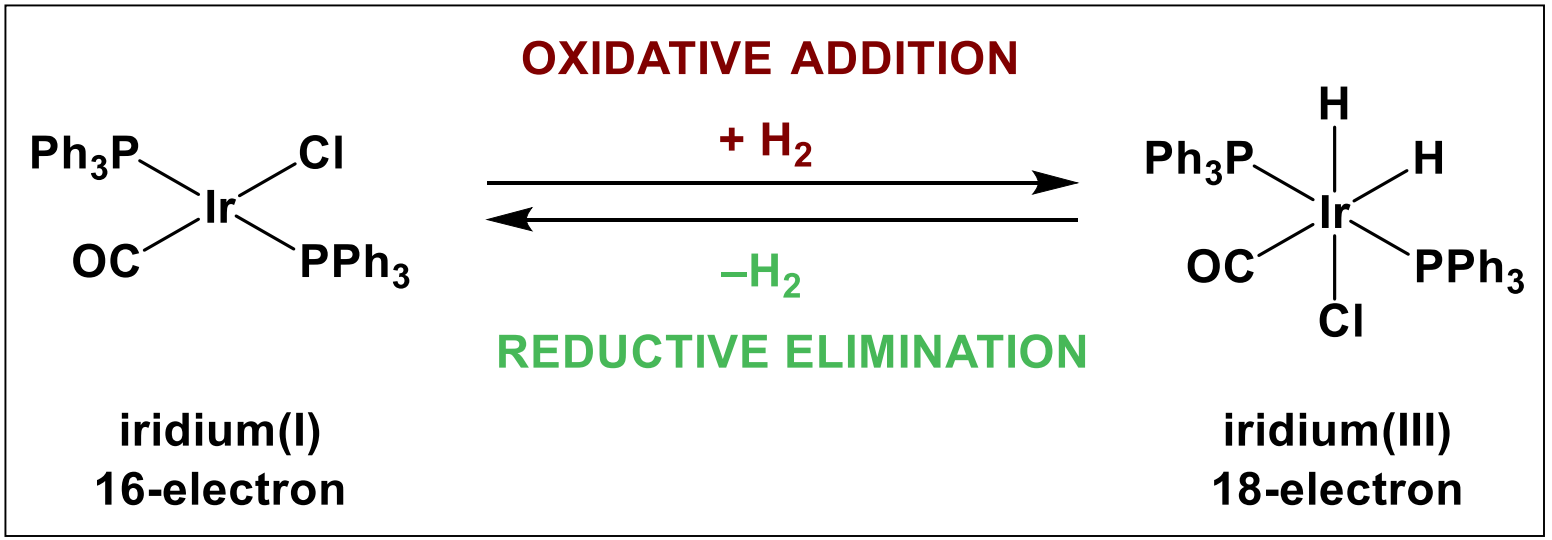
Oxidative Addition/Reductive Elimination

OXIDATIVE ADDITION

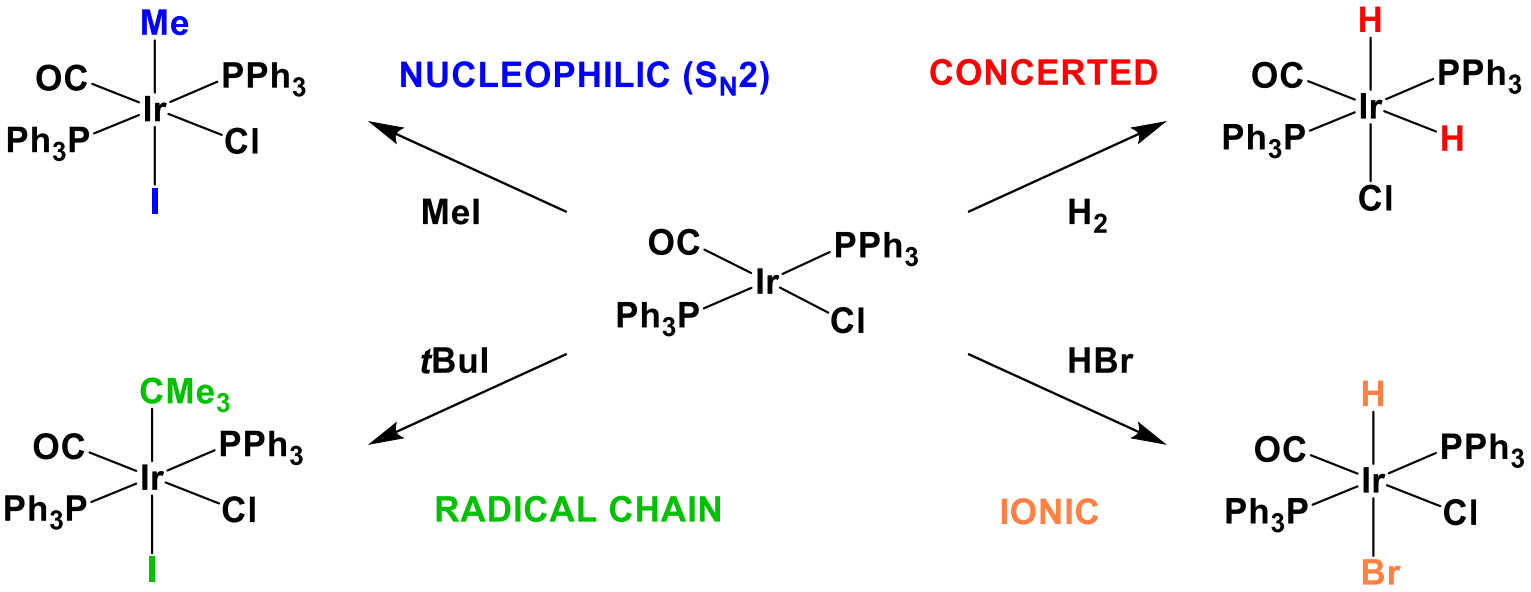
- Addition of R–X (*e.g.* H_2, $HSiR_3$, HBR_2, ArI, HCl) to the metal.
- Metal oxidation state increases by 2 units (e.g. $Ir^{I} \rightarrow Ir^{III}$).
- Various mechanisms possible (concerted, S_N2, Radical x 2, Ionic – *see later*).
- Familiar main group example = Mg + ArBr → ArMgBr Grignard.

