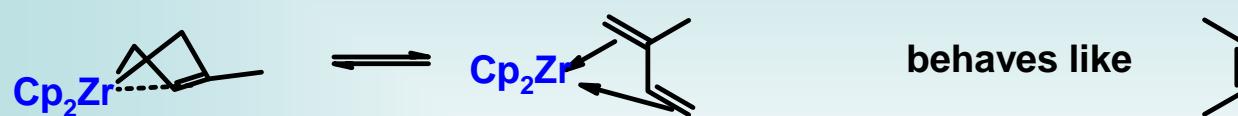
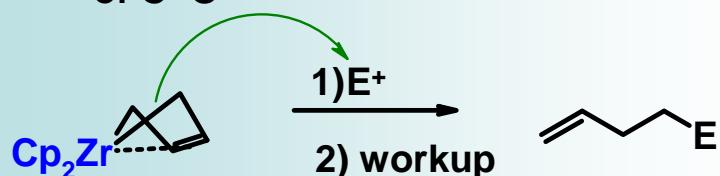


η^4 -Diene Complexes as Nucleophiles

- early transition metal diene complexes don't really behave like dienes
- dominated by Cp_2Zr complexes

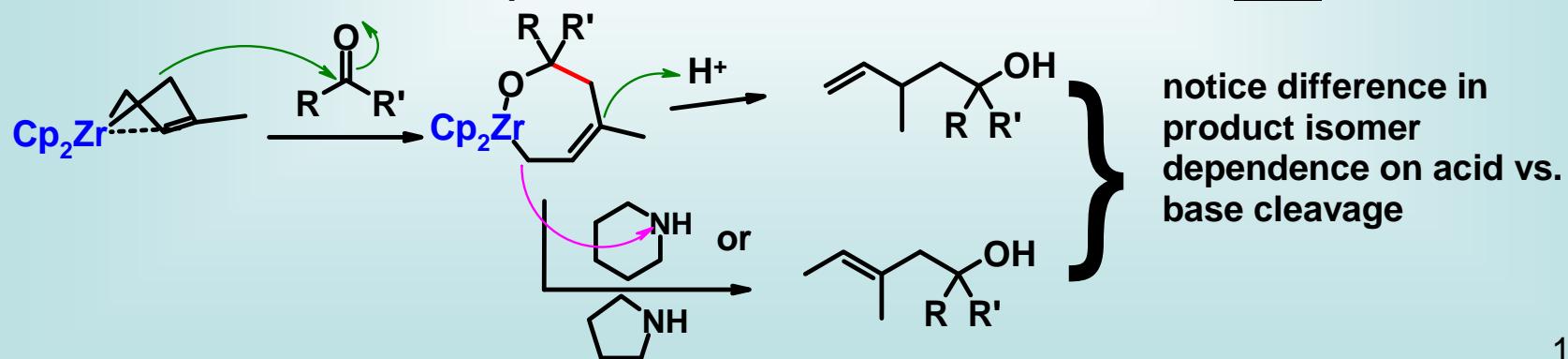


-therefore, the zirconium dienes are reactive as nucleophiles, especially with oxygen containing electrophiles, where $=\text{O}:$ coordination to Zr can increase the electrophilicity of $\text{C}=\text{O}$



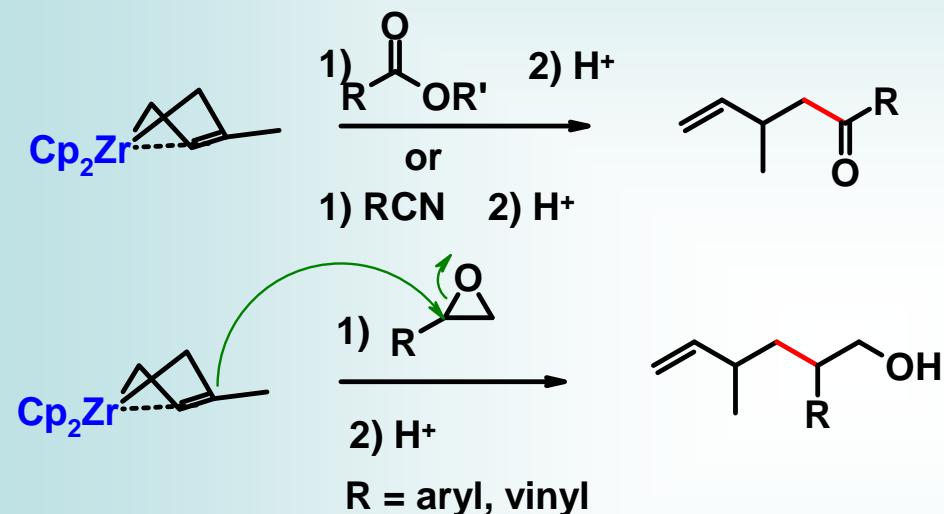
Regiochemistry

- if a substituent is at the 2-position of the diene, the rxn occurs at the more substituted end

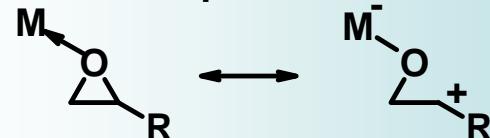


- in acid, the allylZr cleaves via S_E2' (remote end, much like allylsilanes)
- in base, the product is the result of direct C-Zr bond cleavage

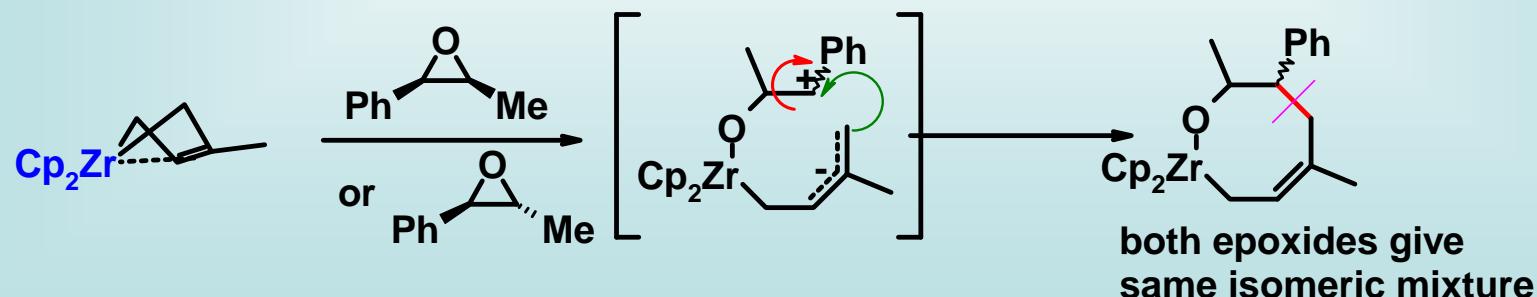
-other oxygen bearing E⁺'s include.....
esters (or nitriles), and epoxides



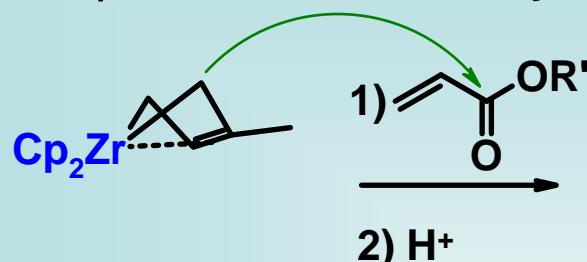
Note: Rxn is at the more substituted end of the epoxide



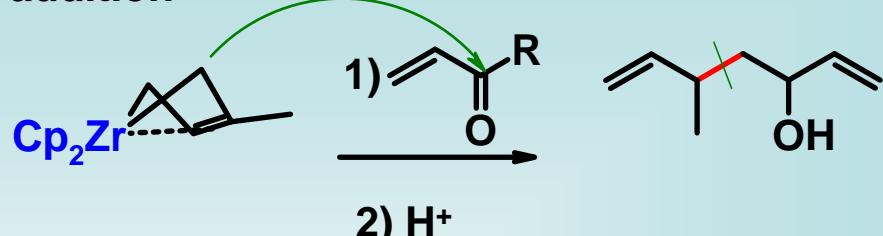
- that is evidence of S_N1 - type reactivity
- further evidence is the loss of stereochemical integrity of the epoxide, i.e.,



α, β -unstaurated carbonyls

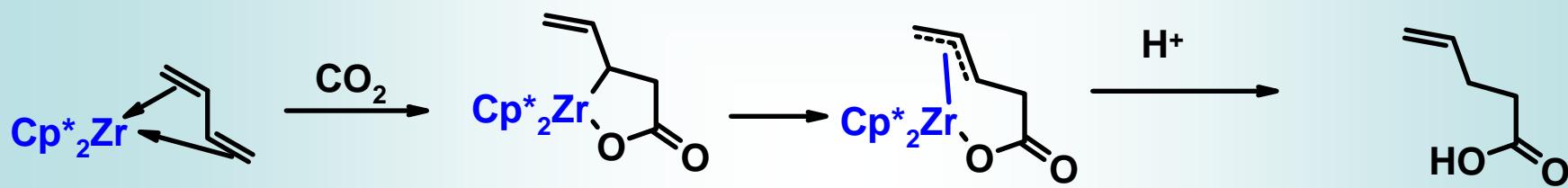


-give high 1,2-addition



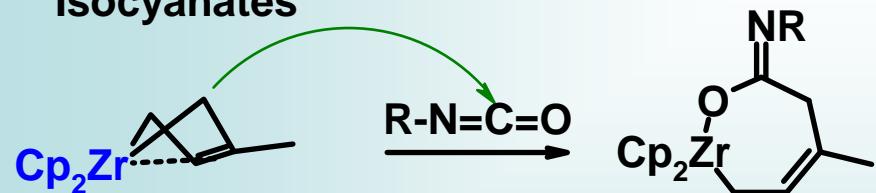
Other electrophiles

CO_2



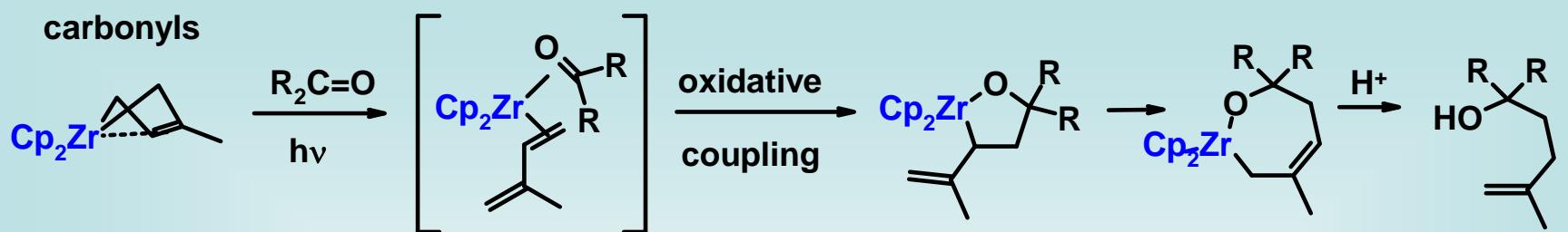
But in many cases, further reaction can't be stopped

