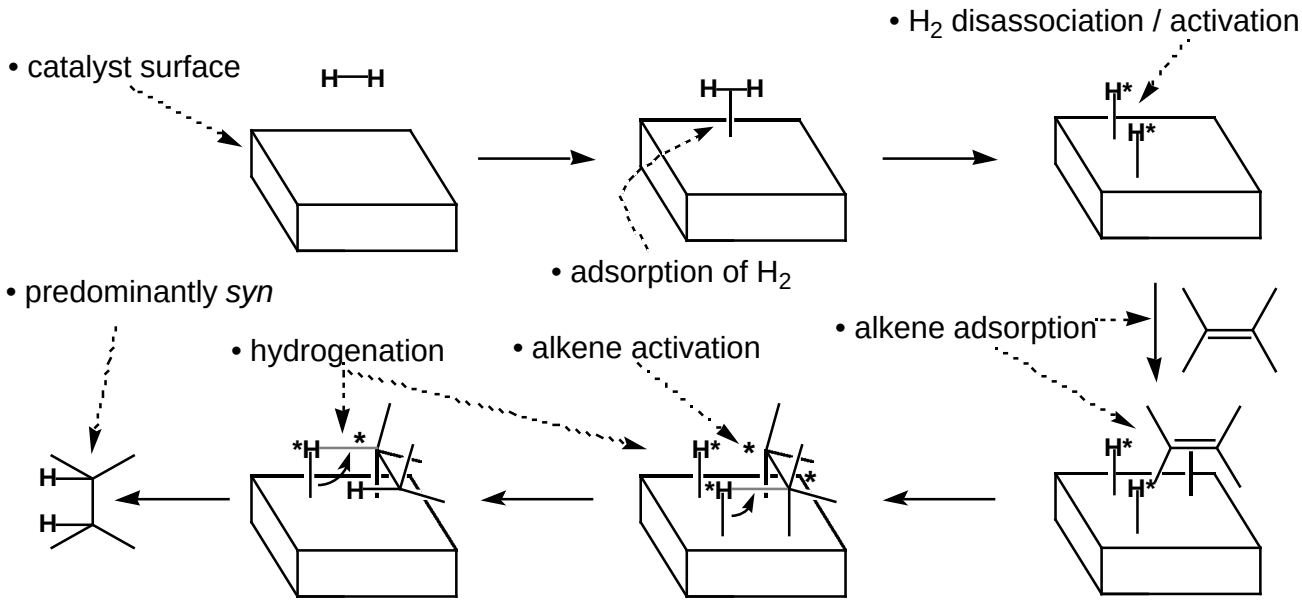
HYDROGENATION

• Concerned with two forms of hydrogenation: ***heterogeneous*** (catalyst insoluble) and ***homogeneous*** (catalyst soluble)

Heterogeneous Catalysis

• Catalyst ***insoluble*** in reaction medium
• Reactions take place on catalyst ***surface***
• Rate of reaction and selectivity dependant on ***active sites*** on surface
• ***Active sites*** are the part of the catalyst substrate and hydrogen can adsorb on
• By *blocking* or ***poisoning*** active sites the reactivity of a catalyst is reduced and the ***selectivity increased***
• Good poisons are *metal cations, halides, sulfides, amines and phosphines*
• Reaction is a ***surface phenomenon*** and not fully understood



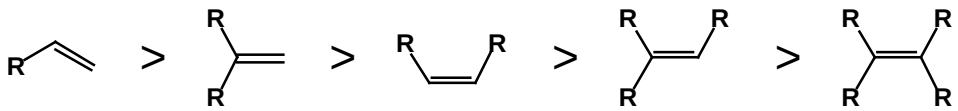
• Differences in catalyst arise due to ability of each metal to bind to various substrates and the different modes of binding

• **Order of Reactivity of Various Metals**

Pt = C=O >> C=C > {H} > Ar
Pd = C=C > {H} > C=O > Ar
Ru = C=O > C=C > Ar > {H}

{H} = hydrogenolysis
C–X → C–H

• **Order of Alkene Reactivity**

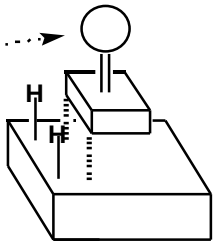


• **Note:** many other factors involved (eg. the release of ring-strain)
• Co-ordination of alkene on catalyst can lead to ***double bond isomerisation***
• Possibility of migration related to the degree of *reversibility* of co-ordination
• Pd ***allows migration*** presumably *via* reversible co-ordination
• Pt essentially binds irreversibly resulting in ***no isomerisation***