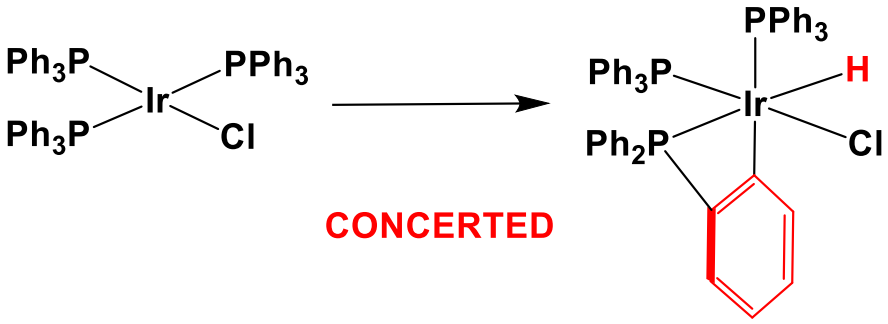
REDUCTIVE ELIMINATION

- Opposite of Oxidative Addition



Oxidative Addition Mechanisms

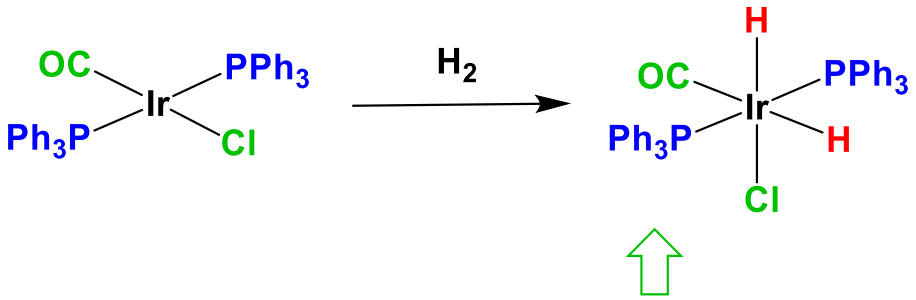




Intramolecular OA = Cyclometallation (or just metallation)

Concerted Oxidative Addition (of H_2)

- Concerted O.A. is typical for non-polar substrates (H_2, H–C, H–Si, H–B)



THERMODYNAMICS for O.A. of H_2 = OK

H_2 dissociation energy = 104 kcal mol^{-1}

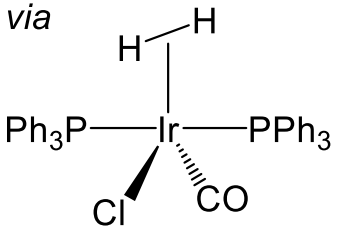
2 x Ir–H bonds = 120 kcal mol^{-1}

ΔS = –30 e.u.

