ is an oxidation process, so the electrons released from the O will need to reduce another atom. Since the oxidation of H₂O is not an easy process, a rather high oxidation state metal will be necessary to make the process favorable.

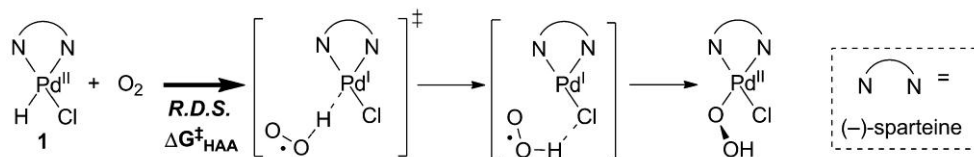
f) If you were conducting this research, what do you see as the next important step to prove the validity of the Mn₃Ca metal cluster model as a mimic of photosystem II?

It would be important to see that the Mn₃Ca metal cluster model can effectively catalyze the reaction of photosystem II that is the oxidation of H₂O to O₂.

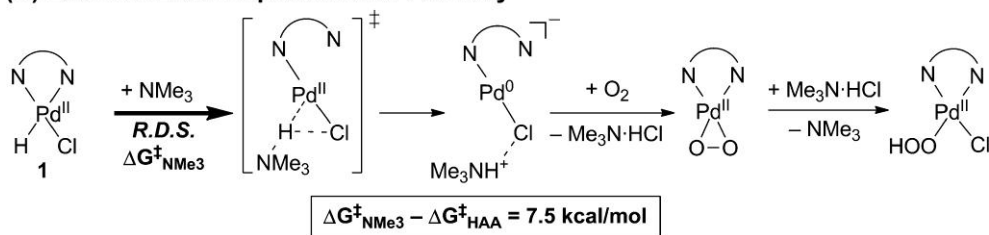
4. Answer the following questions about the article “Reaction of O₂ with [(-)-Sparteine]Pd(H)Cl: Evidence for an Intramolecular [H–L]⁺ “Reductive Elimination” Pathway” by Shannon S. Stahl et al. (*J. Am. Chem. Soc.*, **2011**, *133*, 13268–13271), which we discussed on December 1, 2011.

a) The authors showed the following possible mechanisms (A and B, below) and postulated that the pathways could be differentiated by the effects of O₂ pressure/concentration on the reaction. Why did they see this as critical? Be as explicit as possible.

(A) H-Atom-Abstraction (HAA) Pathway



(B) External Base Deprotonation Pathway

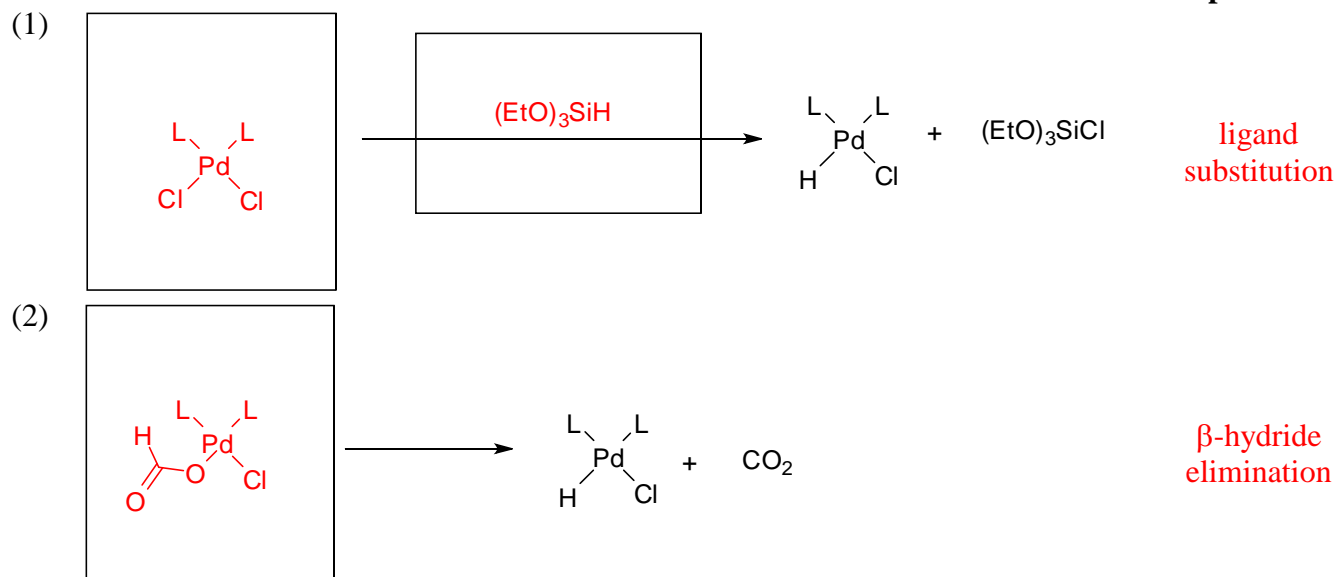


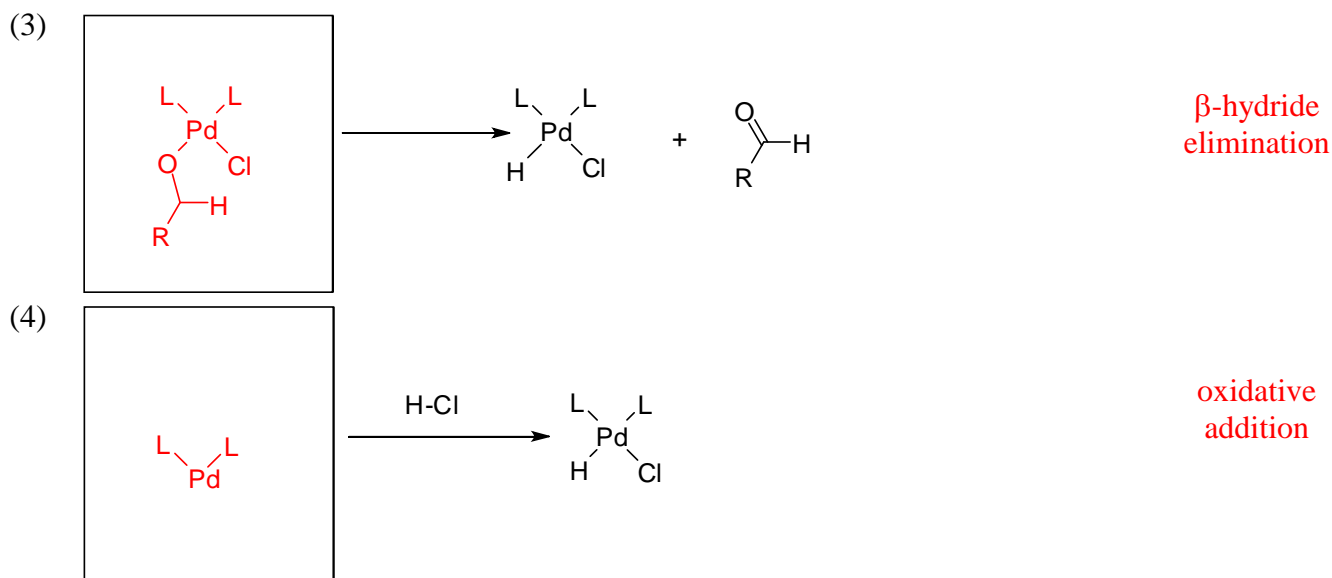
In proposed mechanism A, O₂ is involved in the first and rate determining step, therefore if the amount of oxygen was altered, then the reaction rate would change. In mechanism B, O₂ is involved, but it is not the rate determining step and therefore would not impact the rate of the reaction.

