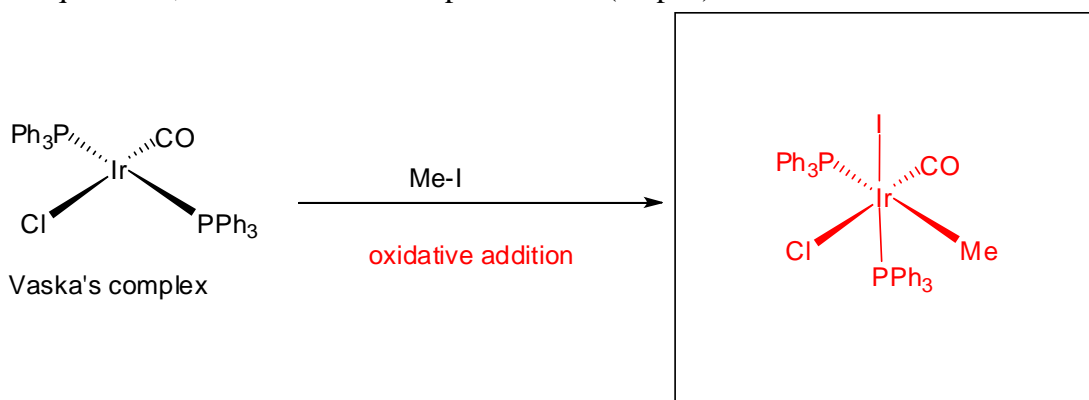
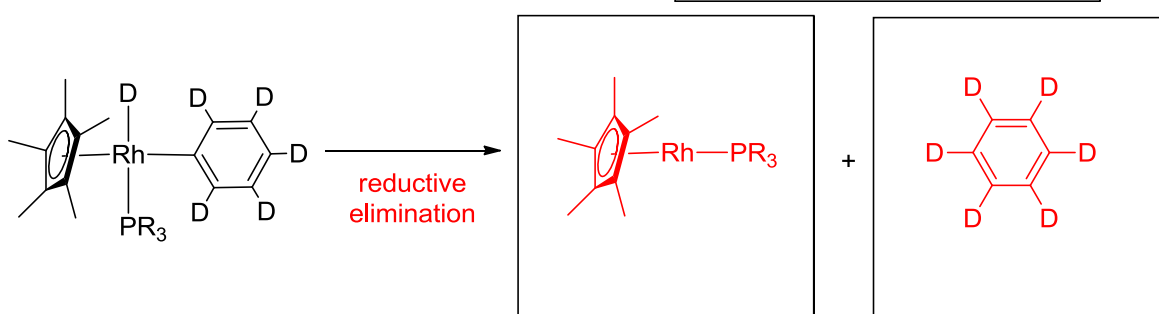


1. Provide the product and the type of mechanism occurring in the reactions below. CHE-334 students do 6 of 8 questions; CHE-534 must complete 7 of 8. (20 pts.)

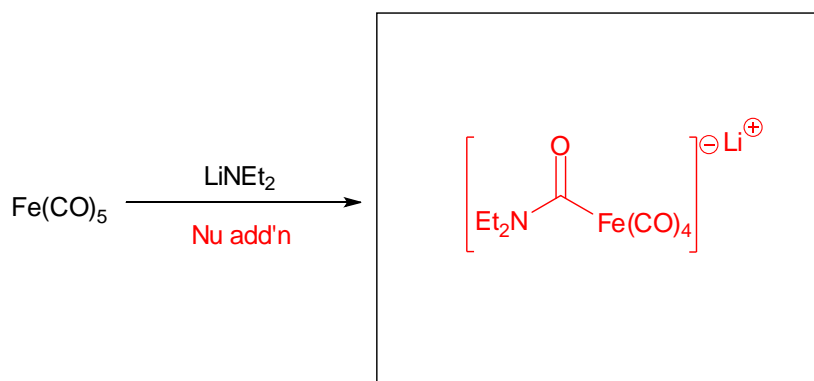
a)