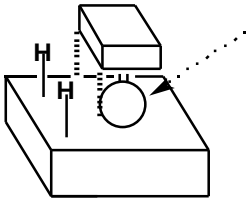
Stereoselectivity

• Mechanism (*vide supra*) indicates the addition is predominanly ***syn***
• As substrate and hydrogen are both bound to surface addition occurs from the ***least hindered face*** as more readily binds to surface)
• **Problem:** isomerisation can lead to ***anti*** addition
• **Problem:** predicting which face will bind to surface not as simple as above statement suggests
• ***Haptophilicity*** is the ability of a functional group to anchor to the surface and ***direct*** which face of alkene co-ordinates

• functional group



• normally hydrogen adds from least hindered side

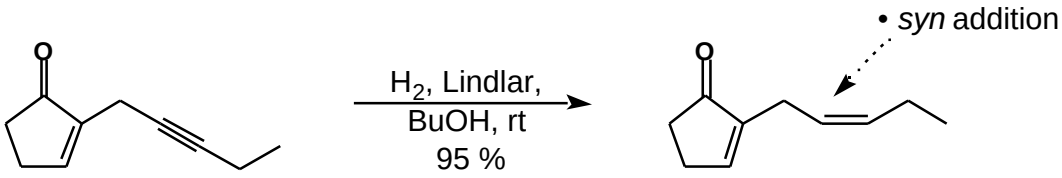


• functional group attracted to surface

• hydrogen adds from opposite face

Alkynes

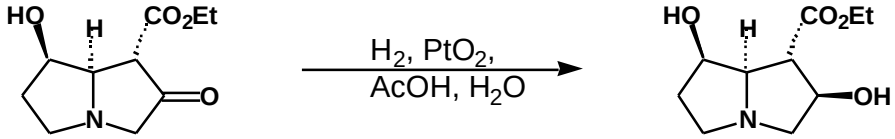
• ***Lindlar catalyst (Pd / $CaCO_3$ / PbO)*** optimum catalyst to prevent *over-reduction* and *cis / trans isomerisation*



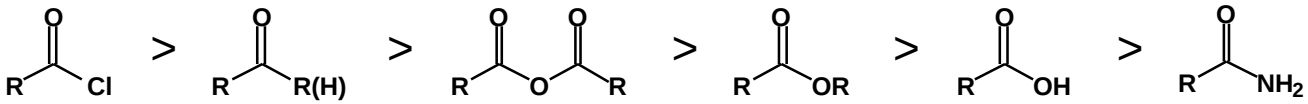
Heteroatom Hydrogenations

Carbonyl Moiety

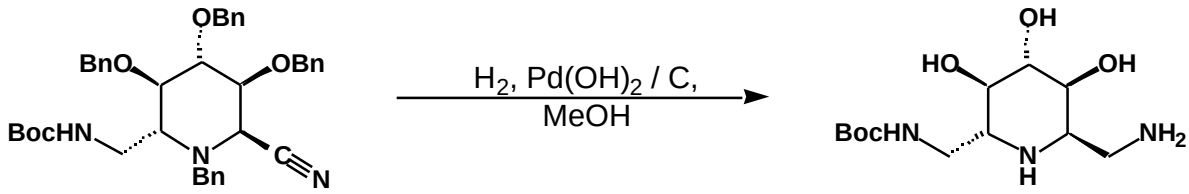
• Can be hydrogenated
• Stereoselectivity hard to predict so prefer hydride reagents
• ***Platinum*** reagents preferred as C=O faster than C=C (*vide supra*) especially when poisoned