b) One of the key steps in their quest to understand O₂ reactions with (Sp)Pd(H)Cl was to actually generate (Sp)Pd(H)Cl that could then be studied experimentally. In the text, the authors describe basically four procedures that they explored and parts of these procedures are shown in the equations below. Provide the starting materials and reagents as requested for three of the four equations below. Identify the type of reaction process occurring in the three equations you answer.

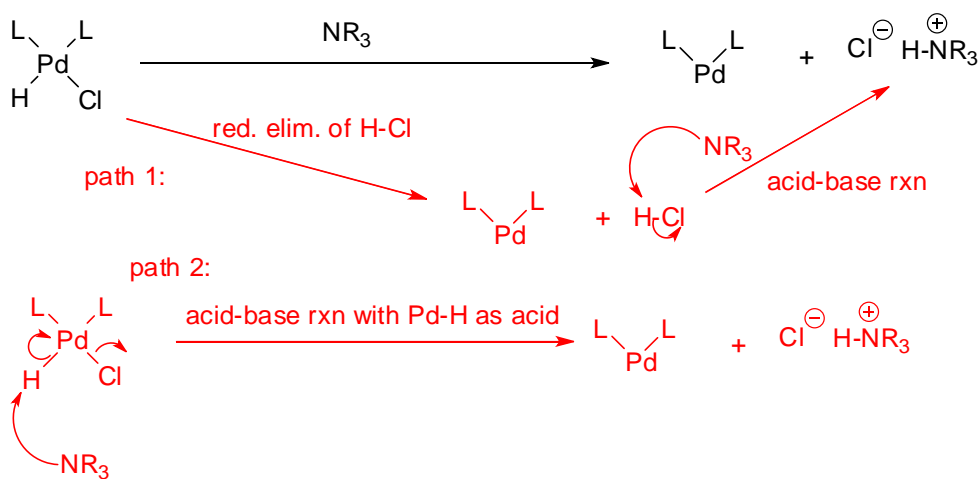
reaction to form (Sp)Pd(H)Cl

type of reaction process



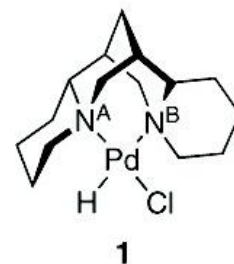


c) As I described in class, there are actually two ways to see the sequence of events in the reductive elimination of a $L_2Pd(H)Cl$ complex to form L_2Pd and $ClHNR_3$. Draw both paths. Use electron flow arrows and/or text as necessary to explain your concept.



d) The authors of the paper computationally determined the $Pd-N_B$ bond to be longer than the $Pd-N_A$ bond in the $(Sp)Pd(H)Cl$ (Sp =sparteine) complex below. What is the likely reason for this difference?

The $Pd-N_B$ bond is trans to the strong σ donor H^- . This strong electron donation, also known as the trans effect makes the $Pd-N_B$ bond lengthen.

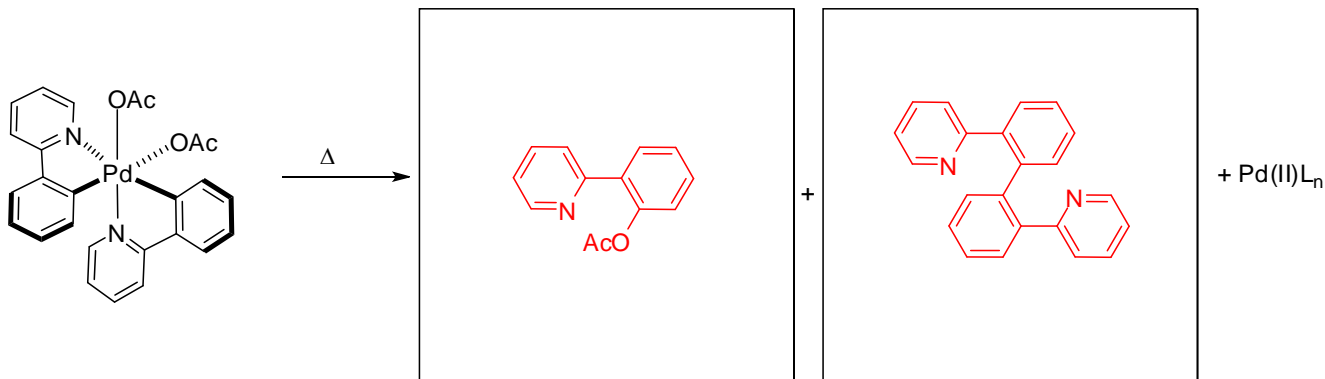


e) Why was the lengthening of the $Pd-N_B$ bond critical in their proposal?

With $Pd-N_B$ lengthening, the bond can break and the free amine can act as a base to deprotonate the H on Pd. That begins the reductive elimination of Pd which provides $Pd(0)$ for the reaction with O_2 .

5. The following questions are based on the work of Melanie Sanford and co-workers as described in a recent article that we reviewed (*J. Am. Chem. Soc.* **2009**, *131*, 10974–10983).

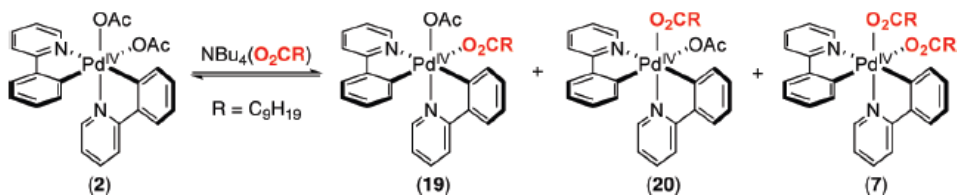
a) The reaction that was studied is shown below. Provide the TWO POSSIBLE ORGANIC PRODUCTS in the boxes to the right. (Note that the focus is on organic products because this course is ORGANOMETALLIC chemistry where the organo comes first!)



b) Although the authors proposed three mechanistic possibilities, they favored a two step process that first involved dissociation of one of the acetate ligands. The authors tried two experiments that demonstrated rapid exchange of one acetate ligand. Briefly describe one of these examples. Be sure to include an equation and the analytical tool that was used to identify the exchange.