ΔG = –7 kcal mol^{-1} at 25 °C

Cl and CO are *cis* to one another

via



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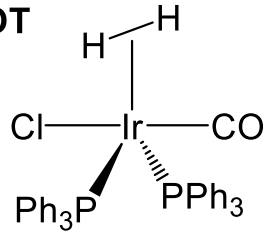
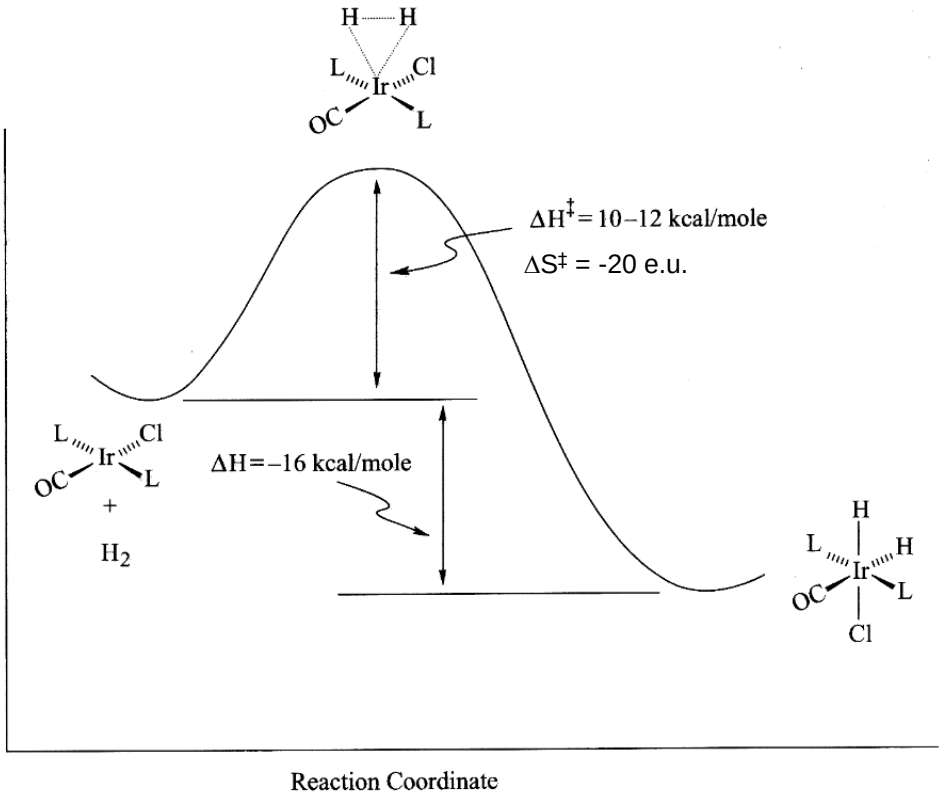
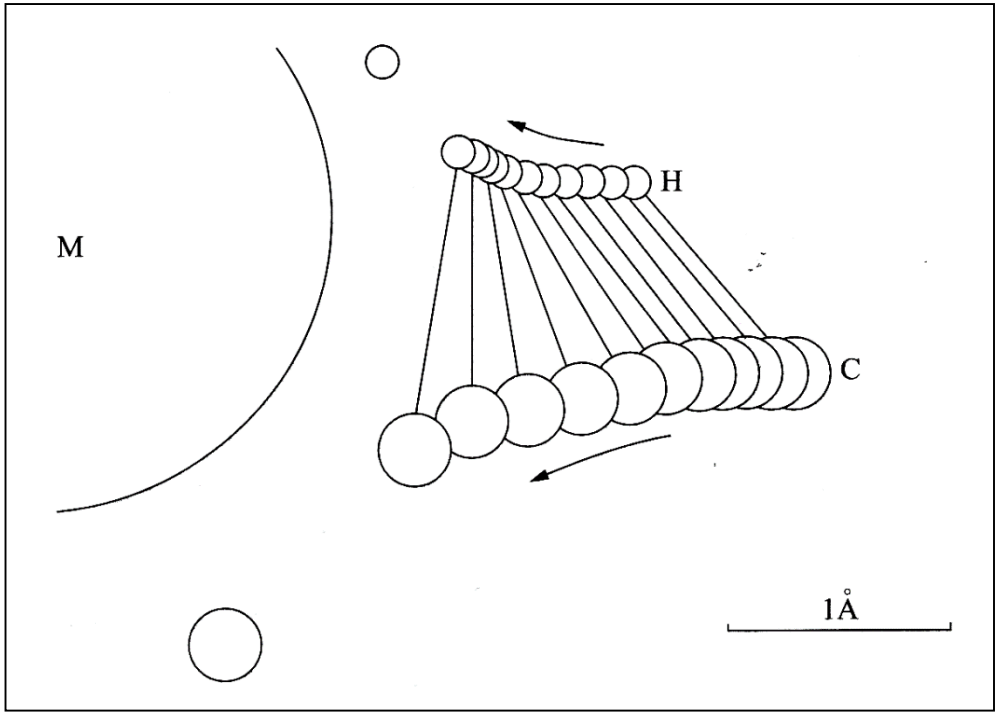


Lower energy TBP transition state if the strongest π-acceptor ligand is in the equatorial plane - very similar to the trans effect (for associated substitution in square planar complexes).