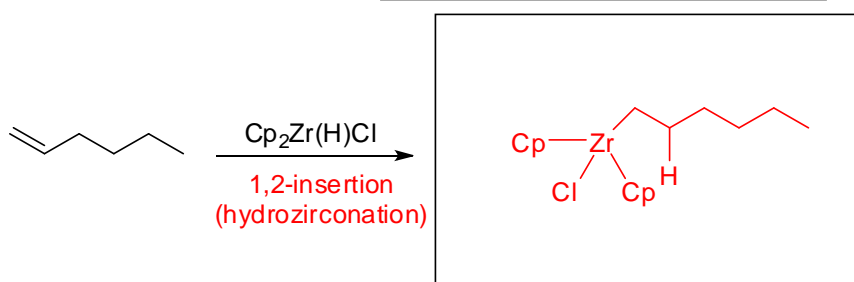
b)

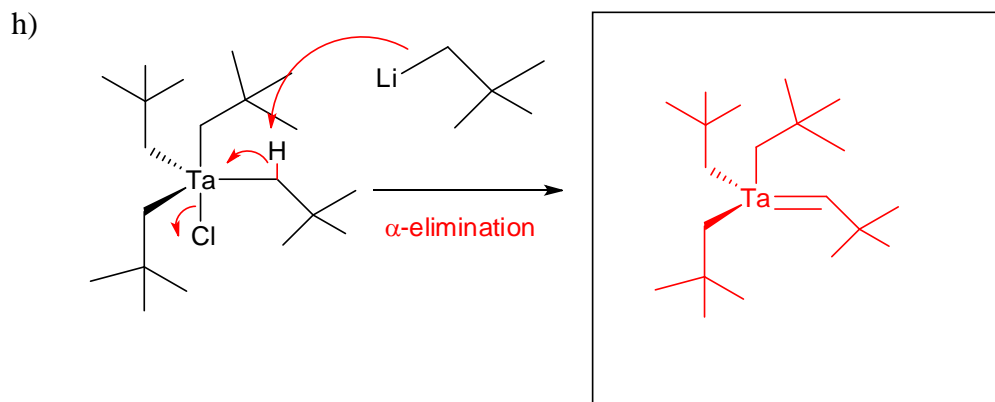
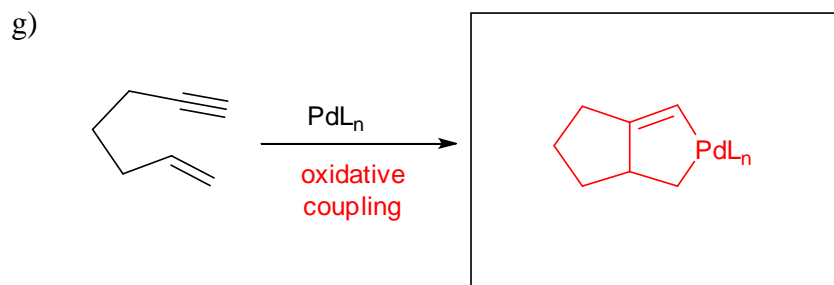
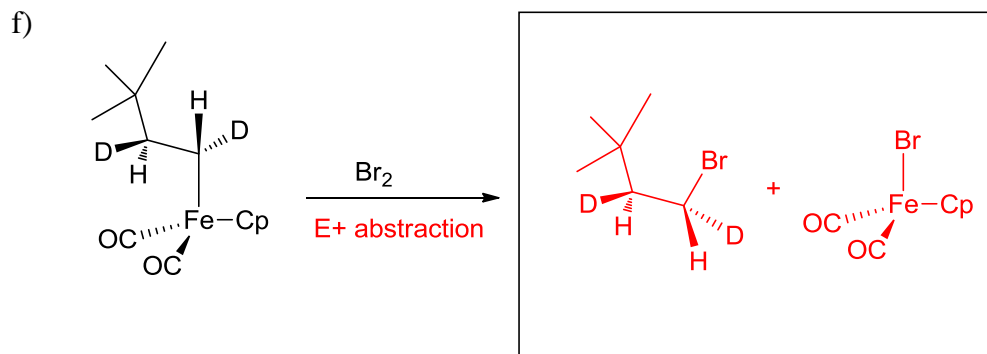
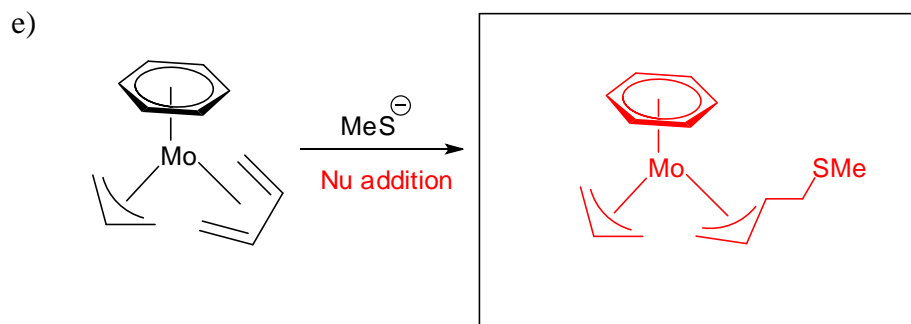


c)



d)