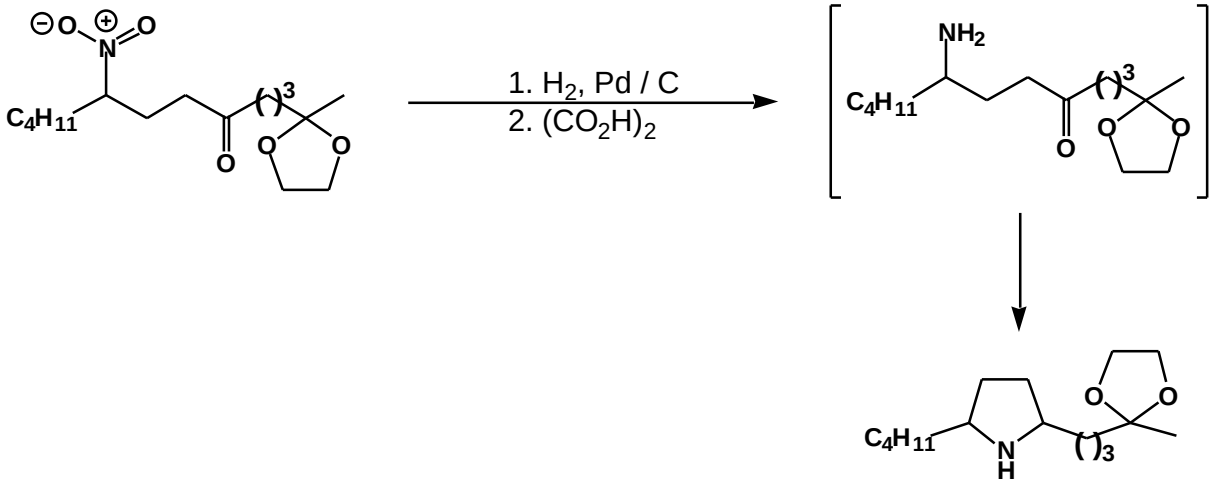
• Order of carbonyl reduction



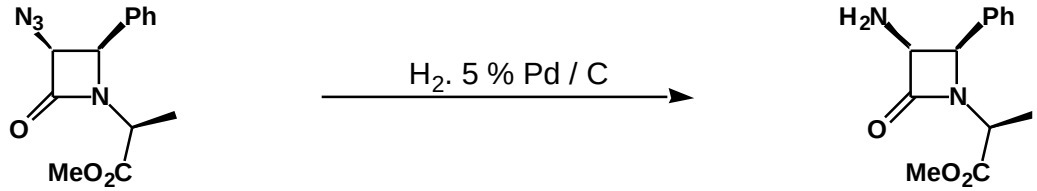
Nitriles



Nitro Group



Azides



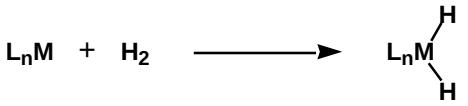
Homogeneous Catalyst

- Soluble in reaction medium
- Mechanisms much better understood
- **Advantages:** mild conditions (non-polar solvents which dissolve H_2 better)
- **Advantages:** less catalyst required (each molecule is available for reaction and not just surface)
- **Advantages:** improved or complimentary selectivity (far more predictable)
- **Advantages:** directed hydrogenations
- **Advantages:** asymmetric hydrogenations

Alkene Hydrogenation

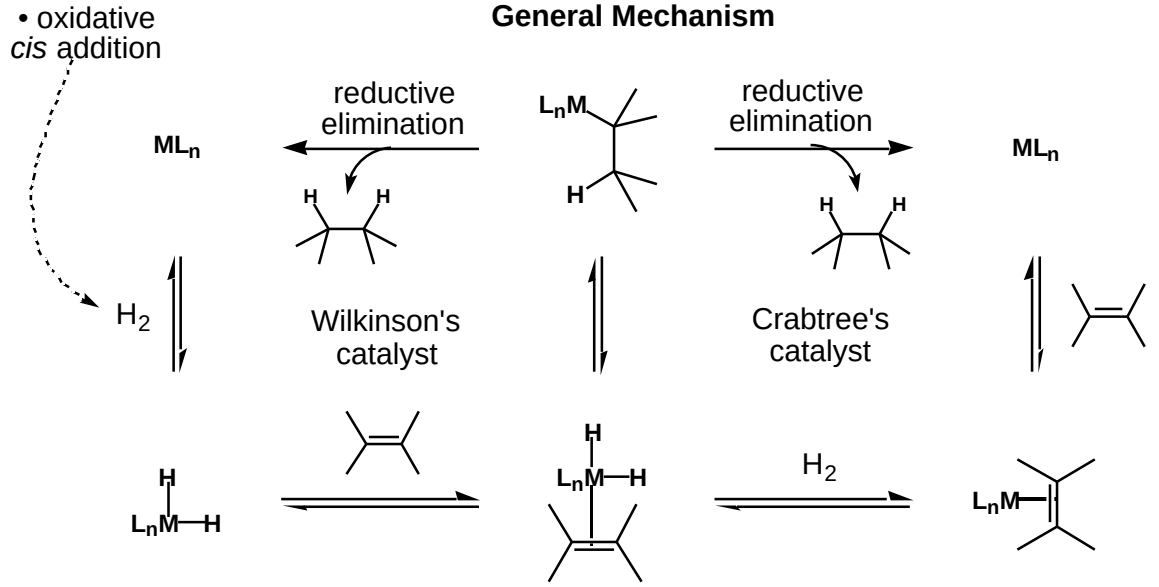
- 2 main types of homogeneous catalysts: ***dihydride*** and ***monohydride*** catalysts