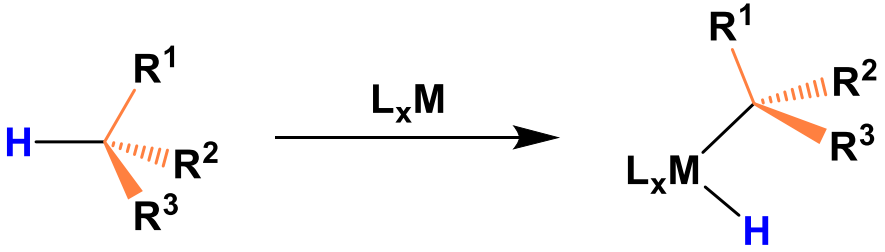


Concerted Oxidative Addition (C–H bonds)

- C–H bond O.A. could be a very important means to convert abundant, cheap but unreactive hydrocarbons (*e.g.* methane, benzene) into more complex products.

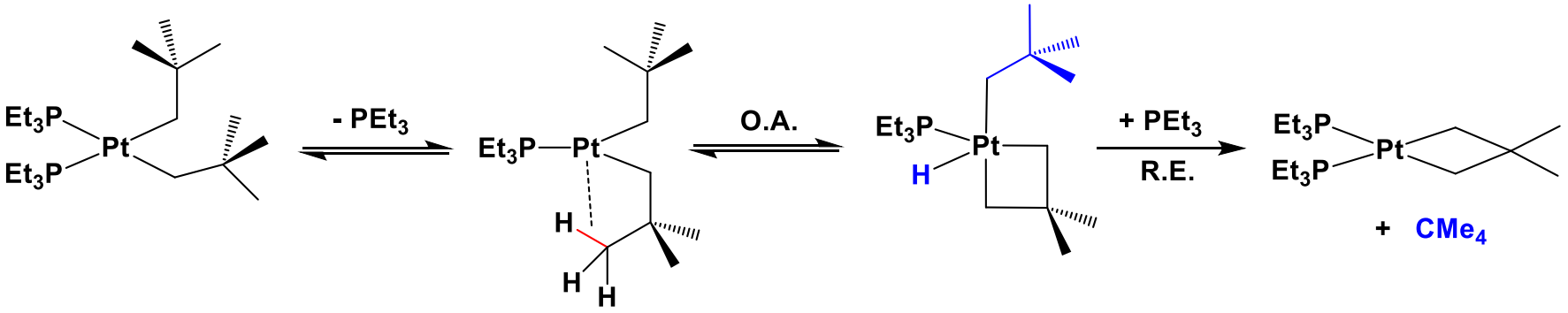


- Concerted Mechanism → **retention of configuration**

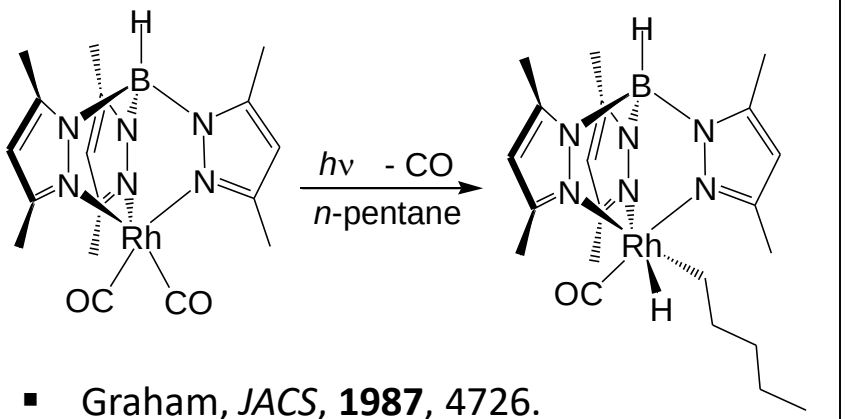


Concerted Oxidative Addition (C–H bonds)

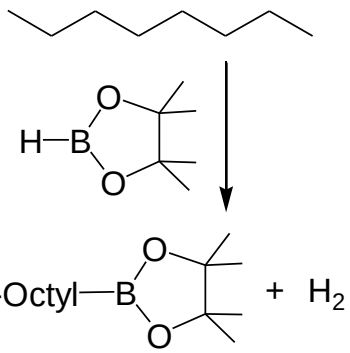
- Intramolecular C–H bond activation → abundant



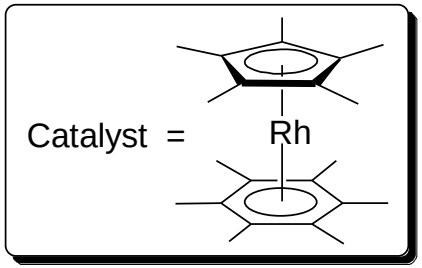
- Intermolecular C–H bond activation → rare



- Graham, *JACS*, **1987**, 4726.