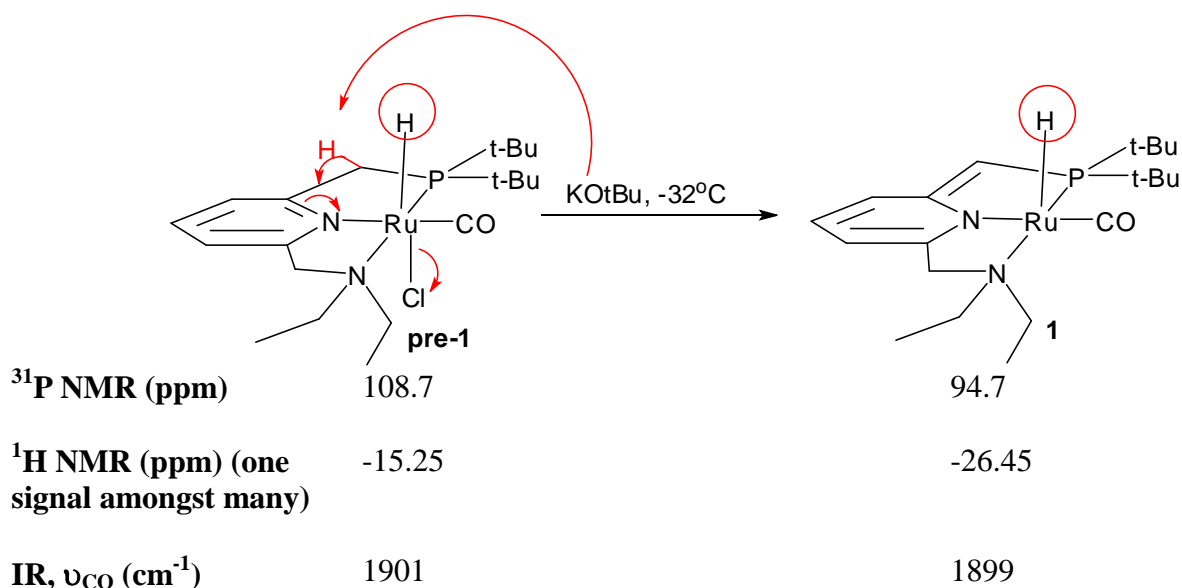




Questions 2-5: CHE-334 must complete 2 of the 4 questions, while CHE-534 must complete 3 of 4 questions. (20 pts. each)

2. While I was in England last spring, David Milstein, a former DuPont researcher currently at the Weizmann Institute of Science in Israel, came to speak. He discussed the chemistry of complex **1** below which he has been exploring for the last decade. Ru complex **1** was synthesized from **pre-1** by reacting with KOt-Bu .

a) Show electron flow arrows that rationalize the formation of **1** from **pre-1**.



A portion of the reported spectroscopic information for compound **pre-1** and **1** is shown above.

Answer the following questions about the data based on our discussions in the course.

b) Of the 30 or so protons present in **pre-1** and **1**, circle the proton that is most likely responsible for the signal listed, i.e. -15.25 ppm in **pre-1** and -26.45 in **1**.

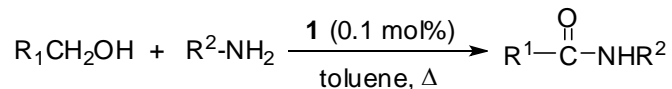
c) What does the NMR information suggest about the electronic nature of complex **1** and the Ru atom at its core versus complex **pre-1**?