Isocyanates

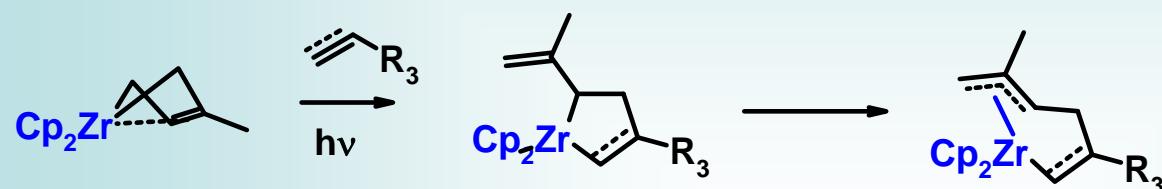


Photochemical Reactions

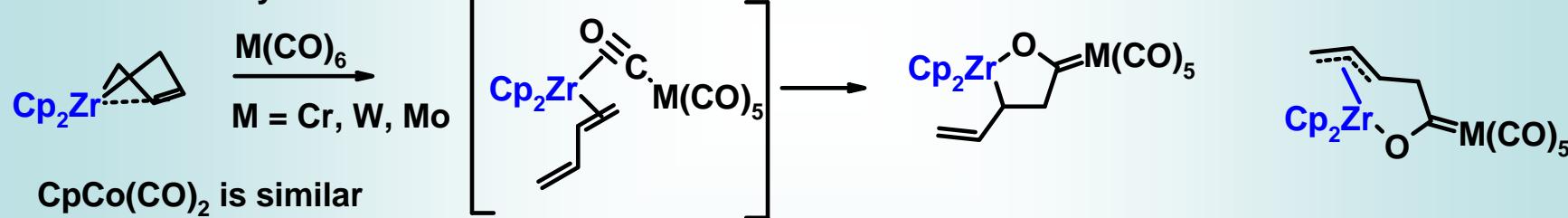
- with carbonyl compounds and alkenes/alkynes, a photochemical reaction occurs at much lower T (-70°)
- one big difference - the reaction now occurs away from a 2-substituent



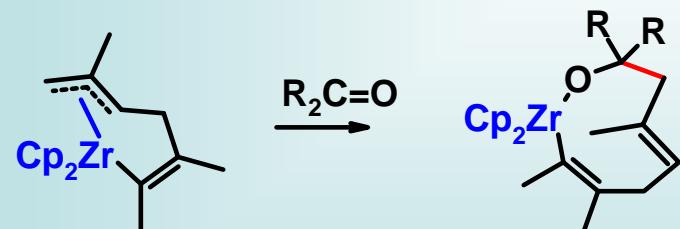
alkenes/alkynes



Metal carbonyls



Finally, at least for some products, the allylZr products themselves can be reacted with carbonyls



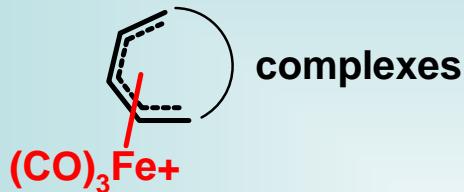
carbonyl, metal carbonyl adducts do this to
-always get 9-membered ring with trans C=C

see R Yasuda, H.; Nakamura, H. *Angew. Chem. Int. Ed. Engl.* 1987, 26, 723.
R Taber, D. F. et al *Curr. Org. Chem.* 2000, 4, 809.

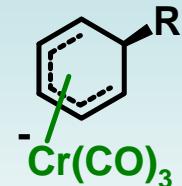
other Fe diene review R Gree, R. *Synthesis* 1989, 342.

η^5 -Dienyl Complexes

-dominated by



and to a much lesser extent by



we will cover this under η^6 - complexes

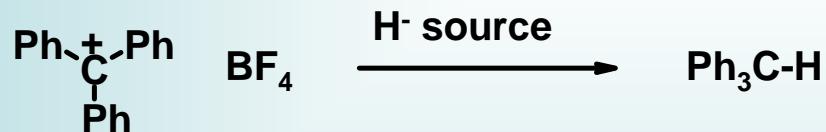
authors -dominated by A.J. Birch initially

-more recently by A.J. Pearson (Case Western)

W.A. Donaldson (Marquette) (acyclics)

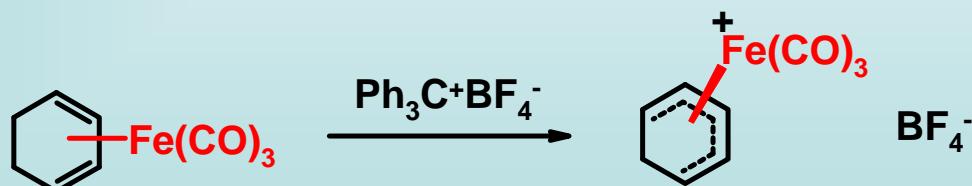
Generation of η^5 -Cationic Complexes

-most commonly made by hydride abstraction from diene complexes, normally by trityl cation



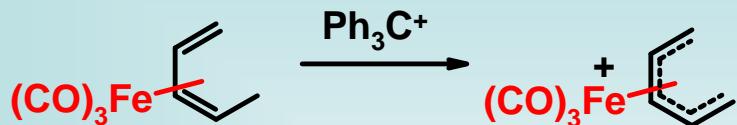
triphenylmethyl (trityl) cation

-thus....

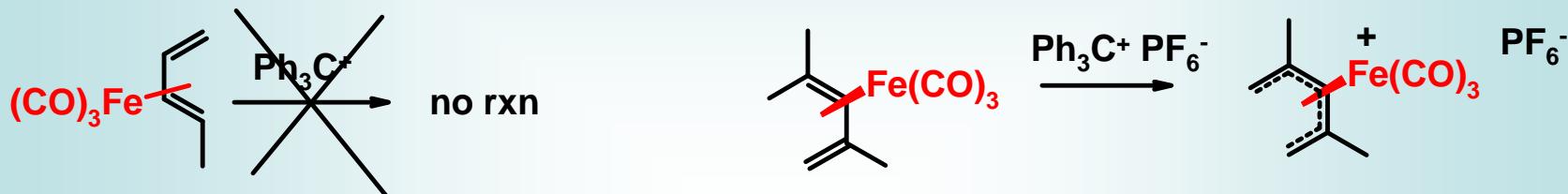


-works very well for cyclic dienes, as adjacent substituent must be cis

-with acyclic dienes, one can normally abstract H⁻ if the source is cis
i.e.,



-but, if the "H⁻ source" can only be trans, the abstraction usually fails



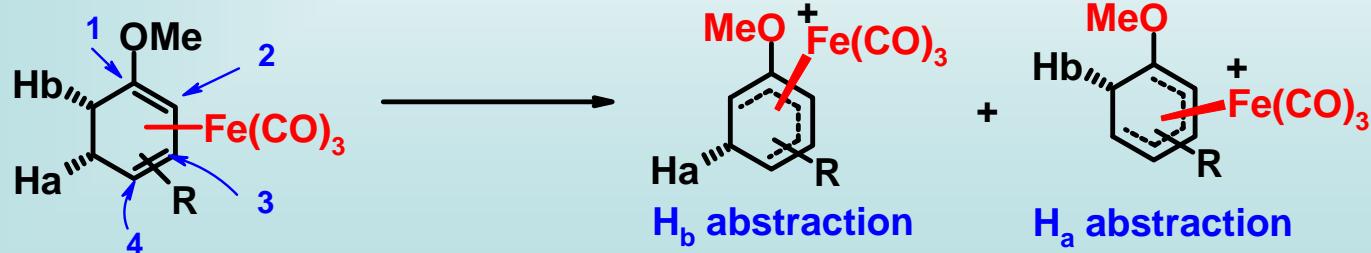
Regiochemistry of Hydride Abstraction

-this abstraction is usually pretty selective, but not that readily predictable. It does not correspond to the most stable cation

-Pearson has made an orbital interaction based explanation - for those interested, see.

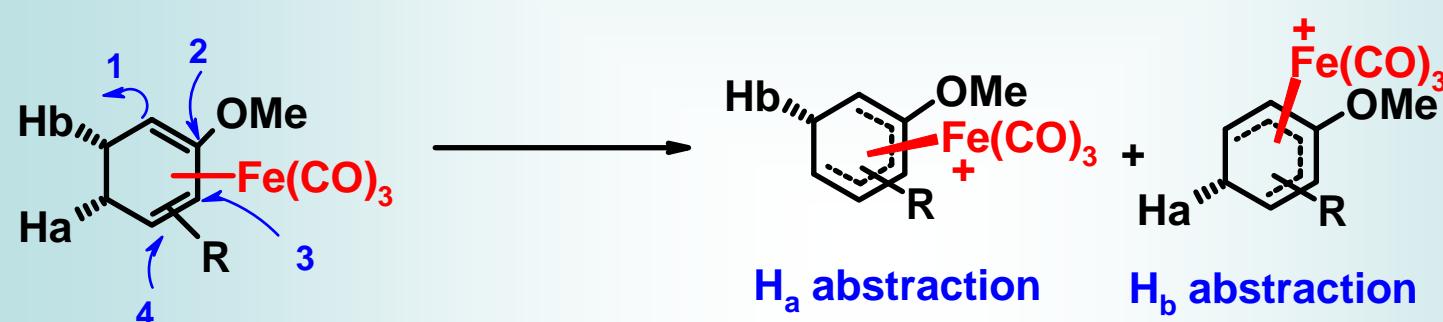
Pearson, A.J. et al *Organometallics* 1984, 3, 1150.

-examples



R	H _b abstraction	H _a abstraction
H	20	80
3-CH ₃	0	100
4-CH ₃	90	10
3-OCH ₃	56	44
4-morpholino	100	0

-N(CH₂)₂O-



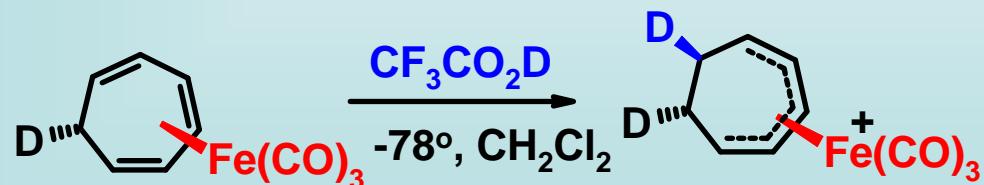
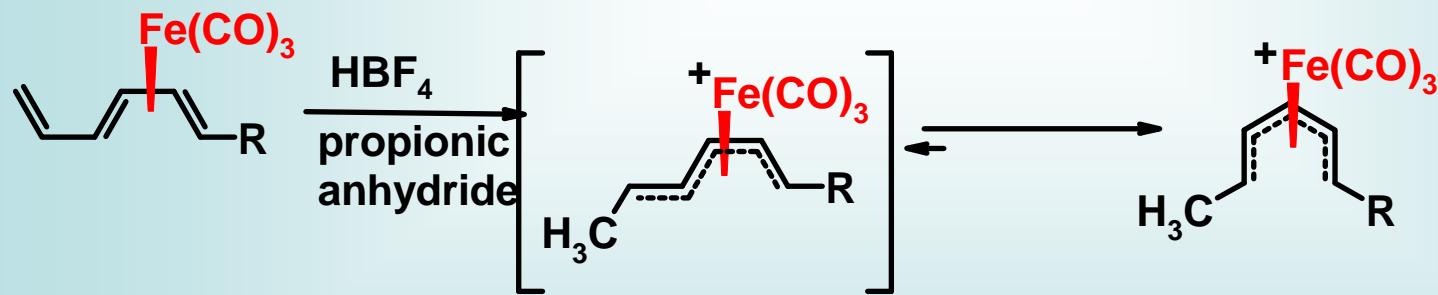
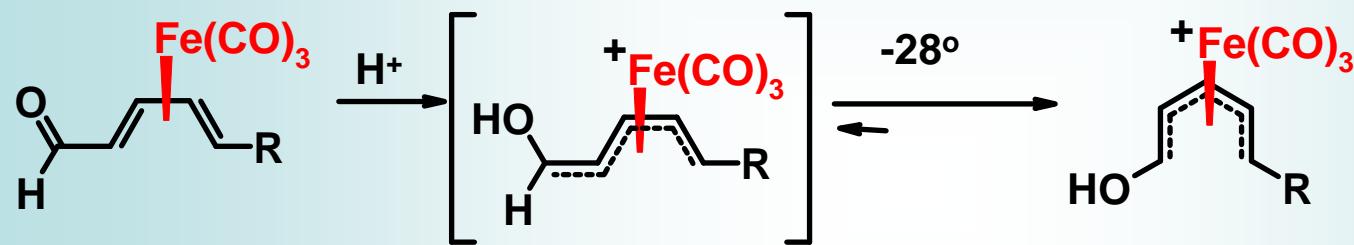
R	ro	H _a abstraction	H _b abstraction
H		90	10
1-CO ₂ Me		100	0
4-CO ₂ Me		0	100
4-CH ₃		0	100
4-OCH ₃		56	44