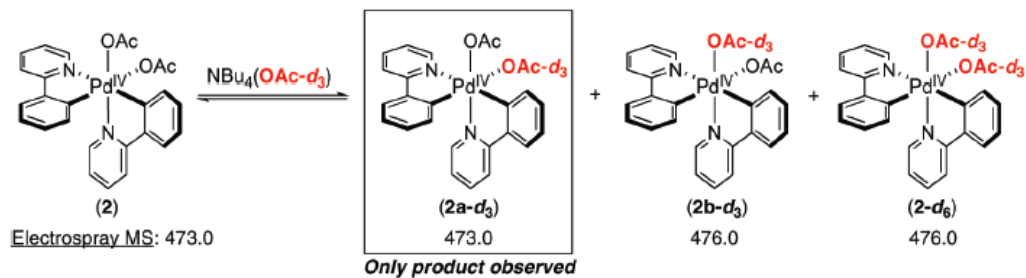
1) Exchange reaction monitored by ^1H NMR.

Scheme 8. Potential Products of Carboxylate Exchange Reaction



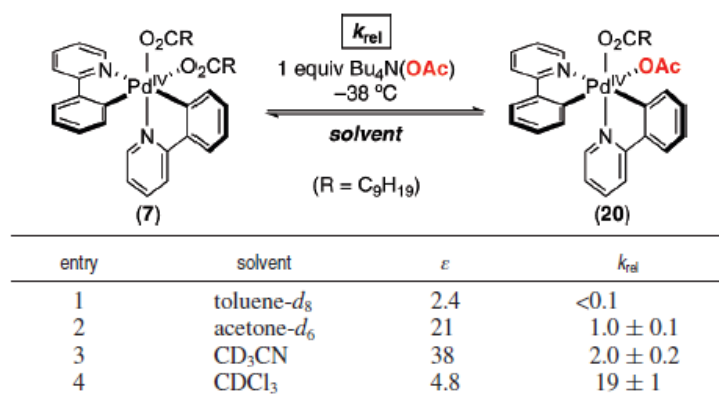
2) Exchange with deuterated acetate ligand and analysis by electrospray ionization mass spectrometry (ESI-MS).

Scheme 10. Electrospray MS Data for Reaction between 2 and $NBu_4(OAc-d_3)$



Another experiment looked at the effect of solvent on the acetate ligand exchange process. The table below illustrates their results.

Table 2. Effect of Solvent on the Rate of Carboxylate Exchange from **7**



c) If the acetate ligand dissociation was the first step in the mechanism, what did the authors expect to see when changing the solvent polarity?

The authors expected that a more polar solvent would enhance the rate of acetate ligand dissociation because the organometallic complex intermediate that formed from acetate dissociation was a charged complex. A more polar solvent should stabilize this charged intermediate.

d) Based on the results in the table, what did the experiment show?

The experiments showed no correlation between the relative rate of the exchange reaction (k_{rel}) and the polarity of the solvent (ϵ , dielectric constant; higher number is more polar). This was counter to what the researchers expected.

e) The article also reported on electronic effects of phenyl ring substitution on the reductive elimination. The results are shown below. What do these results say about the nature of the reductive elimination process and the role of the phenyl group?

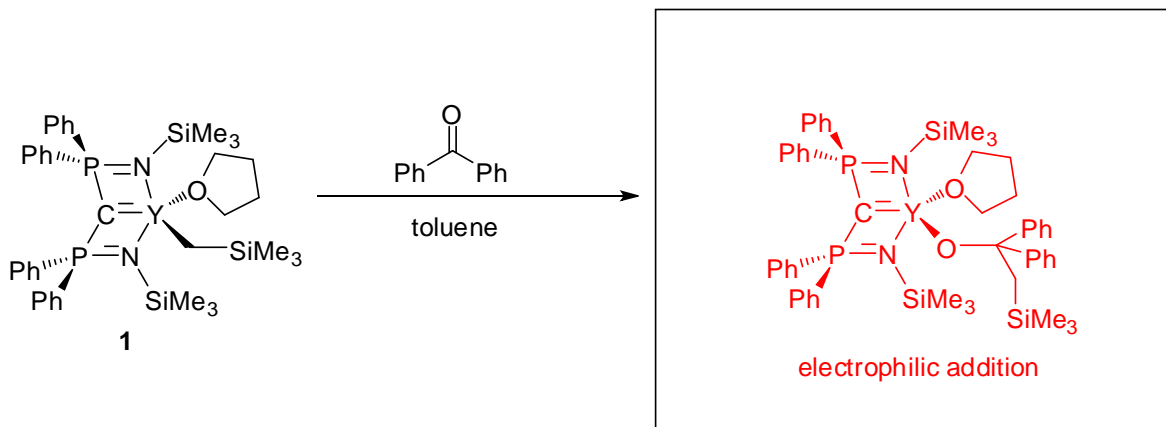
Table 5. k_{obs} for Reductive Elimination from $(Arpy)_2Pd^{IV}[O_2C(p-AcC_6H_4)]_2$

Compound	k_{obs} ($s^{-1} \times 10^5$)
*OMe (46)	$\sim 3^a$
Me (47)	4.81
H (15)	20.0
F (48)	3.64
Cl (49)	36.9
*CF ₃ (50)	$\sim 320^a$

Since the reaction rate (k_{obs}) increases with more electron withdrawing substituents (Cl, CF₃ fastest), this suggests that a more electron deficient phenyl ring is better for reductive elimination. The authors concluded that the phenyl ring is acting as the electrophilic partner in the reductive elimination process; in particular, the reductive elimination that leads to C-O bond formation.

6. The following work was reported by Stephen Liddle and co-workers in the *Journal of the American Chemical Society* ([J. Am. Chem. Soc., 2010, 132, 14379–14381](#)).

a) Provide the product and identify the type of mechanistic process shown below.

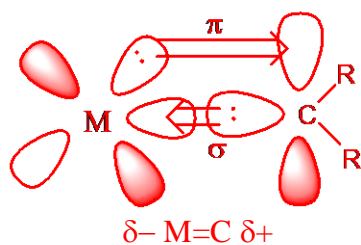


b) What is the generic name of the $\text{C}=\text{Y}$ moiety?