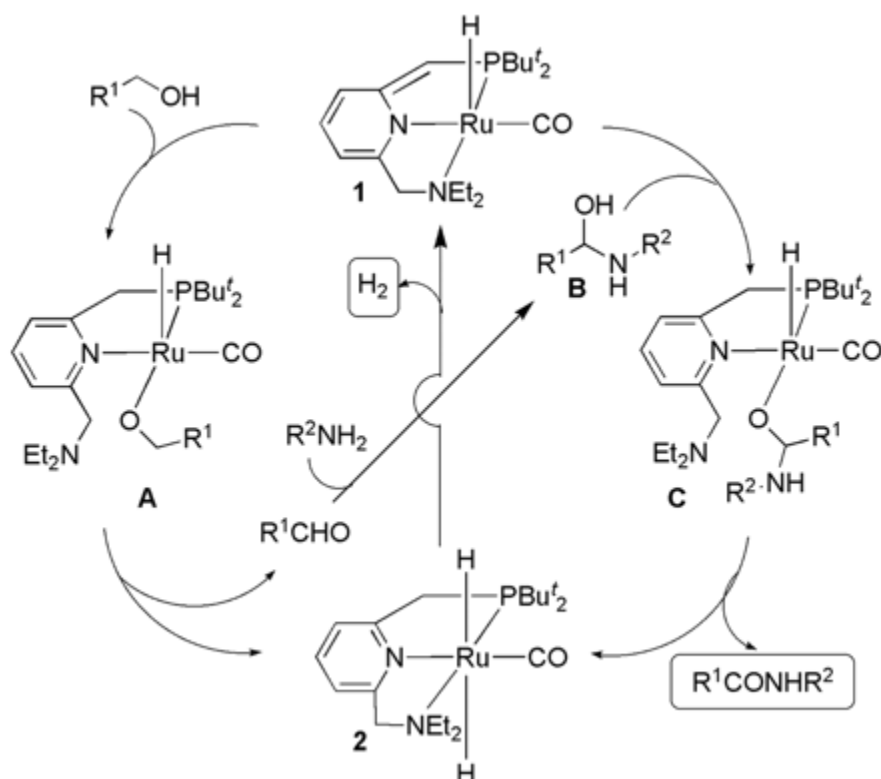
Both the ^{31}P and the ^1H signal suggest a greater shielding of the respective signals or atoms. This would result from more electron density being around the Ru atom as a result of the deprotonation and nitrogen anion formation.

d) Does the IR information confirm this conclusion or does it suggest something else?

The CO stretch changes very little which seems to contradict the NMR results. With more electron density around the Ru, you would expect more backbonding and therefore an even lower CO stretch. Perhaps the already low CO value in **pre-1** is not capable of even greater backbonding in **1**.

3. One of the processes catalyzed by **1** is shown in the reaction and catalytic cycle below.





a) Identify the steps in the catalytic cycle by determining the type of process shown. If more than one fundamental mechanistic process occurs, then list them all in the space provided. (3 pts. each)

<i>Reaction:</i>	<i>Type of process:</i>	<i>Reaction:</i>	<i>Type of process:</i>
1 to A	electrophilic addition (H+ rxn with ligand) and ligand substitution	1 to C	electrophilic addition (H+ rxn with ligand) and ligand substitution
A to B	β -hydride elimination and ligand substitution	C to 2	β -hydride elimination and ligand substitution
2 to 1	H-elimination and electrophilic abstraction		

David Milstein et al. [Science](#) **2007**, *317* (5839), 790-792.

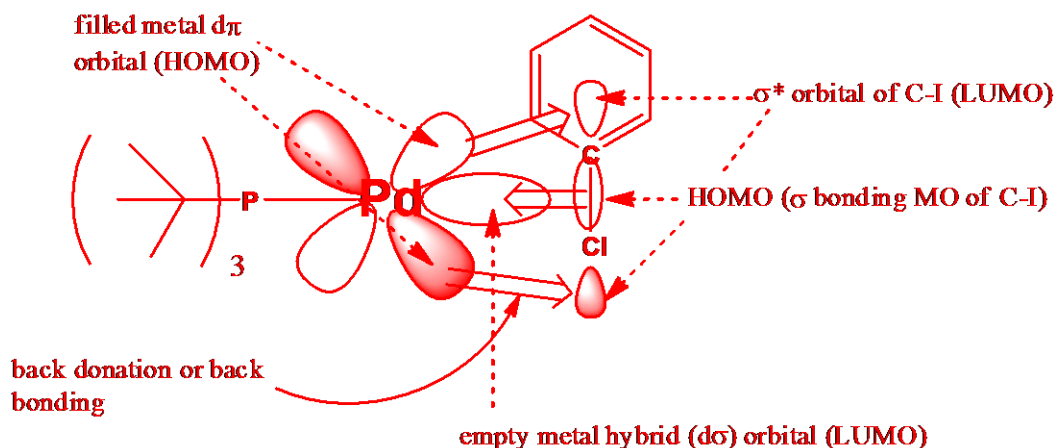
b) Does the spectroscopic information in the previous problem for **1** (versus **pre-1**) support the type of reactivity seen in the reaction? Be as specific as possible. (5 pts.)