-the most common method for formation of acyclic pentadienyliron complexes is by protonation of an η^4 -dienyl alcohol complex by a strong acid



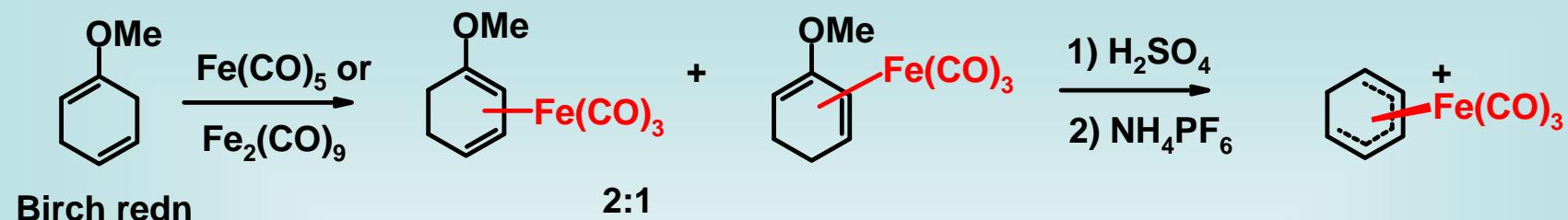
see R. Donaldson, W.A. Aldrichim. Acta 1997, 30, 17.
also Magyar, E.S. et al Inorg. Chem. 1978, 17, 1775.
Beihl, E.R. et al J. Organomet. Chem. 1979, 174, 297.

-there are related methods for preparation of dienylirons, from carbonyls, alkenes (triene)

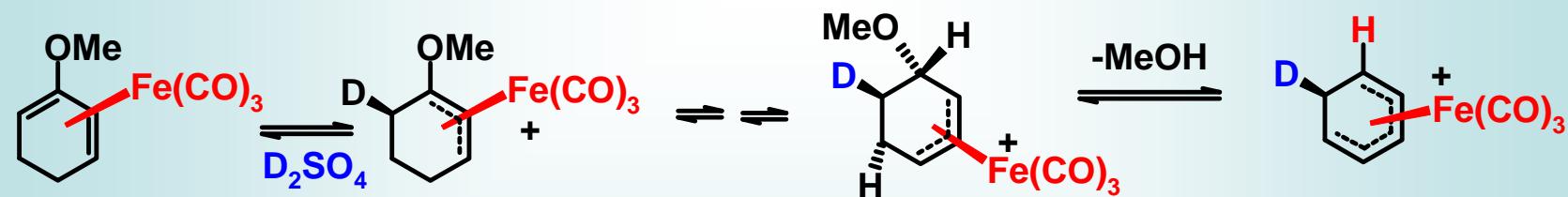
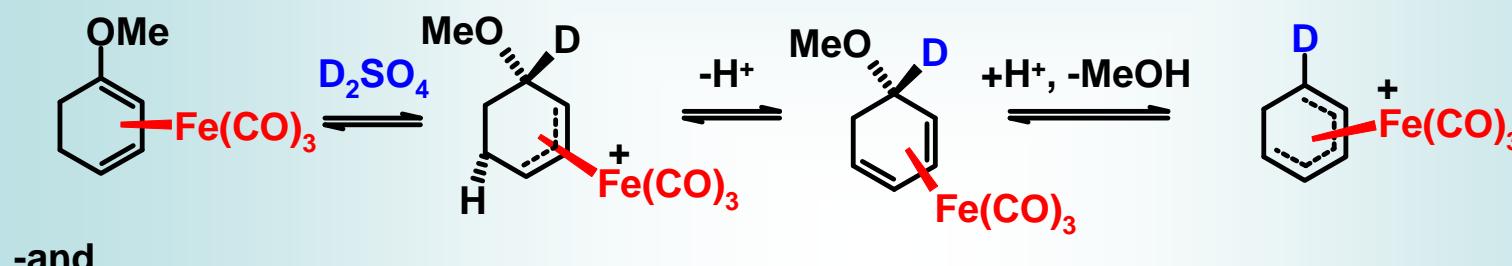


notice the stereochemistry of attack
J. Chem. Soc., Dalton Trans. 1977, 794 and 2340

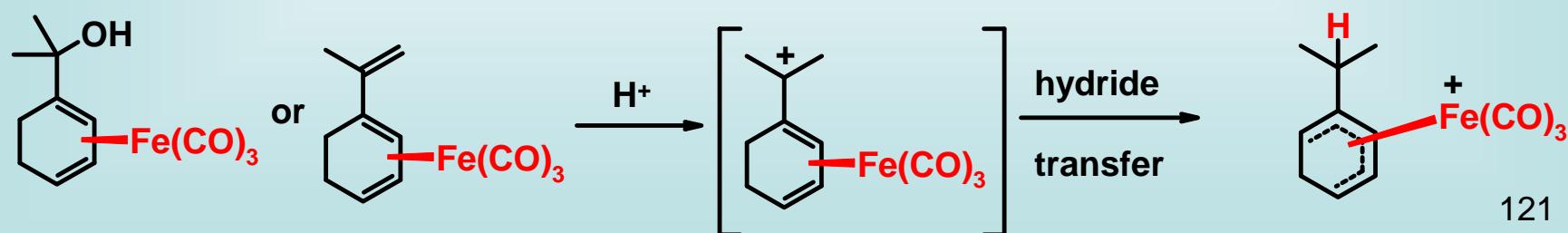
-from alkoxy-substituted diene complexes and strong acid



This goes via....



-by cation rearrangement



Reactions as Electrophiles

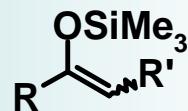
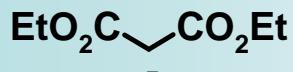
Nucleophilic Attack on η^5 -Complexes

-these cations readily react (normally) with nucleophiles to give C-C or C-heteroatom bond formation

-attack is from the exo- face (stereoselective, away from iron)

'normal' mode of attack is at C-1 terminus

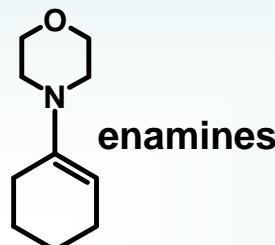
Nucleophiles: C-C bonds



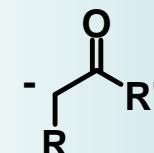
stabilized enolates

silyl enol ethers

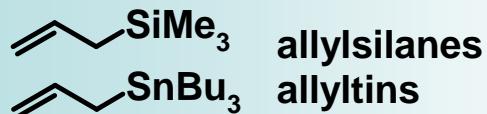
silyl ketene acetals



enamines



enolates work
only
sometimes



allylsilanes

allyltins

RLi, RMgBr usually fail

R₂Cd, R₂Zn, R₂CuLi, RCu(CN)ZnI usually better

C-X bonds

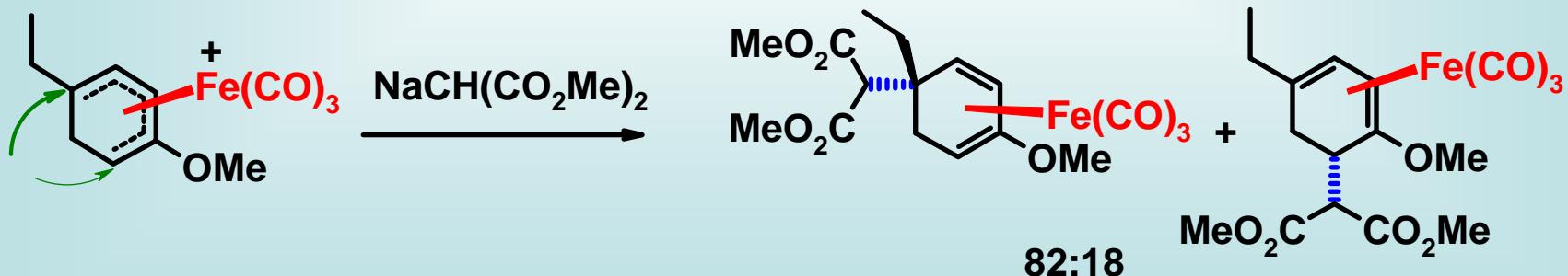
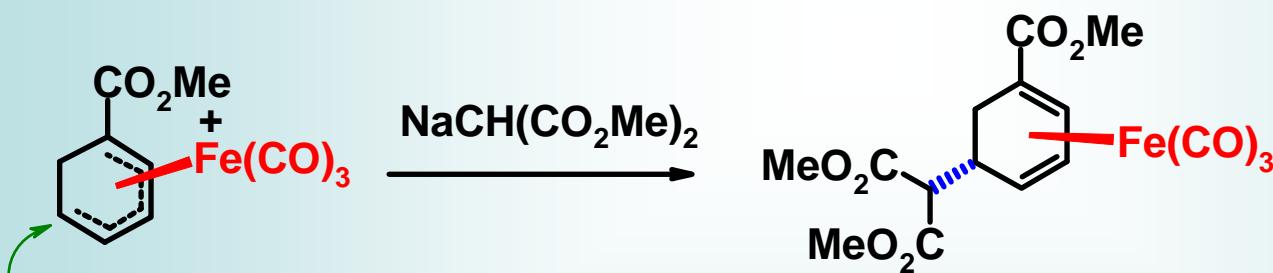
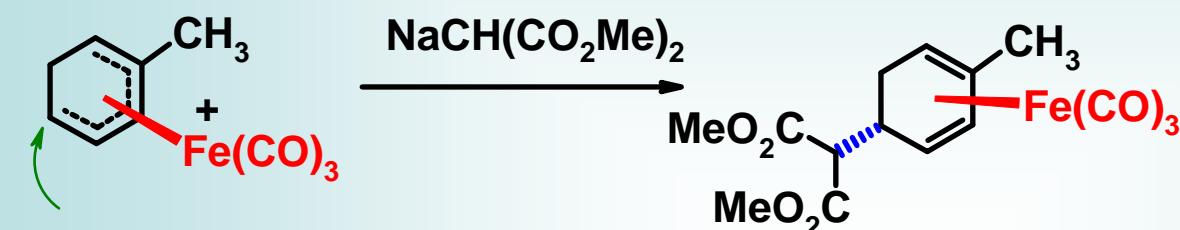
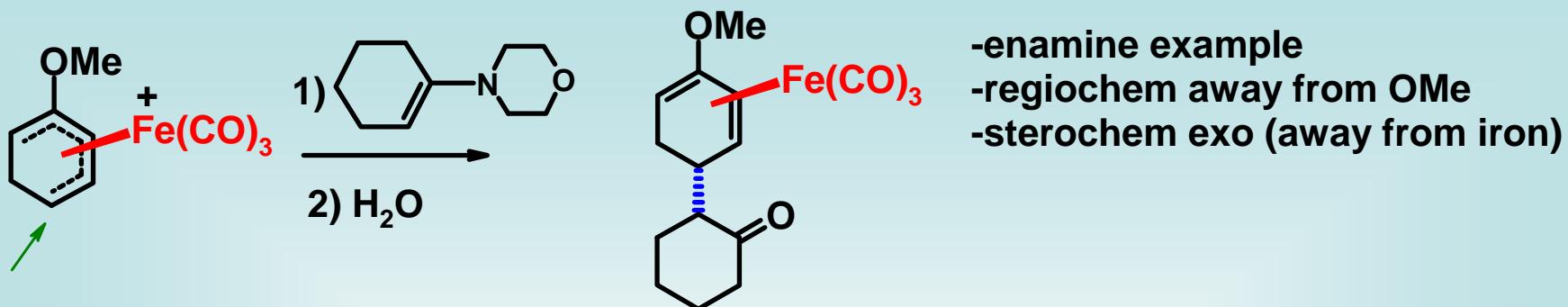
R₂NH (amines), H₂O, MeO⁻, R₃P (phosphines), (RO)₃P (phosphites), R₃As (arsines)