- Hartwig, *Science*, **2000**, *297*, 1995.



Concerted Oxidative Addition (C–H bonds)

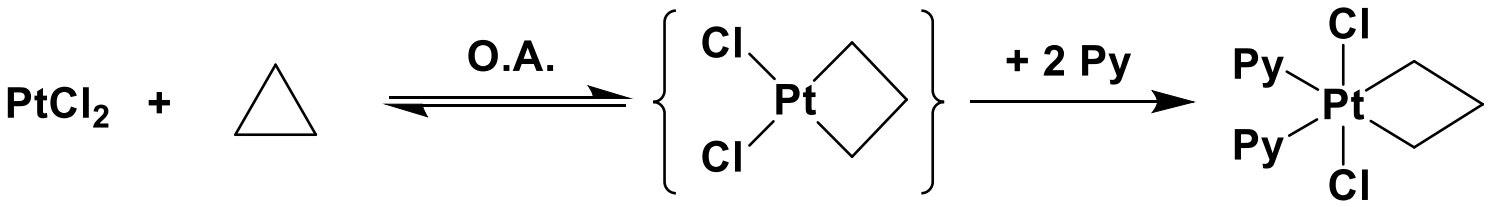
- **Problem with Intermolecular C–H bond activation: THERMODYNAMICS**
  - C–H bond ~95 kcal mol^{-1}, M–H ~60 kcal mol^{-1}, M–C = 30-45 kcal mol^{-1}
  - ΔS = negative ($L_xM + H\text{-}CR_3 \rightarrow L_xMH(CR_3)$)
  - ΔG = usually positive

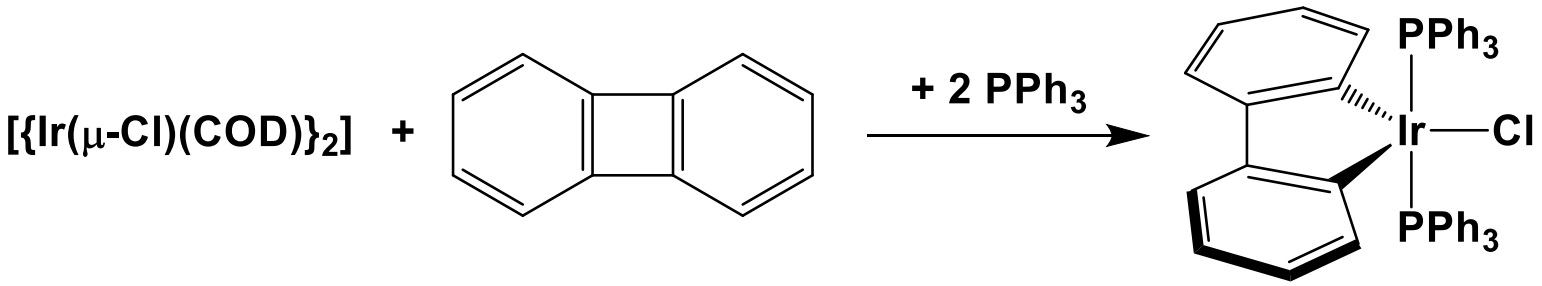
- **General Trends for C–H bond O.A.:**
  - H–Aryl > H–Alkyl [because M–Aryl is stronger than M–Alkyl (thermodynamic) and perhaps because prior h^2-arene coordination is possible (kinetic)]
  - 3rd row > 2nd row > 1st row (because M–C and M–H bond strengths increase down a group and higher oxidation states also become more accessible)

- **Intermolecular C–H bond O.A. is also more likely to be favorable when:**
  - Metal complex is coordinatively unsaturated
  - Metal complex is sterically uncongested
  - R-groups on the metal are themselves resistant to metallation
  - Metal has a filled orbital capable of interacting with the σ^*-orbital of the C–H bond

Concerted Oxidative Addition (C–C bonds)