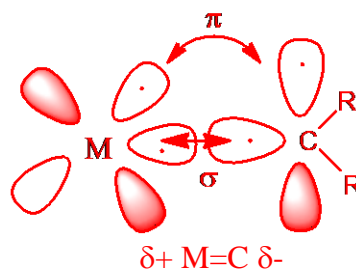
It is a carbene.

c) In class we discussed two versions of organometallic structures with a $\text{C}=\text{M}$ double bond. Provide the name of one of these and draw the electronic structure, i.e. the orbital interactions between the C and the M. Label the σ and π bond. Identify the polarization of the C and M in the example that you choose.

Fischer carbene

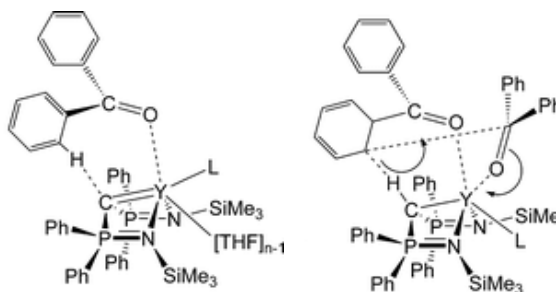


Schrock carbene



d) In one of the reactions studied with the new $\text{C}=\text{Y}$ complex, the researchers proposed the key intermediates shown below. What experiment did they conduct to prove that these intermediates were important and were involved with the rate determining step in the process?

The researchers conducted the reaction with $[\text{D}_{10}]\text{-Ph}_2\text{C}=\text{O}$, that is benzophenone with all protons replaced by deuterium. This caused the reaction rate to slow down considerably as it was harder to break the $\text{C}-\text{D}$ bond than the $\text{C}-\text{H}$ bond. This is an example of a deuterium kinetic isotope effect and it results from the weaker bond vibration of the $\text{C}-\text{D}$ bond versus the $\text{C}-\text{H}$ bond. The heavier D atom is the basis for the weaker bond vibration.

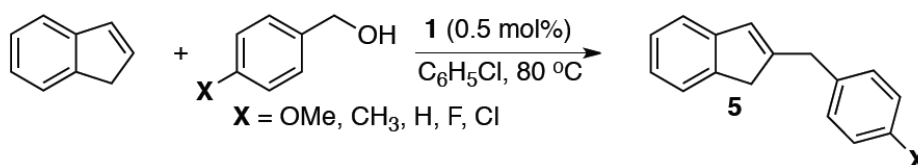


e) The intermediates shown above in part d illustrate a fundamental bonding interaction in chemistry discovered and described by Gilbert N. Lewis. In particular the interaction between O and Y are representative of this type of bonding interaction. Describe this interaction using classical chemistry terminology and briefly explain why the two atoms play their role.

The Y and the O of the benzophenone ($\text{Ph}_2\text{C}=\text{O}$) or THF are engaged in a Lewis acid-base pairing or interaction. The Y is an early transition metal and is particularly electron deficient (d^0) so it is eager to accept electron density. The O has a lone pair of electrons that is available for donation, so it behaves as a Lewis base.

7. In a recent report in *Science*, Chae S. Yi described a new reaction to couple alcohols and alkenes. Answer the following based on our discussion of this report. (Chae S. Yi et al. [Science 2011, 333\(6049\), 1613-1616](#)). Answer 5 of the 6 parts in question 7.

Yi and co-workers reported studying the following reaction in their quest to understand the mechanism of the new reaction that they reported.



By altering X as shown, the researchers generated the Hammett plot below with the triangle dots relating to this particular experiment to form 5.

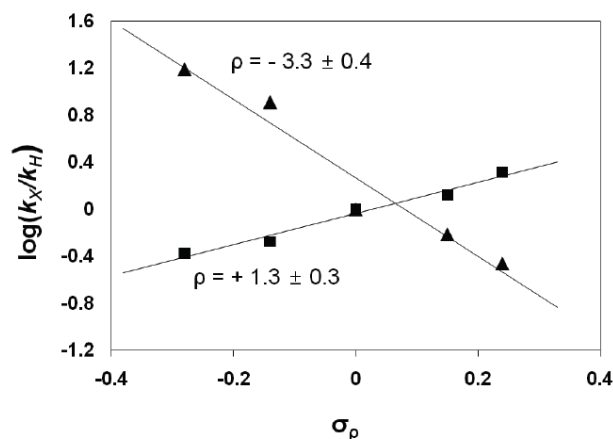


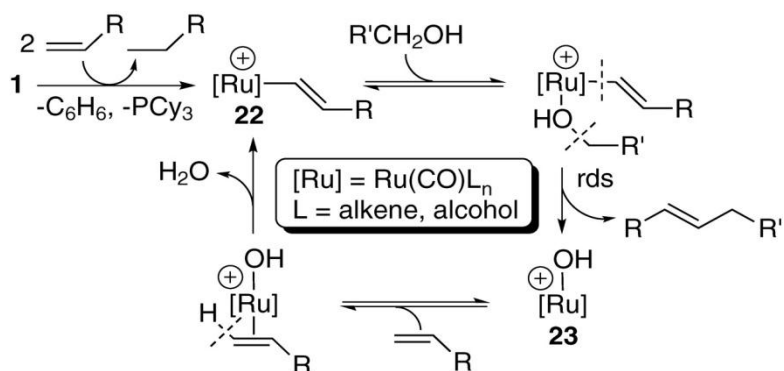
Figure S3. Hammett plot of the alkylation of indene with $p\text{-X-C}_6\text{H}_4\text{CH}_2\text{OH}$ ($\text{X} = \text{OCH}_3, \text{CH}_3, \text{H}, \text{F}, \text{Cl}$) (\blacktriangle), and $p\text{-Y-C}_6\text{H}_4\text{CH}=\text{CH}_2$ ($\text{Y} = \text{OCH}_3, \text{CH}_3, \text{H}, \text{F}, \text{Cl}$) with PhCH_2OH (\blacksquare).

Note: triangles are associated with the substituents listed above in the order listed from left to right.

a) What does the trend from the Hammett plot show and what conclusion was drawn about the mechanism of the reaction?

The plot shows that the reaction was more rapid with more electron releasing groups (OCH_3 and CH_3). Since these groups are on the benzyl alcohol component, this result supports the formation of a carbocation or some electron deficiency on the benzylic position of the molecule. The electron releasing groups would be expected to stabilize an electron deficiency at the benzylic position.

The authors propose the following catalytic cycle based on their mechanistic studies.



b) As noted in the center of the figure, all the Ru complexes are believed to contain a CO ligand, along with alkenes and alcohols. Based on our course discussions, can you suggest another experiment that might be conducted to determine the electronic nature of the Ru metal? Briefly explain what trends might be expected and what they might say about the electronic nature of the Ru metal.