NaBH₄, Et₃SiH, NaBH₃CN (hydride sources)

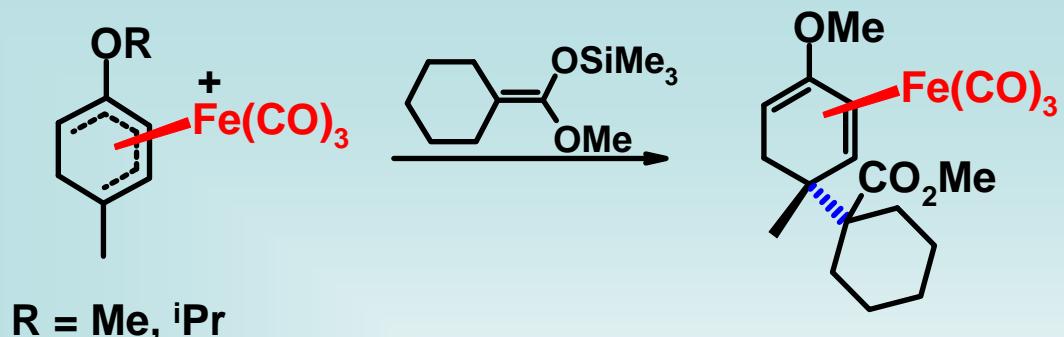
Regiochemistry, part II

-attack of the nucleophiles is at less substituted terminus

-MeO as a substituent is particularly powerful in this respect



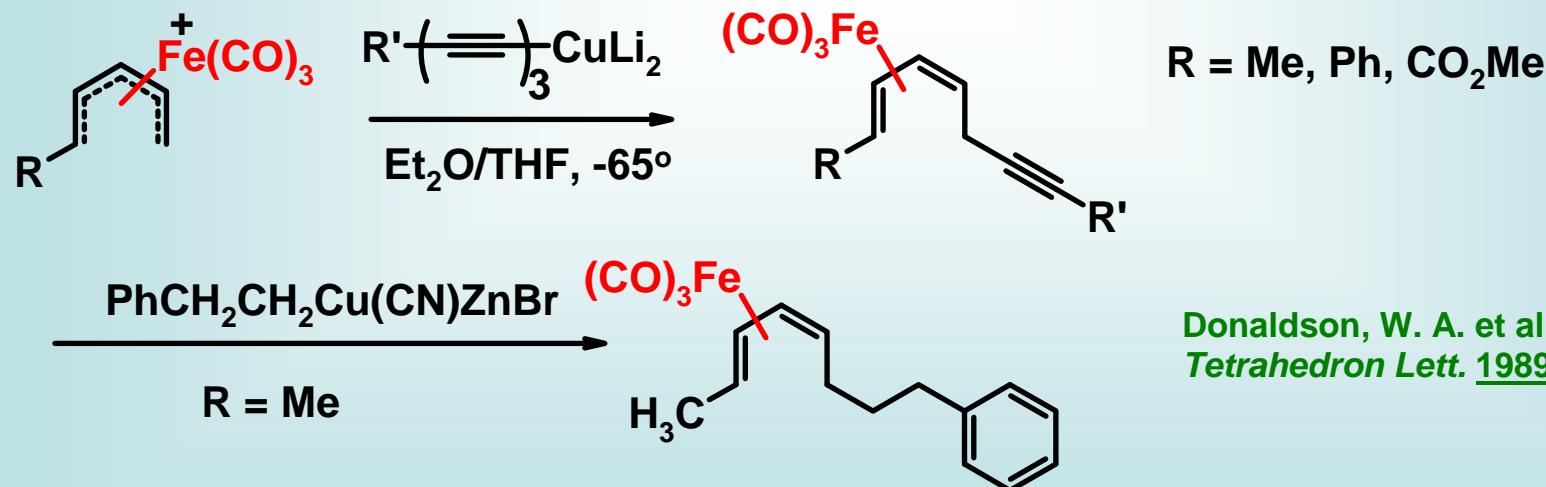
counterion dependent



see R Pearson, A.J., in **Comprehensive Organometallic Chemistry**, Vol. 8, p 939-1011
R **Comprehensive Organic Synthesis**, 1991, Vol. 4, p. 663-694
R **Iron Compounds in Organic Synthesis**, 1994, Ch.5
R ***Adv. Met-Org. Chem.*** 1989, 1, 1

R Harrington, P.J. Transition Metals in Total Synthesis, Ch. 4

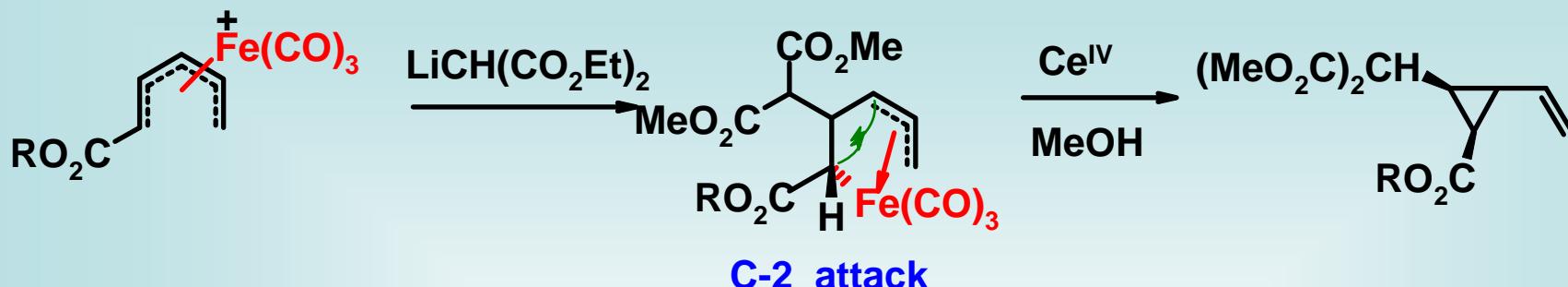
The acyclic cases have also been studied fairly extensively



Donaldson, W. A. et al
Tetrahedron Lett. 1989, 30, 1339.

Also, RNH_2 , H_2O , R_2Cd , $\text{R}'\text{-CC-SiMe}_3 + \text{F}^-$, NaBH_3CN ,
124
silyl enol ethers, allylsilanes (give trans products), and $\text{NaCH}(\text{CO}_2\text{Et})_2$, in many cases

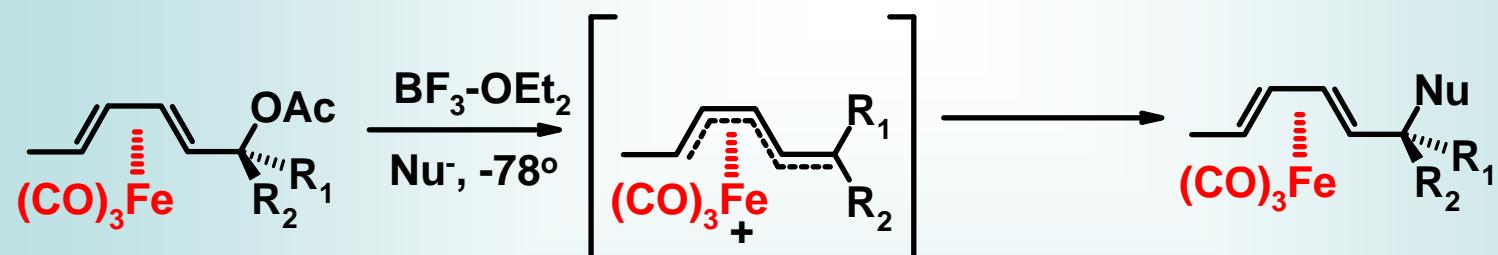
There are, though, at least a few regiochemical exceptions....



see Donaldson reviews....most recent..

R Donaldson, W. A. *Curr. Org. Chem.* **2000**, *4*, 837
R Donaldson, W. A. *Aldrichim. Acta* **1997**, *30*, 17

-geometry of pentadienyl thermodynamically prefers a "U" shape, but if it's generated with an "S" shape, it will keep that conformation (configuration?) until about -30°

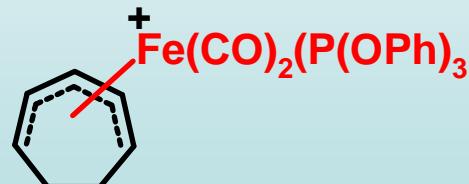


-reacts before isomerization occurs, therefore retention

Uemura, M. et al *Tetrahedron Lett.* **1987**, *28*, 641; Roush, W.R. et al *Tetrahedron Lett.* **1994**, *35*, 7347 and 7351.