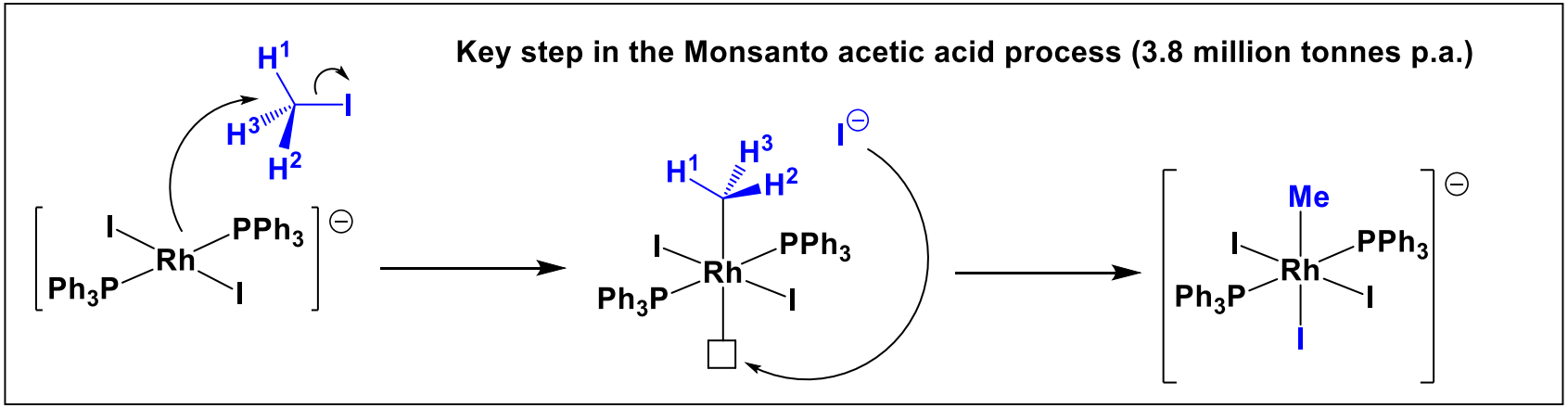
- **C–C bond O.A. could be a very significant reaction** → turn long-chain hydrocarbons into useful molecules (equivalent to the 'cracking' process)
- **Unstrained C–C bonds do not react with TM complexes for thermodynamic reasons**
- **Generally ONLY get C–C bond O.A. in strained molecules**





Nuclephilic (S_N2) Oxidative Addition

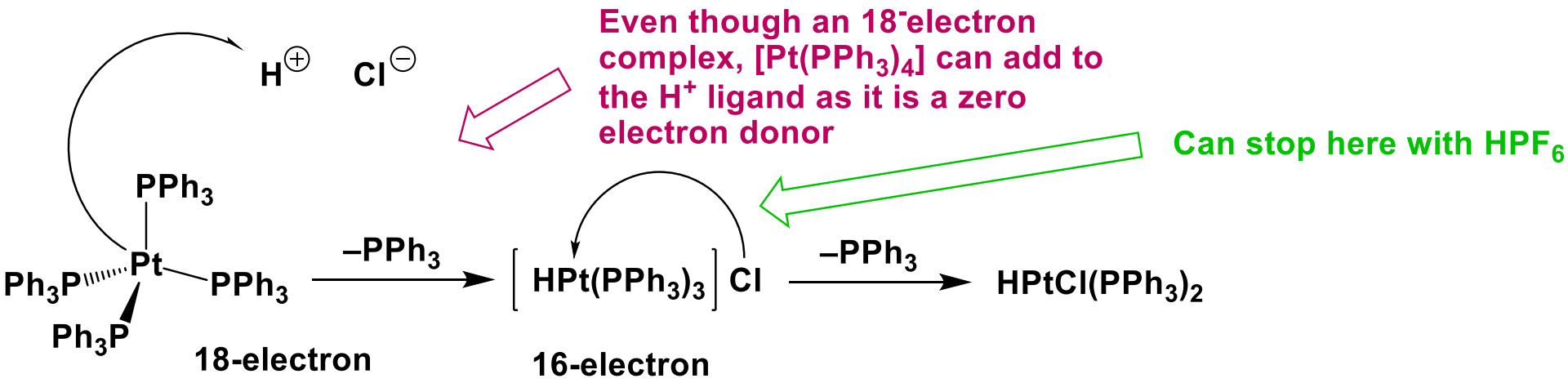
- Always get inversion of configuration at X–CRR'R''
- Typical R groups = Benzyl, Allyl, Acyl, Methyl, Ethyl
- Dependence on leaving group ability: CF_3SO_3 > I > Tosylate ~ Br > Cl
- Rate = *k*[RX][Complex] , $\Delta S^{\ddagger}$ = –40 to –50 e.u.
- Rate: $PhCH_2Br$ > PhCHBrMe (i.e. I° > II°)
- Faster in more polar solvents due to polar transition state