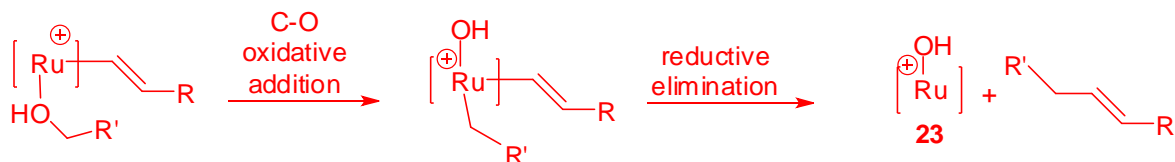
The presence of a CO ligand makes it possible to analyze the various Ru complexes by IR spectroscopy. If the Ru metal was more electron rich, then it would be able to backbond with the CO ligand to a greater extent and this would cause the CO bond order to decrease and the IR stretch to shift to a lower wave number. If the Ru metal was less electron rich, then the converse would be true: decreased backbonding, increased CO bond order and IR stretch at a higher wave number.

The mechanism shown in the article is intentionally abbreviated as the limited mechanistic work does not allow a complete description. Nevertheless, it is possible to propose more details.

c) What is happening in the first step in the main catalytic cycle, i.e. when **22** adds R'CH₂OH?

This is a ligand substitution or ligand association step.

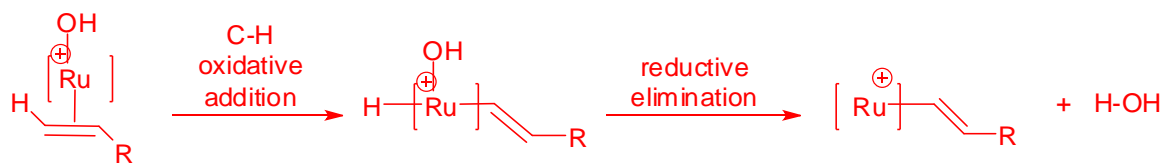
d) The next step is the critical C-C bond forming step. Propose details for this process that forms **23** and R-CH=CH-CH₂-R'. Draw all intermediates and label each step by the type of process occurring.



e) What happens with **23**'s reaction with H₂C=CH-R?

This is also a ligand association or substitution.

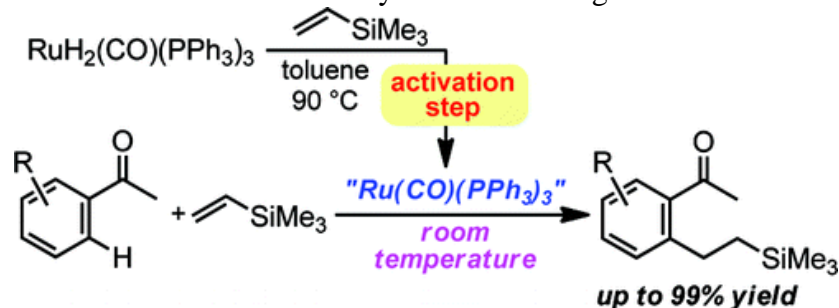
f) Finally the last step in the proposed catalytic cycle could be seen as two steps. Draw these two steps. (Hint: the two steps do change Ru's oxidation state, but because they are complimentary there is no net change in Ru's oxidation state.)



Part II: General Questions

All students complete 3 of 5 questions in this part. Each are worth 15 points.

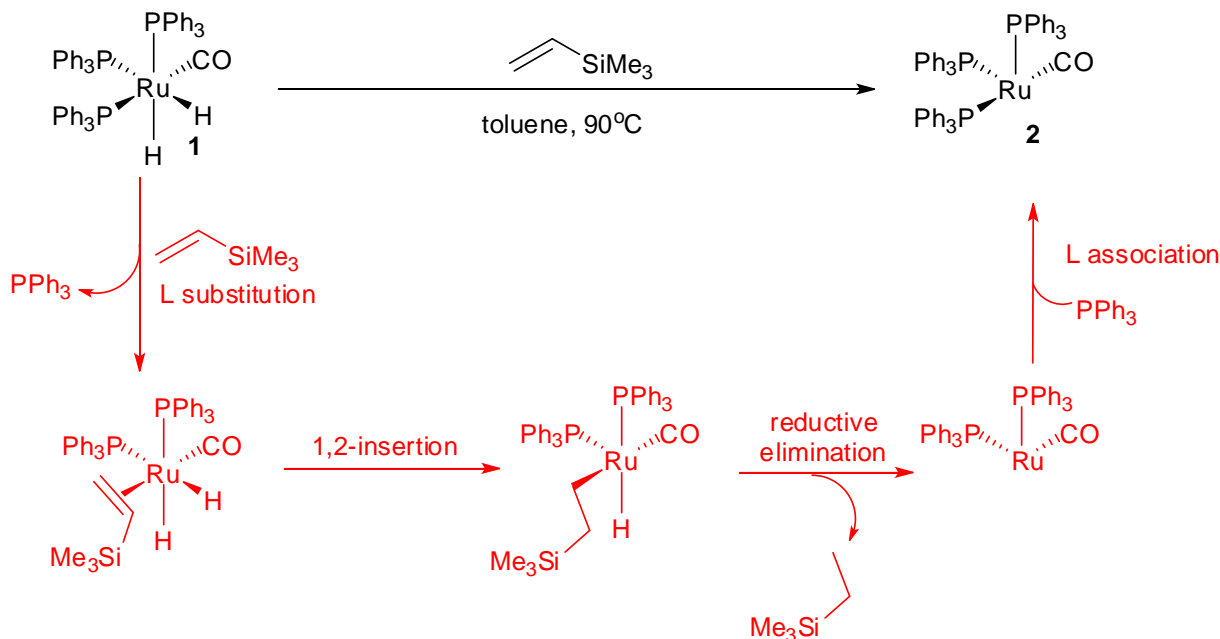
A recent article in the literature described a study of the following reaction:



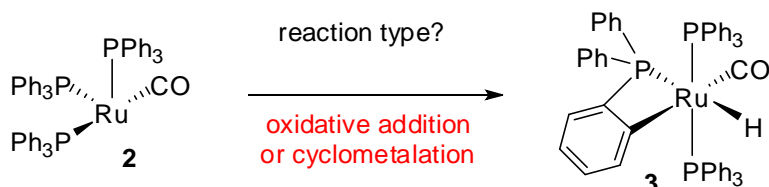
Shinji Murai et. al. *J. Am. Chem. Soc.*, **2010**, *132*, 17741–17750.

The next two questions examine these results in more detail.