doesn't work;
nucleophiles
deprotonate
instead



Pearson's solution
-see book

Synthetic Utility

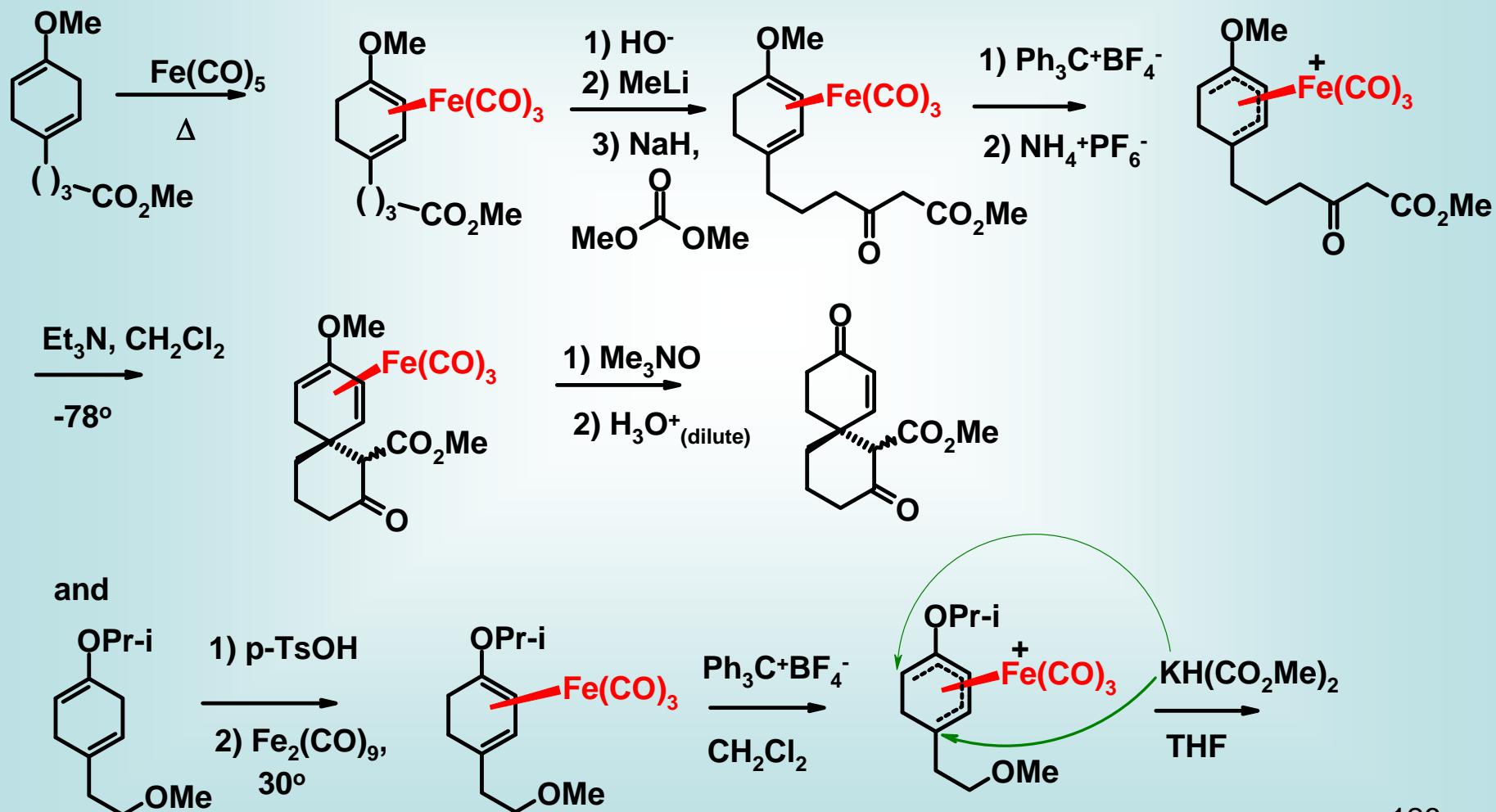
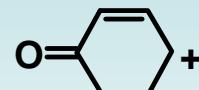
-widely used by Pearson's and Knolker's groups

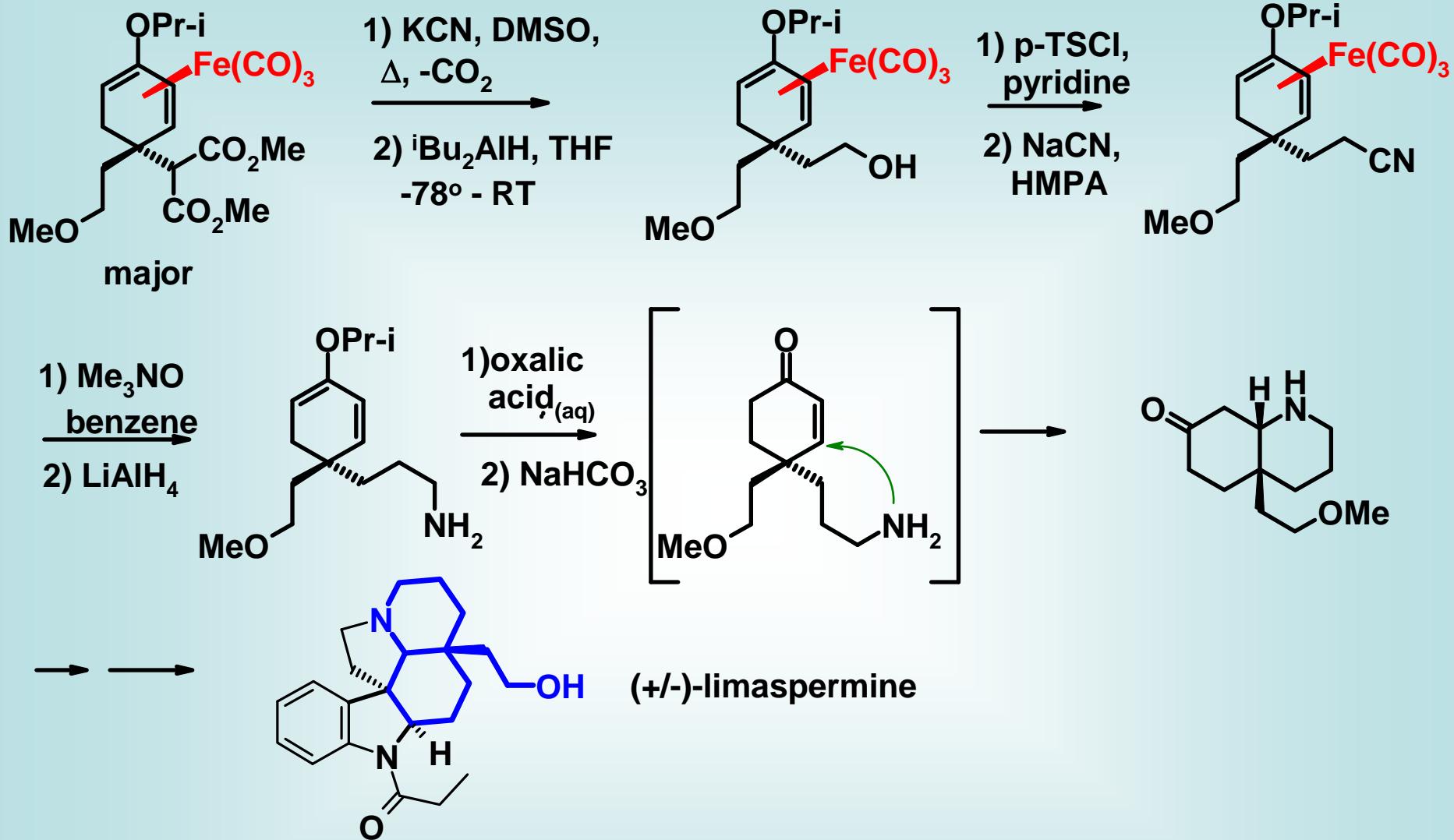
R *Synlett* **1992**, 371

R *Chem. Soc. Rev.* **1999**, 28, 151.

R Pearson, A.J. *Acc. Chem. Res.* **1980**, 13, 463.

Example: as equivalent of cyclohexenone γ -cation

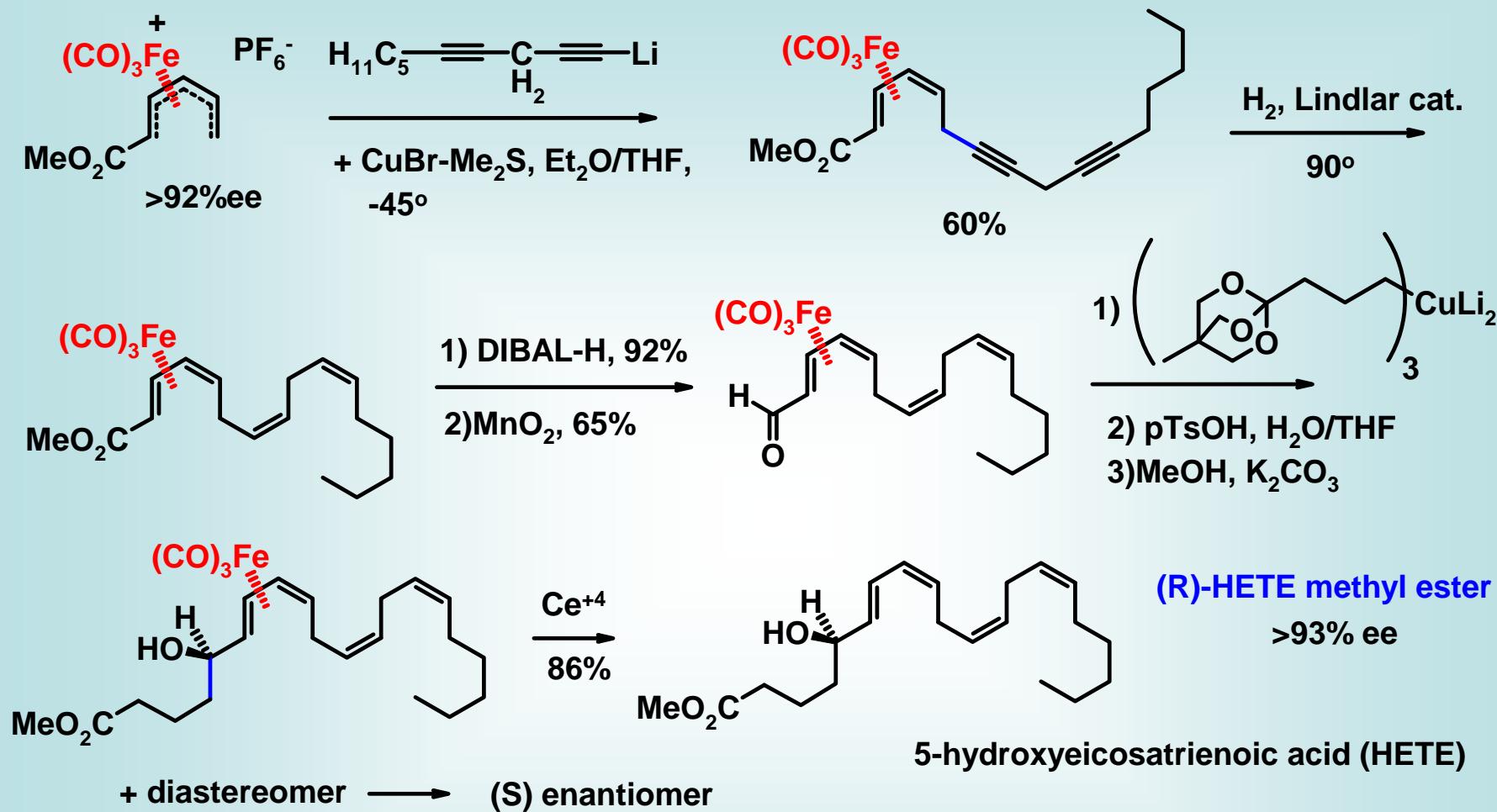




Other Pearson reviews:

R Science **1984**, 223, 895; *R* Pure Appl. Chem. **1983**, 55, 1767;
R Chem. Ind. **1982**, 741; *R* Knolker, H.J. *Chem. Soc. Rev.* **1999**, 28, 151.

Acyclics - synthesis of 5-HETE methyl ester



Tao, C.; Donaldson, W.A. *J. Org. Chem.* 1993, 58, 2134.

For other metal pentadienyls, see:

R Ernst, R.D. *Chem. Rev.* 1988, 88, 1255.

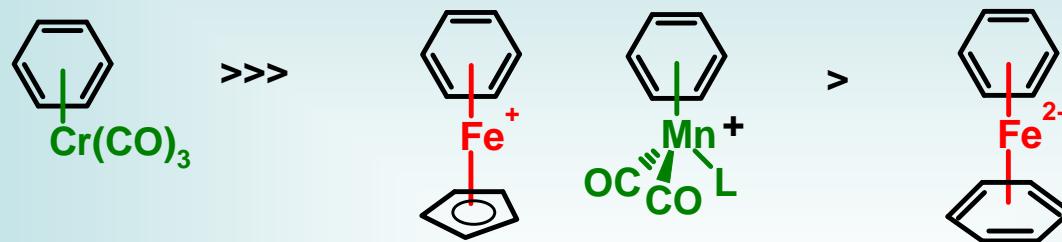
R Powell, P. *Adv. Organomet. Chem.* 1986, 26, 125.