Based on the upfield shifts of the ^1H and ^{31}P NMR signals, complex **1** and the Ru metal are rich with electron density which is causing the shielding of the hydride proton and phosphine. Since the major process occurring in the catalytic cycle is oxidation of the alcohol or hemiaminal through β -hydride elimination, this is consistent. In particular, the Ru atom needs electron density in its d orbitals to cause β -hydride elimination.

The IR information is not necessarily supportive of this activity since it suggests there is no big increase in d electrons since there is little change in backbonding to the CO ligand. However, another interpretation might be that there is an increase in d electron density, but that little is drained into the CO backbond.

4. One recent challenge that organometallic chemists have overcome is the ability to get aryl chlorides to undergo oxidative addition as easily as their bromide or iodide counterpart. This is important because the chloride derivatives tend to be less expensive and more commercially available. One of the important innovations that was used to accomplish oxidative addition was to use phosphine ligands such as $\text{P}(\text{Cy})_3$ and $\text{P}(\text{t-Bu})_3$ instead of the traditional PPh_3 that was commonly used in earlier versions of the reaction.

a) Draw the molecular orbital interactions that occur in the oxidative addition of $\text{Pd}(\text{P}(\text{t-Bu})_3)_2$ with chlorobenzene. Assume this is a concerted addition. Identify the $d\sigma$, $d\pi$, σ and σ^* orbitals. Label the HOMO and LUMO orbitals of both the metal and the chlorobenzene. Identify the direction of electron donation and backbonding.



b) It is believed that in many oxidative additions, the most active catalytic form of the Pd is a monoligated form, i.e. $\text{Pd}(\text{P}(\text{t-Bu})_3)$. Furthermore, as described above, phosphine ligands with cyclohexyl and t-butyl groups were most successful with aryl chlorides. Provide a steric reason and an electronic rationale for the success of these ligands in aryl chloride oxidative additions. In the electronic case, reflect on your answer to part a and be as specific as possible in characterizing the essential interactions that lead to oxidative addition.

Steric reason: Since the coordination number of the complex increases by 2 in an oxidative addition, it is important to have space around the Pd to accommodate the two new ligands. The $\text{P}(\text{t-Bu})_3$ and $\text{P}(\text{Cy})_3$ are large phosphine ligands and therefore they deter a second phosphine ligand from binding and thereby more easily allow the addition of two new ligands.

Electronic reason: The alkyl phosphine ligands are strong σ donors making the Pd relatively electron rich. If a more electron rich Pd is important for successful oxidative addition, then that suggests that more backbonding into the σ^* orbital of the C-Cl bond is essential to cleaving the bond.

5. At -20°C , the ^1H NMR spectrum of the agostic species shown below (**1**) consists of a complex phenyl region (30 H's) and six signals at the following chemical shifts:

peak number	$\delta(\text{ppm})$	peak information
1	2.88	doublet, 1 H
2	2.39	singlet, 3 H
3	1.62	singlet, 3 H
4	0.48	doublet, 1 H
5	-2.23	broad singlet, 3 H
6	-24.65	doublet of doublets, 1 H

a) Assign the six peaks in the table to protons on complex **1**. Note: peaks 1/4 and 2/3 cannot be definitively assigned to one particular proton, so they may be assigned as a group.

see structure for answers

b) Why is peak 6 a doublet of doublets?