8. a) As indicated, the first step of the catalytic process was an activation step for the catalyst, i.e. the transformation of **1** to **2** (below). Propose a mechanism for the activation process. Include all intermediates and label all steps by the type of process occurring.



b) The Ru(0) complex **2** is actually not stable and undergoes the following reaction. What is this reaction type?



9. a) The authors were able to characterize **3** by NMR. In particular they found a signal for the Ru-H in the ^1H NMR. What chemical shift (δ) in the ^1H NMR spectrum would you expect for the Ru-H signal?

-0 to -40 ppm. The Ru-H was actually found at -8.18 ppm.

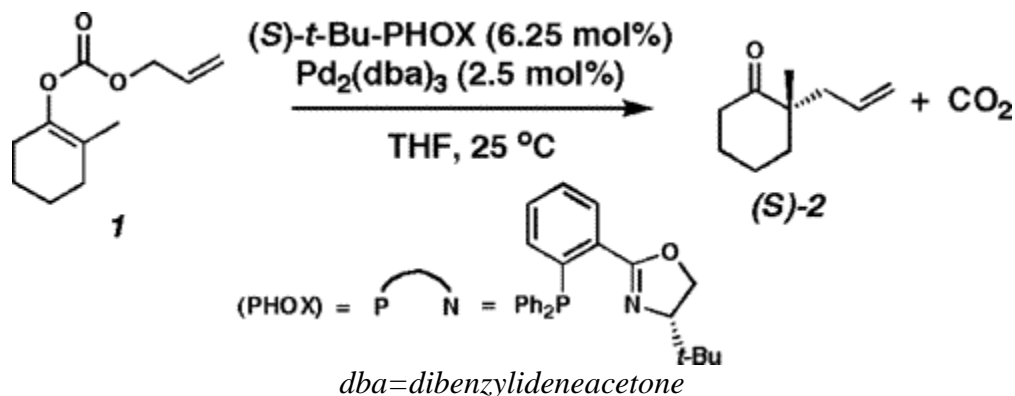
b) The splitting pattern reported for the Ru-H proton was dt or a doublet of triplets. Explain this splitting by describing all the coupling partners that generate the dt.

The dt arises from a large coupling of the H to the trans P ($^2J_{HP}=83.6$ Hz) and a two smaller couplings to each of the cis P's ($^2J_{HP}=26.5$ Hz).

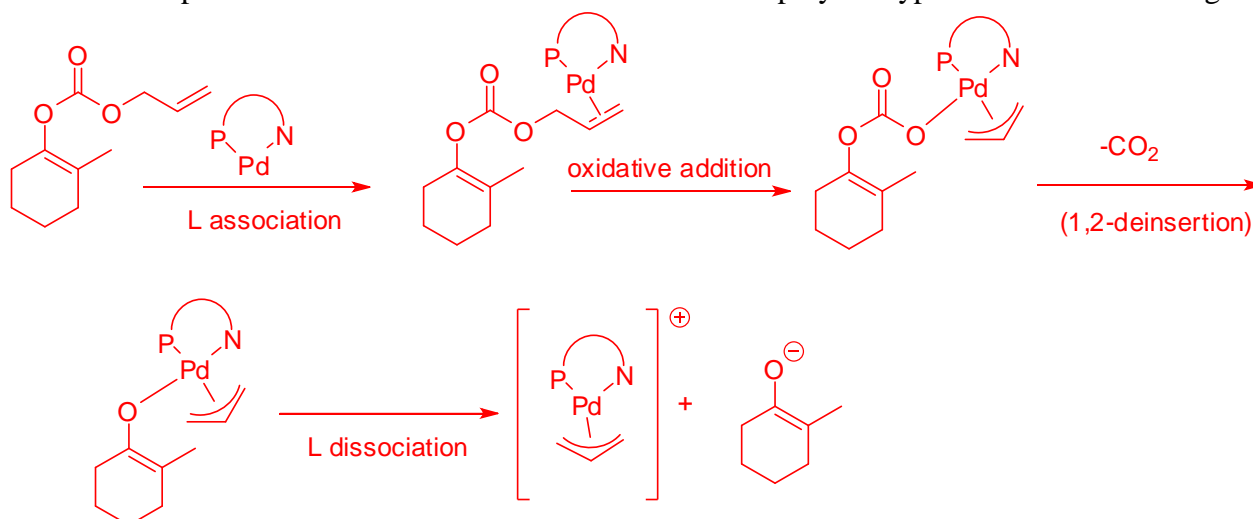
c) The ^{31}P NMR had two signals: $\delta -35.3$ (t, $J_{PP} = 15.2$ Hz) and 52.1 (d, $J_{PP} = 15.2$ Hz) ppm. What does the chemical shift say about the difference in the two phosphorus atoms? Suggest an assignment for the signals to a particular P in complex **3**.

The one at -35.3 ppm is much more shielded than the ^{31}P at 52.1 . This is likely due to more electron density from the Ru metal. It is likely this is the P that has undergone oxidative addition to form the metallocycle structure and is located trans to the H ligand. Furthermore, the splitting to a triplet for the peak at -35.3 ppm suggests two chemically equivalent P's nearby, which would also match the P that is trans to the hydride. Similarly, the signal at 52.1 ppm is a doublet which means only one different P nearby. This would also support the assignment of 52.1 being the two PPh_3 phosphines.

10. The following reaction was studied by Brian Stoltz and co-workers and the results of the study were reported in the *Journal of the American Chemical Society* ([JACS 2003, 129\(39\), 11876-7](#)) and discussed in class.