η^6 -Triene Metal Complexes

-dominated by η^6 -benzene metal complexes

-very extensively developed; many, many complexes known

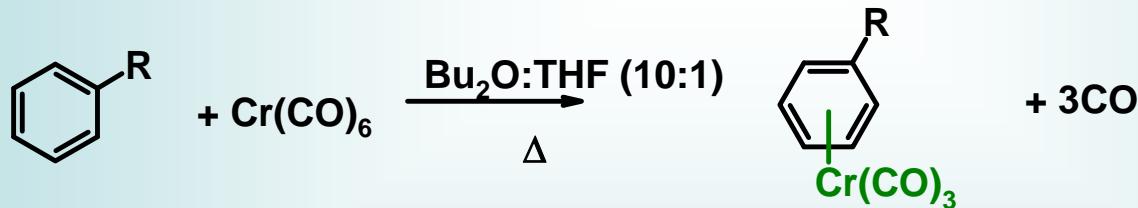
Order of Utility



Preparation of Complexes

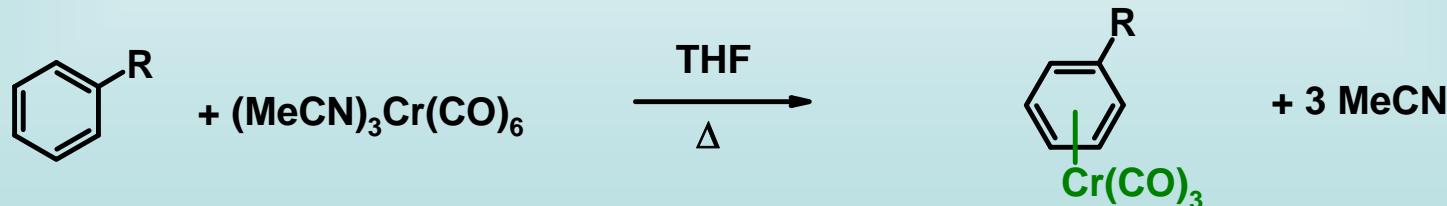
Chromium

a) Standard method - Arene + $\text{Cr}(\text{CO})_6$ + heat

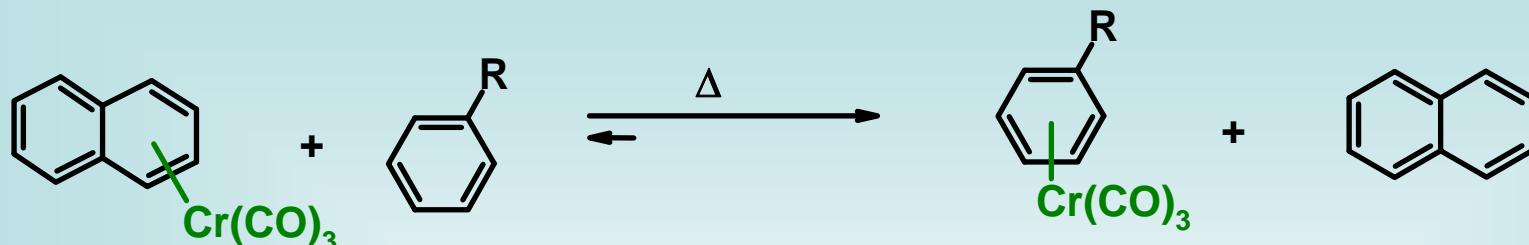


b) milder conditions - arene + $\text{L}_3\text{Cr}(\text{CO})_3$

L = is often acetonitrile - requires only ca. 70°



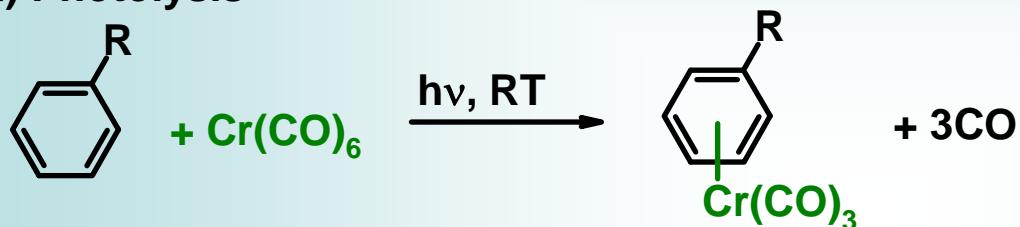
c) by arene exchange - one of the most weakly bound arenes is naphthalene, so



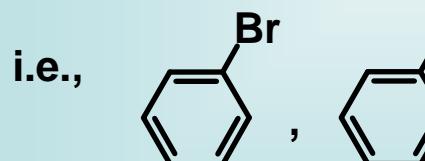
equilibrium is well to the right, normally

Kundig, E.P. et al *J. Organomet. Chem.* 1985, 286, 183.

d) Photolysis



e) last resort, from Cr(CO)(4-picoline)₃ + Lewis acid

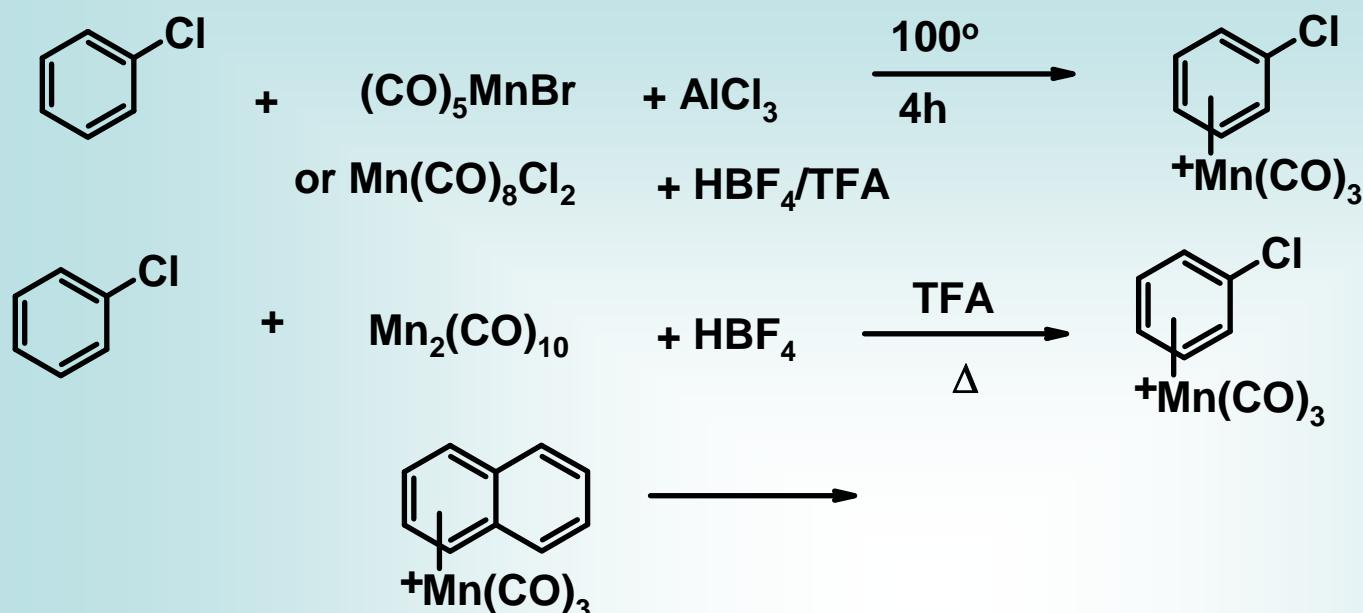


don't work at all under normal conditions,
due to oxidative addition

They do complex under these conditions, although the yields are poor

Ofele, K. *Chem. Ber.* 1966, 99, 1732.

Complexes of Mn



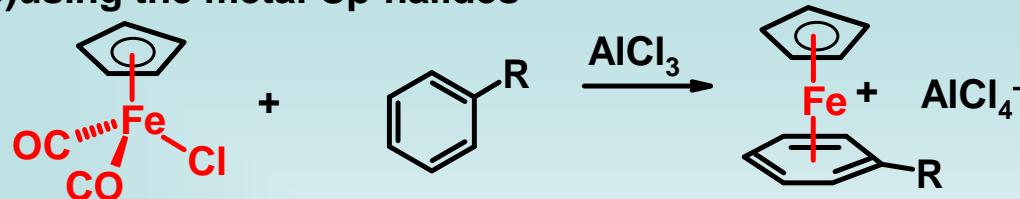
R Sun. S.; Dullaghan, C.A.; Sweigart, D. A. *J. Chem. Soc., Dalton Trans.* 1996, 4493.

Complexes of Iron

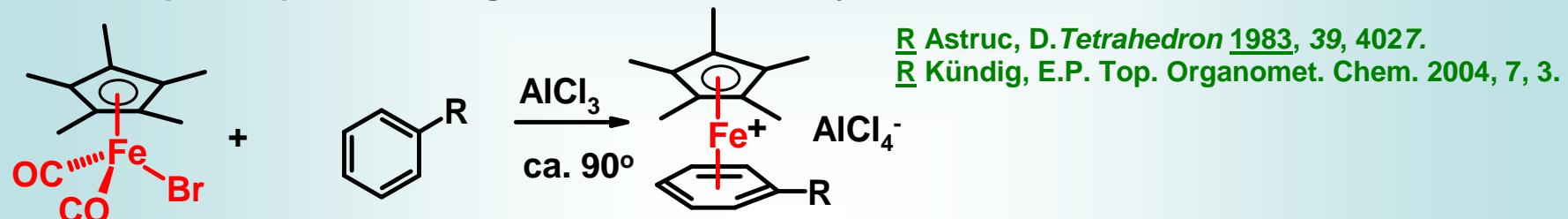
a) Ligand exchange with ferrocene



b) using the metal Cp-halides



original prep, but not used much any more for Cp complexes
-for Cp* complexes, though, it's the default way

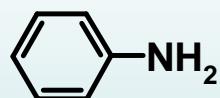


Electronic Effects in η^6 -Complexes

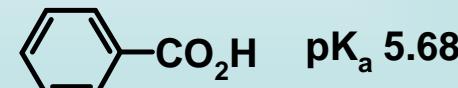
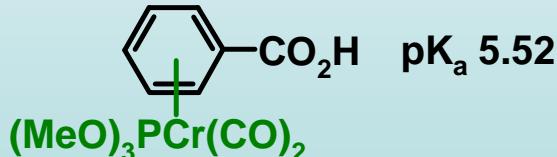
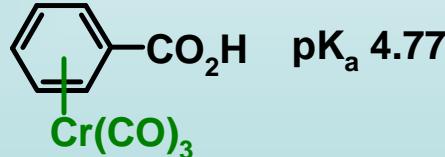
-complexation of the arene by Cr(CO)₃ clearly results in a net withdrawal of π -electron density



is a weaker base than

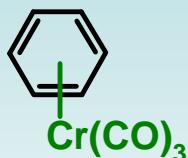


and



Consider $\text{O}_2\text{N}-\text{C}_6\text{H}_4-\text{CO}_2\text{H}$ pK_a 4.48

Therefore,



is often considered electronically equal to.....

-this inductive electron withdrawing ability, as well as resonance electron donating and resonance electron withdrawing ability, contributes to the reactions that arene- $\text{Cr}(\text{CO})_3$ will undergo

-we will discuss these as we encounter them

Nucleophilic Additions to Arene-M

R Pape, A.; Kaliappan, K.P.; Kundig, E.P. *Chem. Rev.* 2000, 100, 2917.
R Top. Organometal. Chem. 2004, 7, Ch.4

background



is not normally a commonly feasible reaction, unless the arene has some strongly electron withdrawing group(s) on it...

But....