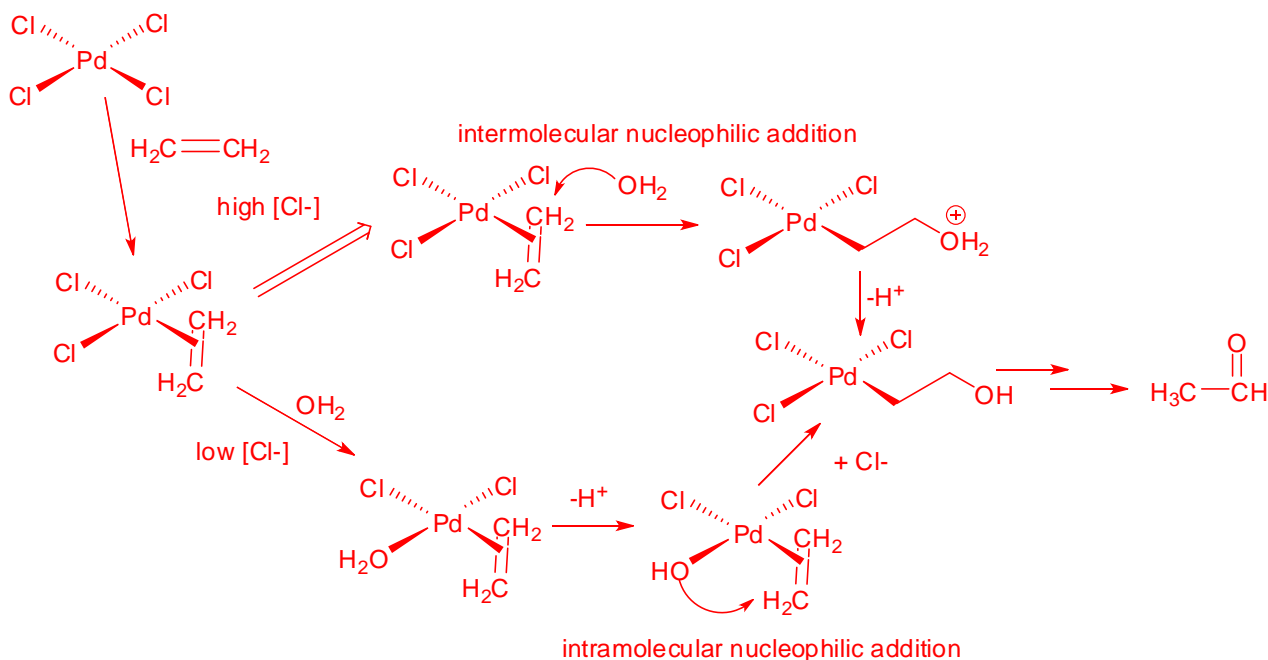
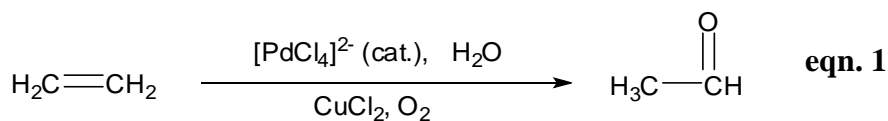
Peak 6 will be split by each of the ^{31}P atoms in the two phosphine ligands. Since these two phosphorus atoms are not equivalent, they will have different coupling constants with the hydride and therefore will afford a doublet of doublets instead of a triplet.

c) Why is the signal at -2.23 ppm a broad singlet? At -80°C , the peak splits into three distinct signals: -9.80 , 0.40 , and 2.71 ppm. Briefly explain what is happening.

The peak at -2.23 is due to the agostic H bound to the Ir. It is a broad singlet at -20°C because at this temperature the all three C-H sigma bonds are forming an agostic interaction with the Ir and they are exchanging quickly. At -80°C , the process has slowed so that there is only one proton with an agostic interaction and the complex is not exchanging this interaction.

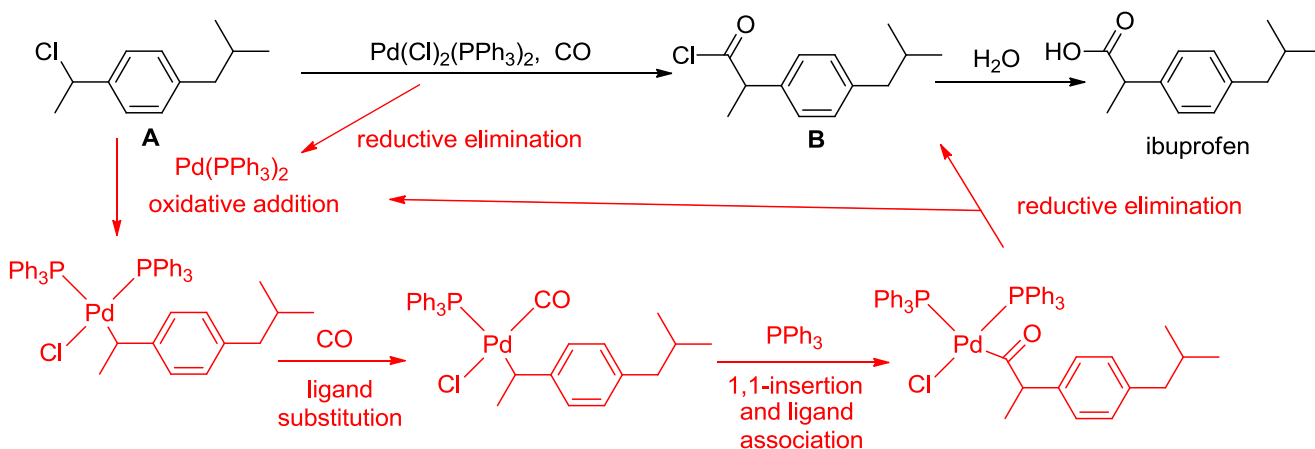
Questions 6-8: CHE-334 and CHE-534 must both complete 2 of the 3 questions. (15 pts. each)