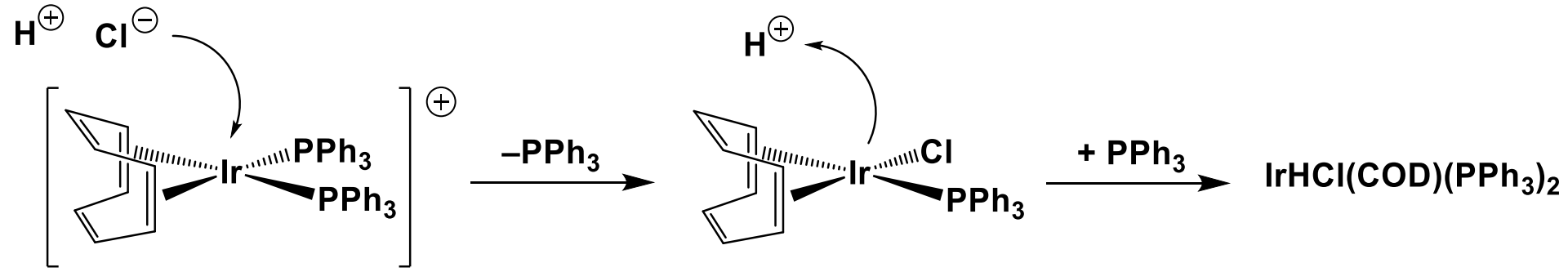


- Fastest for: more electron rich metals, low oxidation state metals, e^--donating ligands [PMe_3 > $P(OMe)_3$], small ligands on the metal (PMe_3 > P^tBu_3)

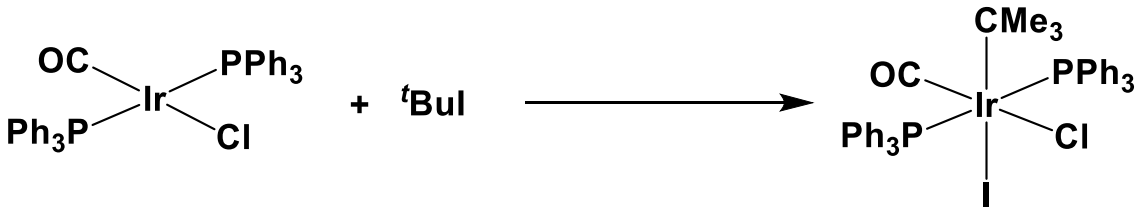
Ionic Mechanism of Oxidative Addition

- For HX that are largely ionized In solution (*e.g.* HCl, HBr)
- Either nucleophilic attack of X^- on the metal, or electrophilic attack of H^+ on the metal can occur as the 1st step.





Radical Chain Oxidative Addition



Initiation

$Init^{\blacksquare} + Ir(I) \longrightarrow Init—Ir(II)$

$Init—Ir(II) + R—X \longrightarrow Init—Ir(III)—X + R^{\blacksquare}$

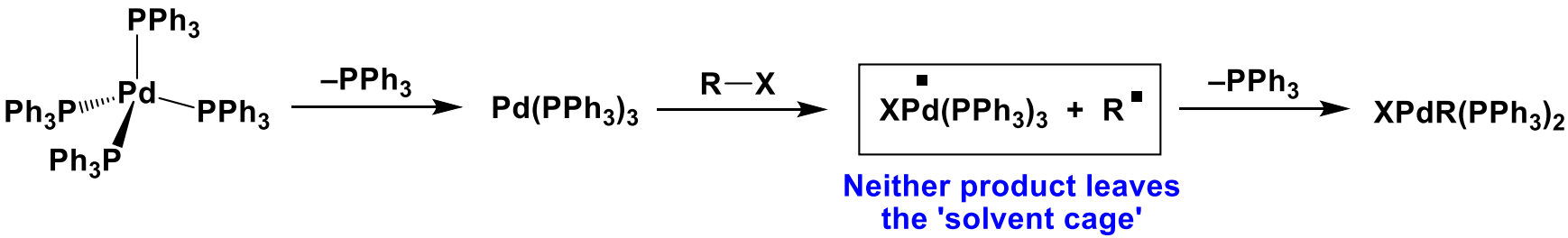
Propagation

$R^{\blacksquare} + Ir(I) \longrightarrow R—Ir(II)$

$R—Ir(II) + R—X \longrightarrow R—Ir(III)—X + R^{\blacksquare}$

- R–I > R–Br > R–Cl
- $III^{o} > II^{o} > I^{o}$ (correlates with the stability of the R• radicals)
- Accelerated by radical initiators (*e.g.* O_2 or peroxides)
- Retarded by radical inhibitors (*e.g.* duroquinone, galvinoxyl, tri-*tert*-butylphenol)
- **RACEMIZATION**