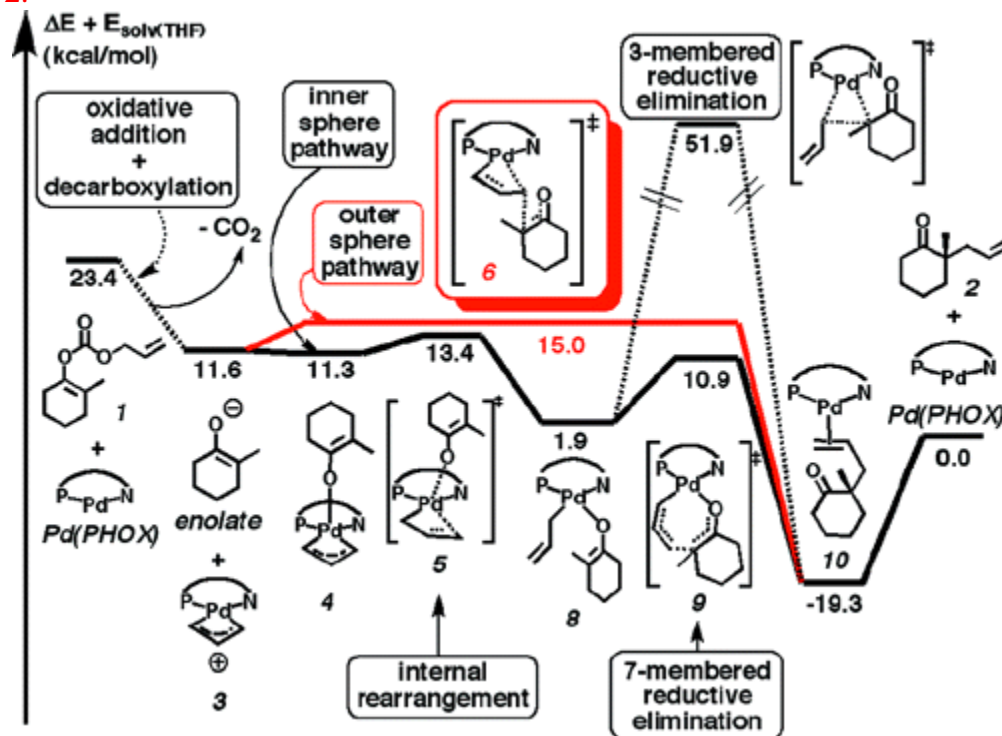


a) The first half of the process involves taking **1** to an η^3 -allyl Pd complex. Propose steps to convert **1** to such a complex. Draw all intermediates and label each step by the type of reaction occurring.

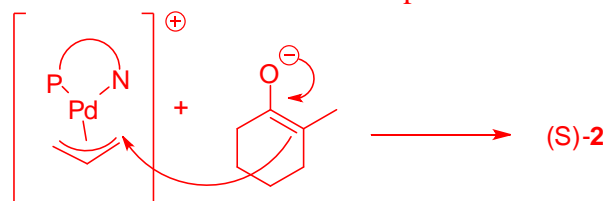


b) There are two basic paths that can lead to (S)-2 from the η^3 -allyl Pd complex. Show one of those two paths.

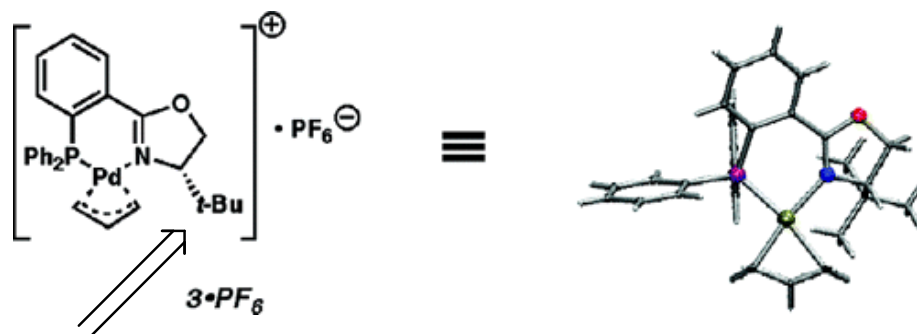
One possible answer was shown in the article and is pasted below. This involves addition of the enolate to the η^3 -allyl Pd and then conversion of the η^3 -allyl Pd complex to an η^1 -allyl complex. Intramolecular attack through a cyclic transition state in a reductive elimination process yields the product (S)-2.



A second path, which was favored in earlier reports (e.g. G. Helmchen et al. *Angew. Chem. Int. Ed.* **1997**, *36*, 2108-2110), envisioned an intermolecular nucleophilic addition to the η^3 -allyl Pd complex.



c) The product is chiral, but 1 lacks a chiral center. Describe or show figures that illustrate how chirality is induced in the final product (S)-2.

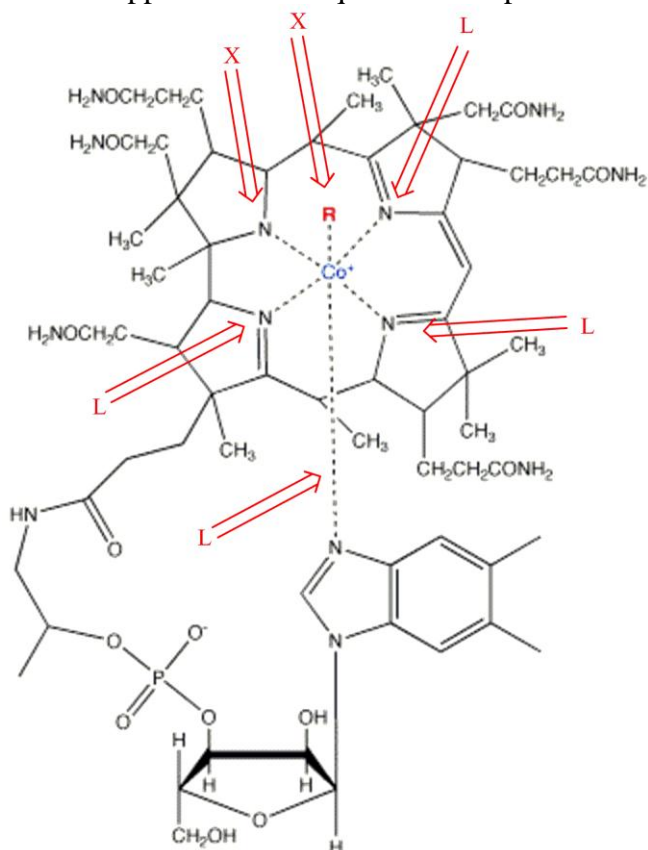


t-Bu group blocks one face of allyl and promotes addition of Nu away from t-Bu.

11. Analyze the structure of vitamin B₁₂ or cobalamin, the most complex of all vitamins, and drawn below. In the figure, R can be CH₃, CN or OH

- Identify the ligands as either X or L type.
- Identify the oxidation state of the cobalt (assume R to be one of the ligands listed above).
- Determine the total electron count at cobalt.