6. The Wacker reaction, equation 1 below, is used to manufacture millions of tons of acetaldehyde each year. The mechanism is deceptively complex and is still not fully understood. Nevertheless, it is believed that the key step is a nucleophilic addition. The nature of the nucleophilic addition is dependent on the concentration of chloride ion. Draw the two different nucleophilic addition reactions and indicate which one occurs under high $[\text{Cl}^-]$ and which one under low $[\text{Cl}^-]$. Briefly describe what causes one to be preferred over the other.

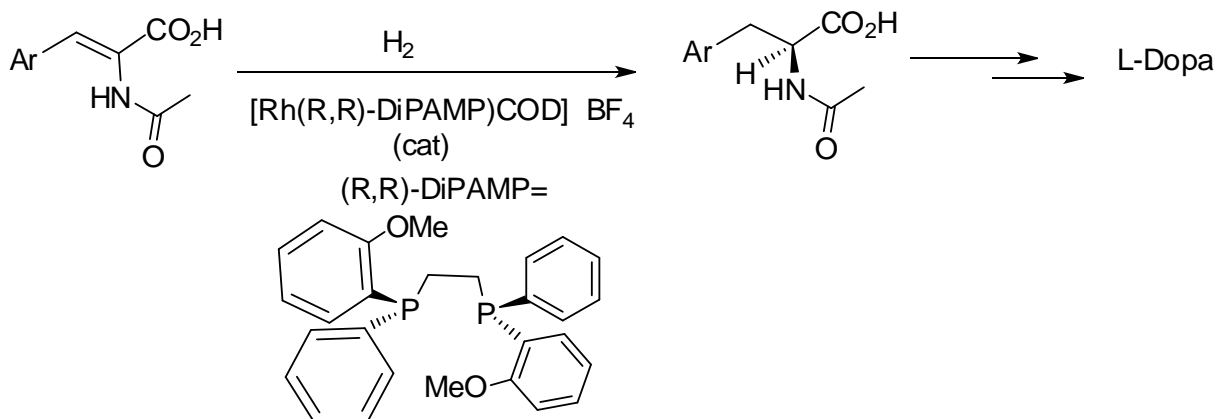


The low $[\text{Cl}^-]$ conditions allow the Cl^- ligand to dissociate from the Pd complex and be replaced by a H_2O molecule. This allows the intramolecular nucleophilic addition to happen after the H_2O becomes a ligand on the Pd and it is deprotonated.

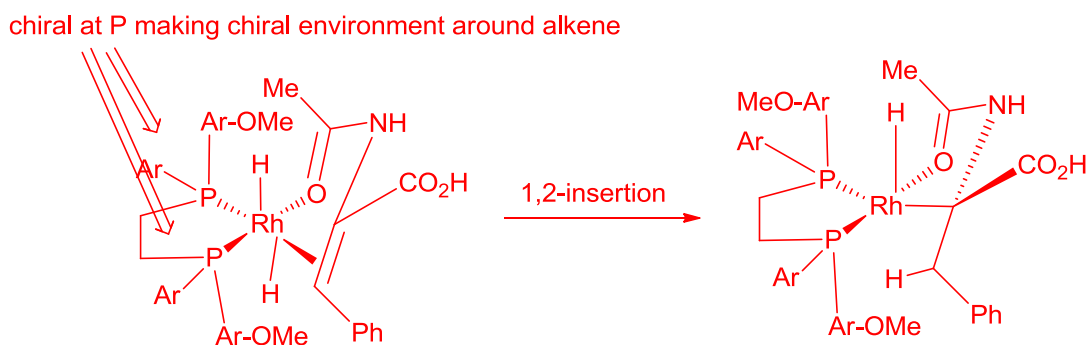
7. The industrial synthesis of ibuprofen is conducted through an efficient three step process called the Boots-Hoechst-Celanese Synthesis. One key catalytic step transforms **A** to **B** as shown below. Based on our class discussions, propose a catalytic cycle that takes A to B. Draw all intermediates and identify all reaction steps in the process.