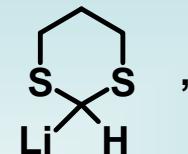
further reaction

is absolutely viable

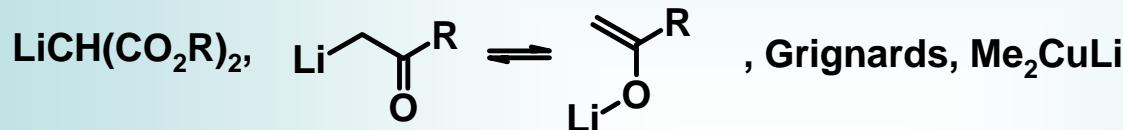
A

-in 'normal' cases, nucleophiles which work in this process are limited to ones whose conjugate acid (i.e., Nu-H⁺) has a pK_a > 20

-therefore, successful nucleophiles include...



Unsuccessful ones..

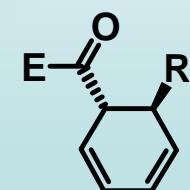


Note: ⁿBuLi, MeLi, ^sBuLi do *different* reactions

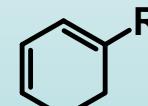
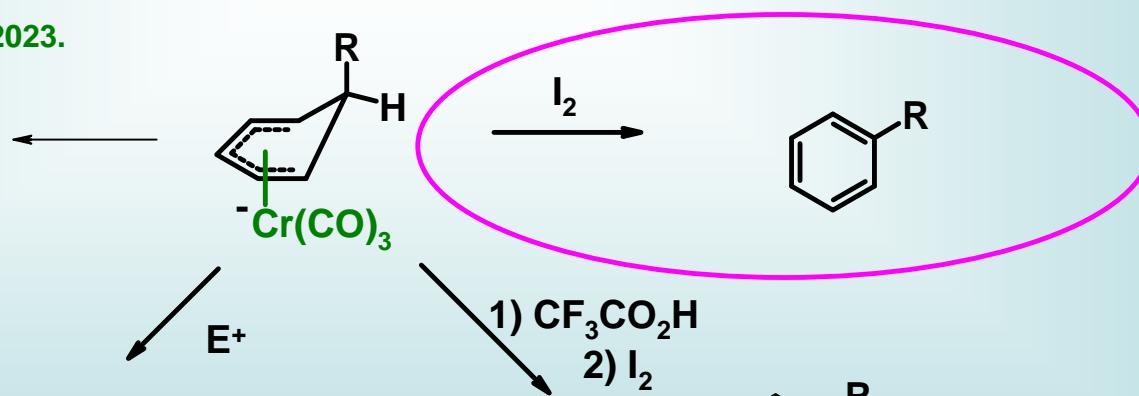
So what does one do with the reaction intermediates, i.e., A ?

Chem. Eur. J. 1998, 4, 251;
Helv. Chem. Acta 1997, 80, 2023.

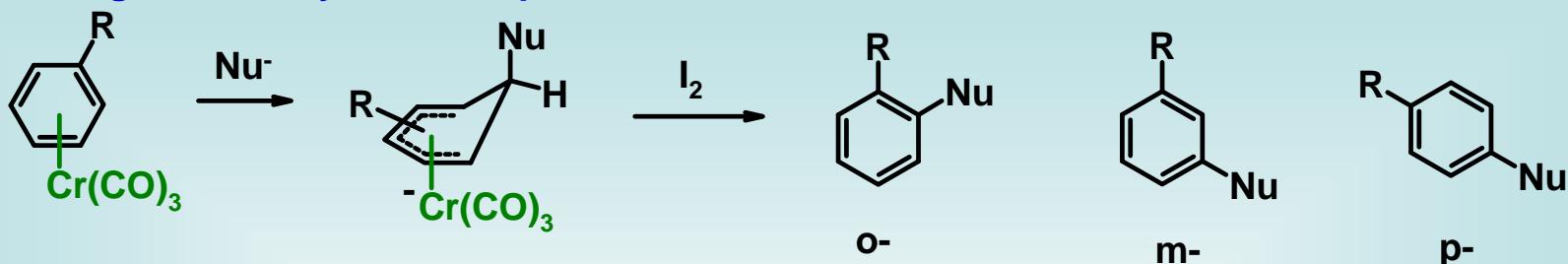
several instances
not that reliable



in some
cases



Regiochemistry of Nucleophilic Attack



-do get mixtures under these conditions, but the general rules are.....

R = electron donating ($-\text{OCH}_3$, $-\text{CH}_3$, $-\text{NMe}_2$)

meta (major)

R = electron donating and large ($-\text{SiMe}_3$, $-\text{tBu}$, $-\text{CH}(\text{tBu})_2$)

para (major)

R = electron withdrawing (i.e., CF_3)

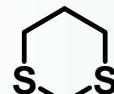
para (major)

R = electron withdrawing and coordinating

ortho

-considerable variation with size of nucleophile

-sterically smaller nucleophiles, such as $-\text{CH}_2\text{SPh}$, give substantial ortho substitution



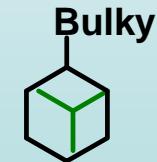
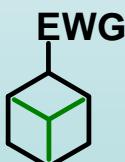
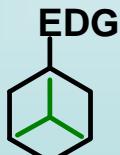
-Note: these are under kinetic conditions (-78°)

Why this regiochemistry?

-best guess - a combination of charge and orbital control

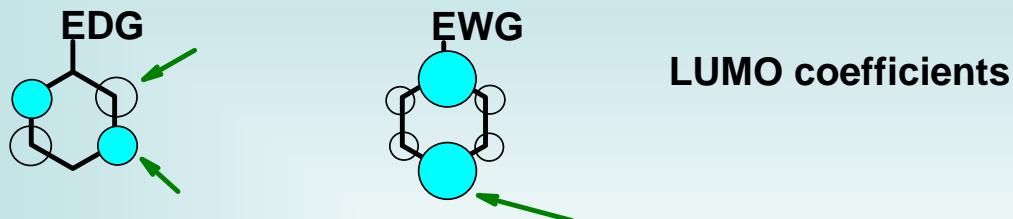
-charge control - charge induced by preferred M-CO conformation

-arene C's eclipsed by Cr-CO are attacked preferentially



Frontier Orbital Control

-attack occurs at the lowest unoccupied arene centred M.O. (LUMO)



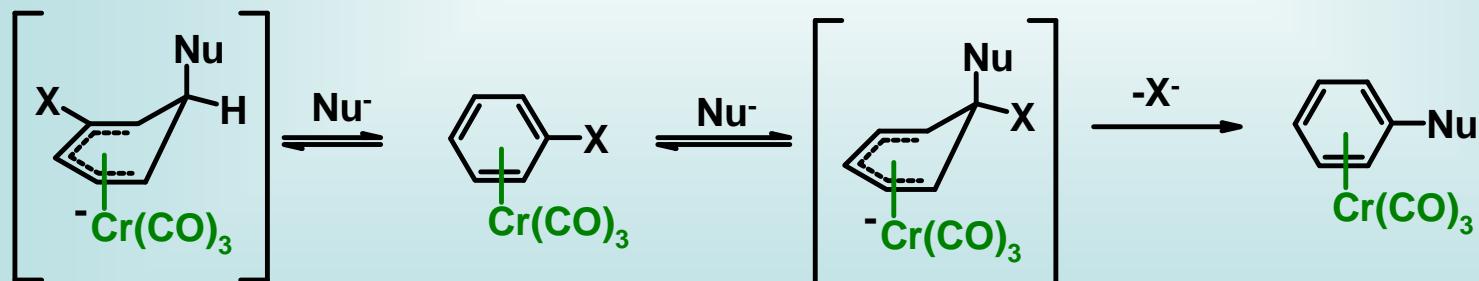
-the argument is that if there is a good energy match between the LUMO of the arene- $\text{Cr}(\text{CO})_3$ and the HOMO of the nucleophile, then orbital control is favoured
-in the absence of this match, charge control operates

see Semmelhack, M.F. et al *Organometallics* 1983, 2, 467.

Thermodynamic Control

-it was later realized that this addition to the arene- $\text{Cr}(\text{CO})_3$ is reversible in many cases; this has a couple of consequences

1) if there is a leaving group present, one should be able to.....



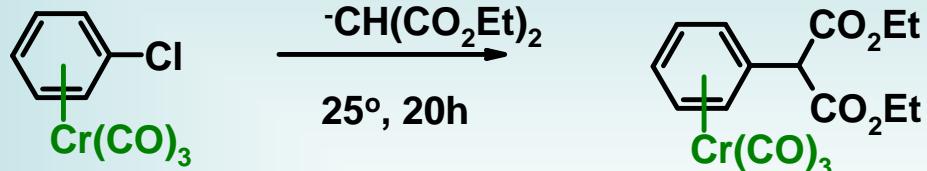
-this is possible, especially for $X = \text{F}$

$X = \text{F} > \text{Cl}, \text{OPh} \gg \text{others}$

2) some nucleophiles which don't give noticeable amounts of addition in non-X bearing cases now work well

i.e., NaOMe,, R₂NH, -CN, -CH(CO₂E_t)₂ now work

thus



Semmelhack, M.F. et al
J. Am. Chem. Soc. **1974**, *96*, 7091, 7092.

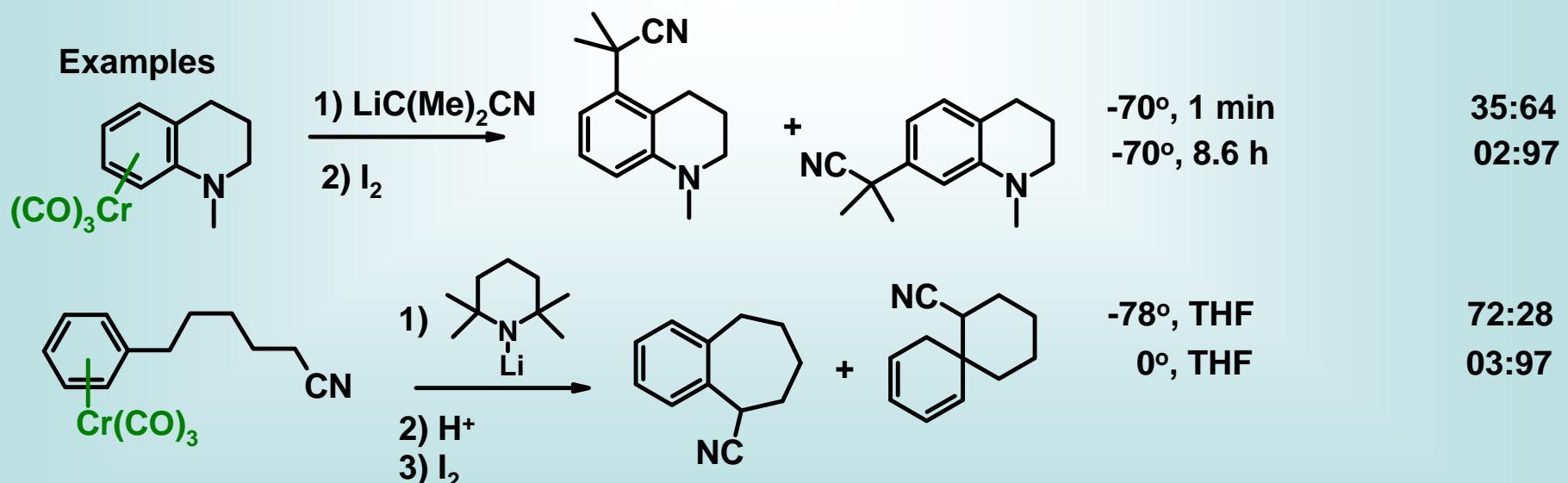
-another consequence

-difference in regiochemistry of addition at different T

-apparent that methoxy still prefers to be *meta*- to nucleophile under thermodynamic conditions