Dr. B approved of this question in top level consultations



a) see figure

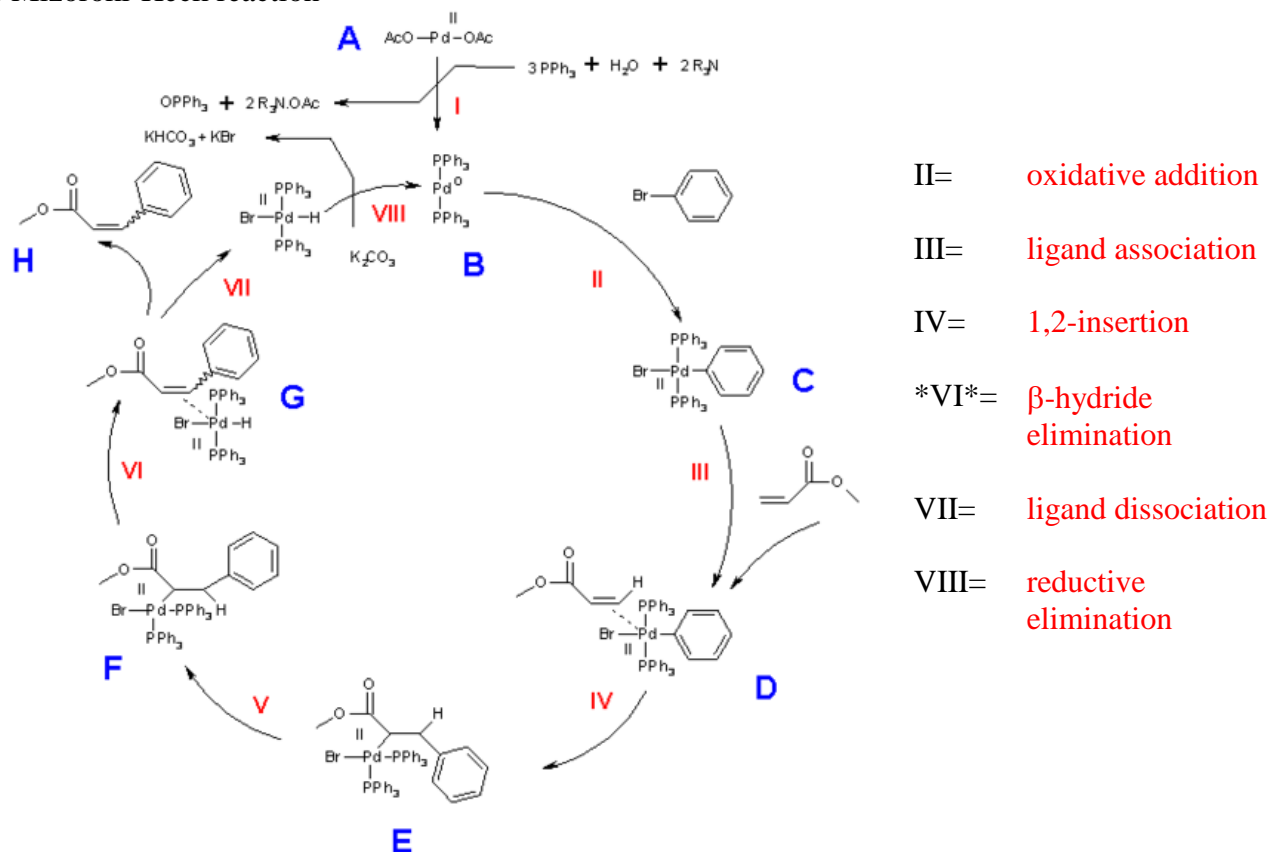
b) Co is +3 with two X type ligands and one positive charge on the Co atom.

c) total e⁻ count = $d^6 + [(2 \times 2 \text{ X-type ligands}) + (2 \times 4 \text{ L-type ligands})] = 18 \text{ e}^-$'s

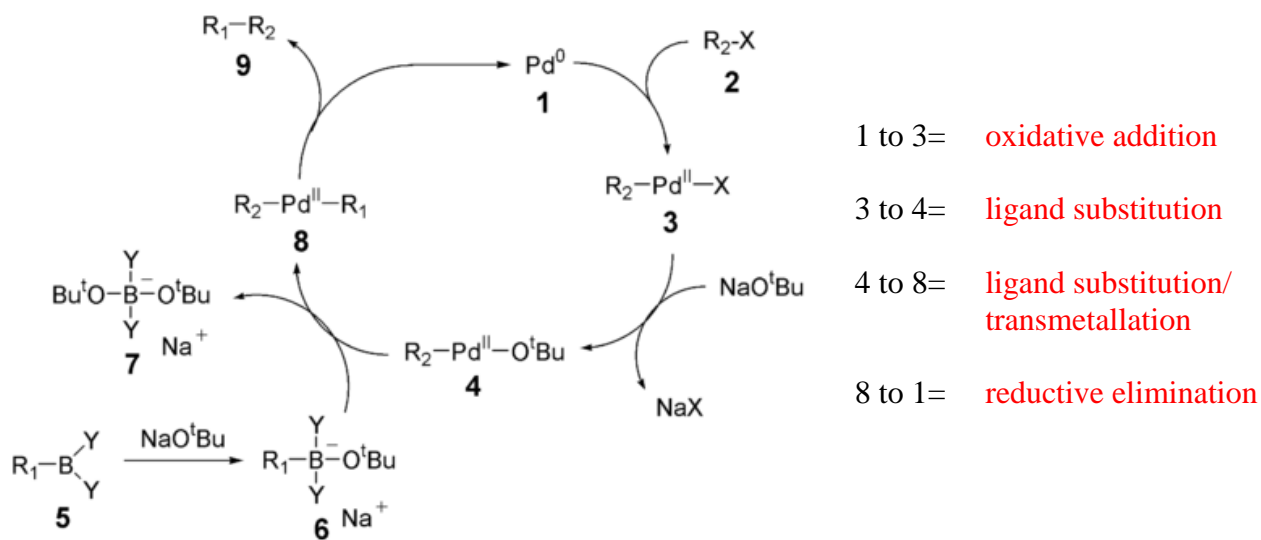
12. On the first day of lecture, I showed the 2010 Nobel Prize in Chemistry announcement. The award was made to Richard Heck, Akira Suzuki, and Ei-ichi Negishi for their contributions to palladium-

catalyzed cross coupling reactions in organic synthesis. The catalytic cycles for all three of these processes are shown below. *Identify the mechanistic steps in two of the three.*

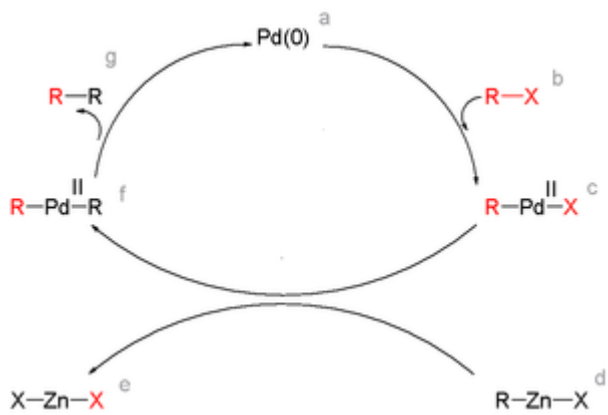
a) Mizoroki-Heck reaction



b) Suzuki reaction.



c) Negishi reaction.



a to c= oxidative addition

c to f= ligand substitution/
transmetallation

f to a= reductive elimination