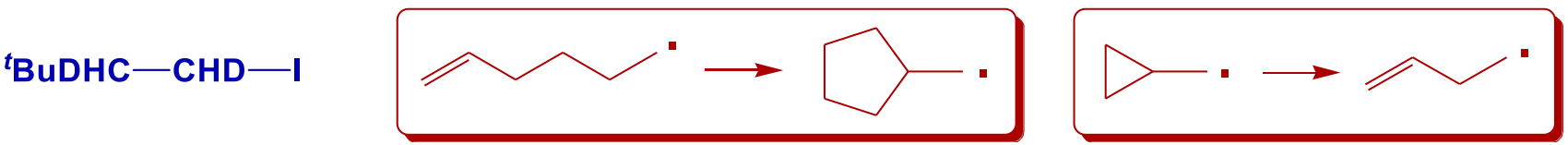
Non-chain Radical Oxidative Addition



- R–I > R–Br > R–Cl
- **RACEMIZATION**
- III° > II° > I° (correlates with the stability of the R• radicals)
- **Unaffected** by radical initiators (*e.g.* O_2 or peroxides)
- **Unaffected** by radical inhibitors
- Common for Ni^0, Pd^0, Pt^0

Useful Mechanistic Probes for O.A. of R–X

- Diastereomeric R–X → can probe the steroeochemistry of the α-carbon by NMR spectroscopy
- R–X Substrates that rearrange rapidly if R• is involved:



Oxidative Addition Mechanisms - Overview

OA Mechanism	Type of L_xM	Type of X–Y	Features
Concerted (3-centre addition)	(1) coord. Unsat., (2) sterically uncongested, (3) 3rd > 2nd >> 1st row TM, (4) filled orbital capable of interacting with the s* orbital of incoming X-Y → Often d^8 complexes [*e.g.* $IrCl(CO)(PR_3)_2$].	Fairly non-polar substrates: H–H, R_3C–H, R_3Si–H strained R_3C-CR_3, Ar–X not very common	(1) *cis*-addition (2) retention of config. at RR'R"C–Y (3) 2nd order, $\Delta S^{\ddagger}$ ~ –30 e.u., rate *not* greatly affected by solvent polarity.
Nucleophilic (S_N2)	Nucleophilic metals *e.g.* $IrCl(CO)(PR_3)_2$, $Ni(PR_3)_4$, $Pd(PR_3)_n$	Polarized substrates: R_3C–X (1° > 2° > 3°) (MeI > EtI > ^{i}PrI), Also Cl_2, Br_2, I_2	(1) *cis*- or *trans*-addition (2) inversion of config. at RR'R"C–Y (3) 2nd order, $\Delta S^{\ddagger}$ ~ –40 to –50 e.u., rate accelerated in polar solvents.
Radical (chain or non-chain mechanisms)	Non-chain = $Ni(PPh_3)_3$, $Pt(PPh_3)_3$ Chain = $IrCl(CO)(PMe_3)_2$ Binuclear = $Mn_2(CO)_5$, $Co(CN)_5^{3-}$	R_3C–X, R_3Sn–X (3° > 2° > 1°)	(1) *cis*- or *trans*-addition (2) racemization of RR'R"C–Y (3) only the radical chain mechanism is accelerated by radical initiators and retarded by radical inhibitors
Ionic (H^+ or X^- attacks first)	(a) 18 e^- $Pt(PPh_3)_4$ + H^+Cl^- (H^+ attacks first) (a) 16 e^- $Ir(COD)(PR_3)_2^+$ + H^+Cl^- (Cl^- attacks first)	H–X (largely dissociated in solution)	

Oxidative Addition Mechanisms - Overview

- **In general :** Non polar substrates (*e.g.* H–H, C–H, Si–H) → Concerted
  Halogens (Cl_2, Br_2, I_2) → Nucleophilic
  Alkyl halides → Nucleophilic (S_N2) or Radical
  Acids (HCl, HBr, HI) → Ionic

- For Alkyl Halides, distinguish a S_N2 or radical mechanism by determining whether 3^o, 2^o or 1^o R–X react faster, whether the reaction leads to racemization or inversion at RR'R"C–X, and whether the reaction is accelerated by radical initiators and retarded by radical inhibitors.

- For a radical mechanism, distinguish between a chain or non-chain process by whether the reaction is affected by radical initiators or inhibitors.

- If it is necessary to distinguish between a concerted or S_N2 mechanism, determine whether X and Y are *cis*- or *trans*-disposed in the product, whether the reaction leads to retention or inversion of stereochemistry in RR'R"C–X, and whether the reaction is accelerated in polar solvents.