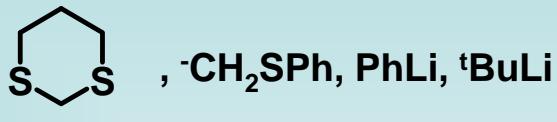
-other substituents are much less predictable

Examples



Semmelhack, M.F. et al *J. Am. Chem. Soc.* **1977**, *99*, 959; Ohlsson, B.; Ullenius, C. *J. Organomet. Chem.* **1984**, *267*, 137, C34

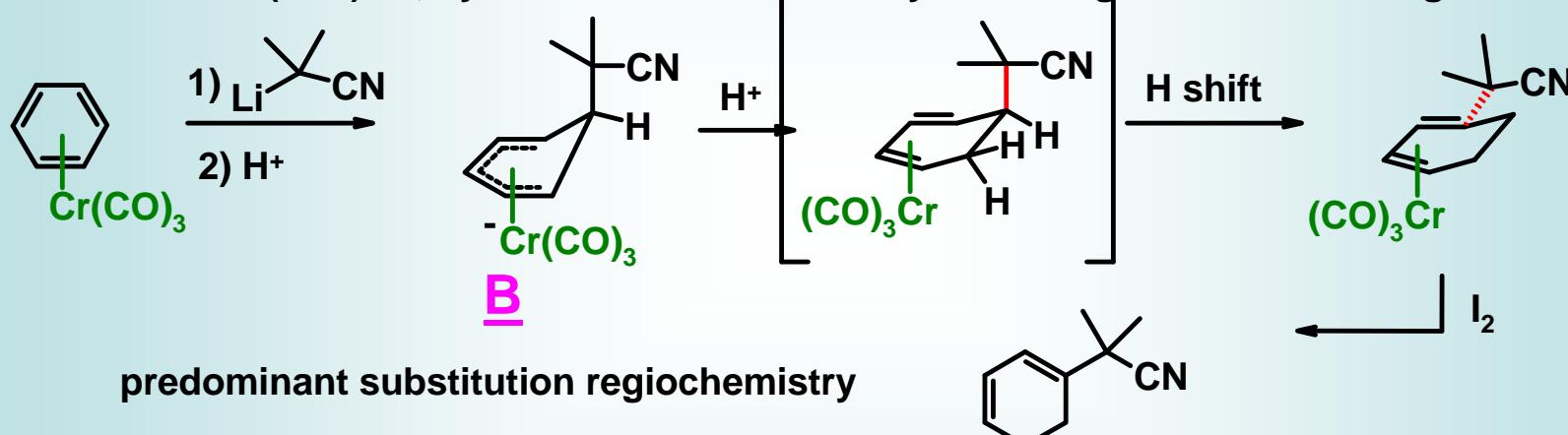
Note: A couple of nucleophiles that do add kinetically do not undergo reversible reaction



Kundig, E.P. et al *J. Am. Chem. Soc.* 1989, 111, 1804.
R Kundig, E.P. *Pure Appl. Chem.* 1985, 57, 1855.

Reaction with protic workup

-if a careful work is done using a proton source instead of I_2 , one gets reduced arene complex which then loses Cr easily - since the transient complex is coordinatively unsaturated ($16e^-$) Cr, hydride shifts occur readily and one gets diene rearrangement



-except



methoxy has very high preference for 1-position

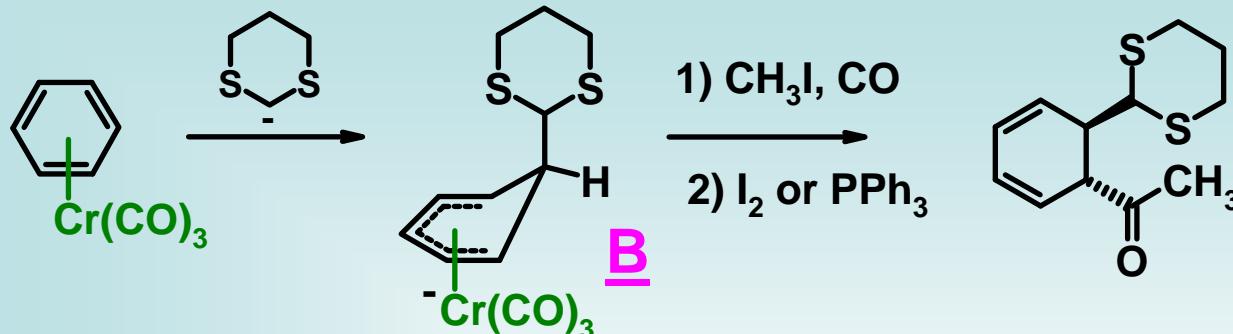
Alkylation of anionic intermediates

-if the incorporated Nu^- is one of the irreversible ones



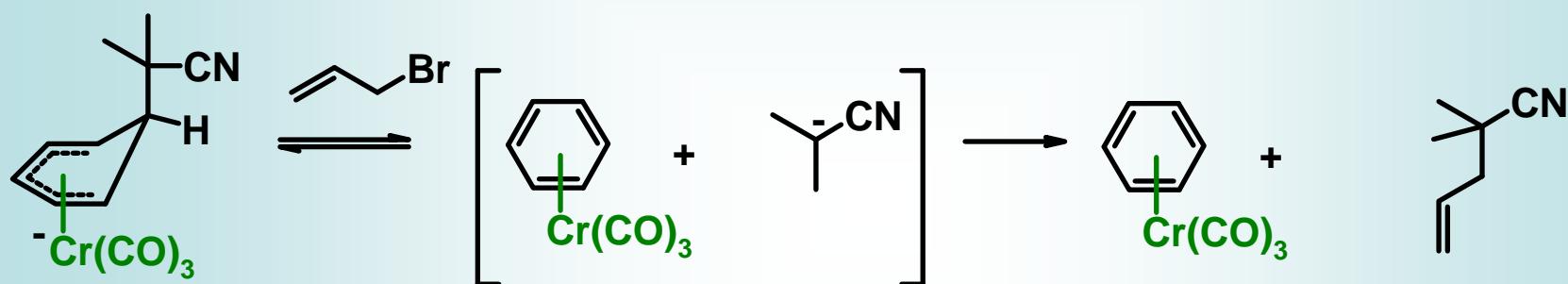
-then the anionic intermediate **B** can be alkylated with 1° alkyl, allylic, benzylic, propargylic iodides, bromides, or sulphonates,

BUT(!), the reaction usually goes with CO insertion (there are exceptions)

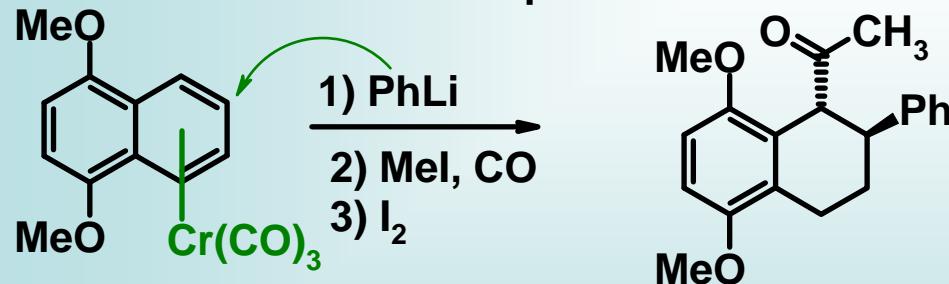


notice stereochemistry
E⁺ attacks from same
side as the metal
-therefore, trans addn

-conversely, nucleophiles which add reversibly fail



-another successful example



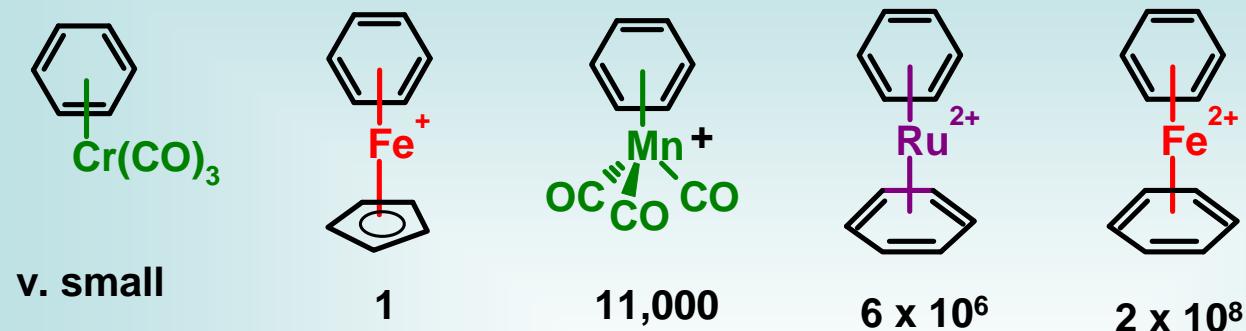
Kundig, E.P. *J. Org. Chem.* 1994, 59, 4773.
Top. Organomet. Chem. 2004, 7, ch 5

Improving Reactivity - Other Metals

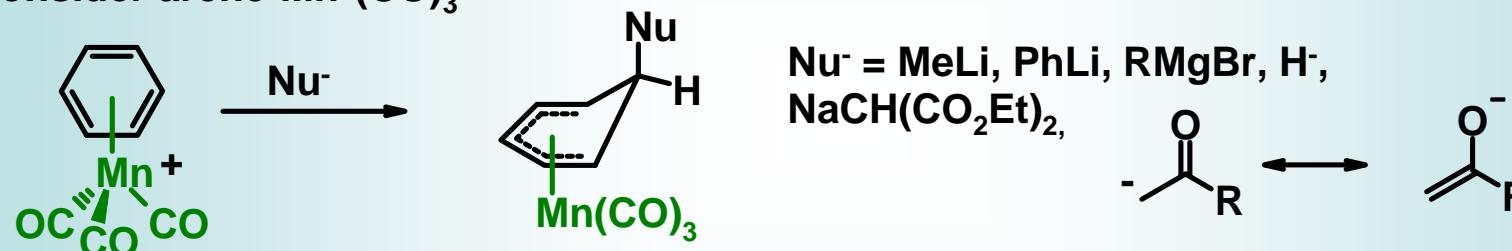
-definite limits on the nucleophilic attack on arene-Cr(CO)₃

-therefore, there is some use for other, more electrophilic, M-arene complexes here

The relative rates of reaction of many of the complexes are known

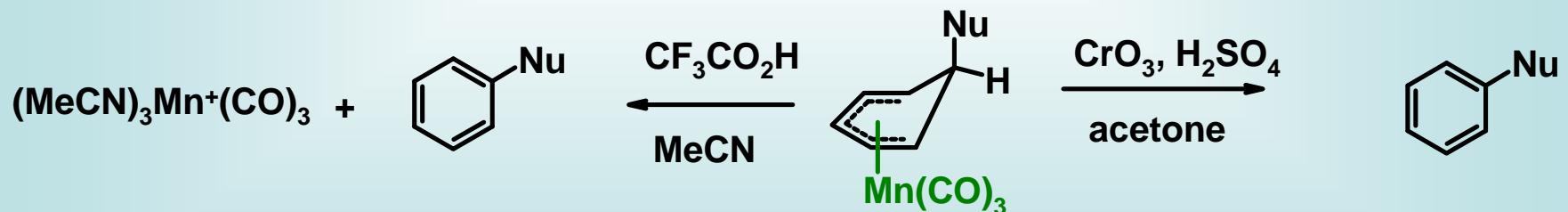


Consider arene-Mn⁺(CO)₃



Note: :CN and :PPh₃ add, but are reversible

-so what now?



-other chemistry is possible with the intermediate dienyls, but it's beyond the scope of the course