8. Building on the work of Sir Geoffrey Wilkinson with Rh catalyzed alkene hydrogenations, William Knowles was able to develop an asymmetric method to make L-Dopa, which is the most commonly used medication to treat Parkinson's disease. The key reaction in the process is shown below. Describe the process by which the hydrogenation occurs. You do NOT need to show the entire mechanism, just a key intermediate that explains the important bond forming step and the basis of the chiral center formation. You should identify the type of reaction shown. You may abbreviate all ligands or structures as long as the key concepts are conveyed.



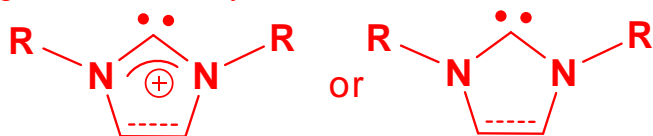
The key step in forming the chiral center is a 1,2-insertion reaction of hydride and Rh on the alkene. The DiPAMP ligand is chiral and creates a chiral environment around the Rh metal leading to the selective delivery of hydride to only one face of the alkene. The key intermediate is shown below:



Questions 9 and 10: CHE-334 and CHE-534 must both complete 1 of the 2 questions. (10 pts. each)

9. N-Heterocyclic carbenes (NHC's) are revolutionizing ligand design. Draw an N-heterocyclic carbene and briefly describe why they are similar to phosphines and how they differ from phosphines.

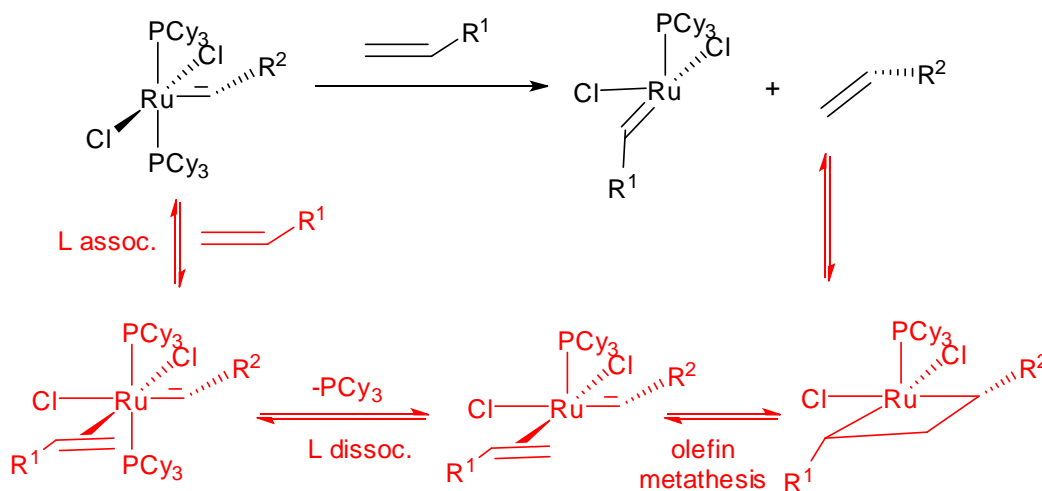
general N-heterocyclic carbene:



N-Heterocyclic carbenes are tunable both sterically and electronically like phosphines. The R groups can be modified to influence steric hindrance. Changes to the ring or substituents on the ring can influence the electronic nature of the NHC.

The NHC's are generally better sigma donors and have little or no pi acid character.

10. a) Draw the mechanism of the olefin metathesis process whose reaction is shown below. Show intermediates and label any steps that we have discussed.



b) What is one way in which the outcome of an olefin metathesis reaction can be controlled?

Since the olefin metathesis reaction is an equilibrium, thermodynamic considerations will control the process. This means that the formation of more stable products (e.g. five or six member rings such as in ring closing metathesis) or products that can be removed from the reaction pot (e.g. ethylene) will result in an equilibrium shift towards the product.