Dihydride Catalysts



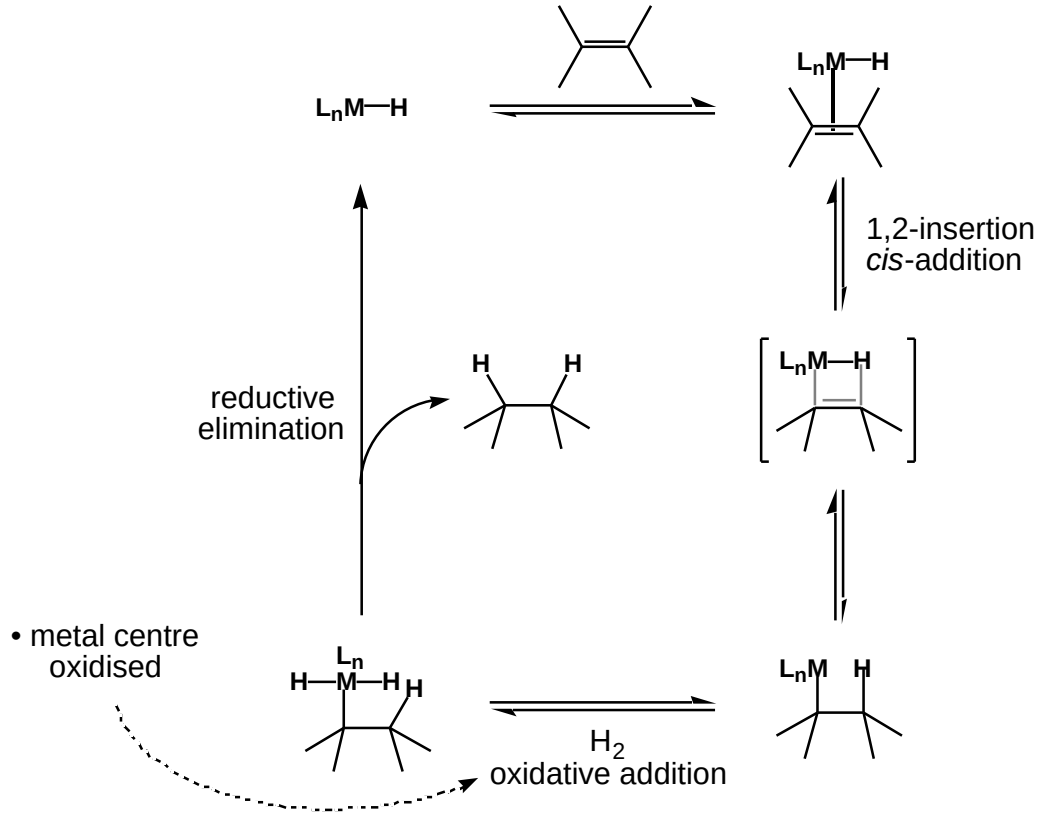
- Examples: *Wilkinson's Catalyst* $ClRh(PPh_3)_3$ (hydrogen adds prior to substrate)
  Crabtree's Catalyst $[Ir(COD)(PCy_3)(pyr)]^+PF_6^-$ (substrate adds before H_2)

General Mechanism

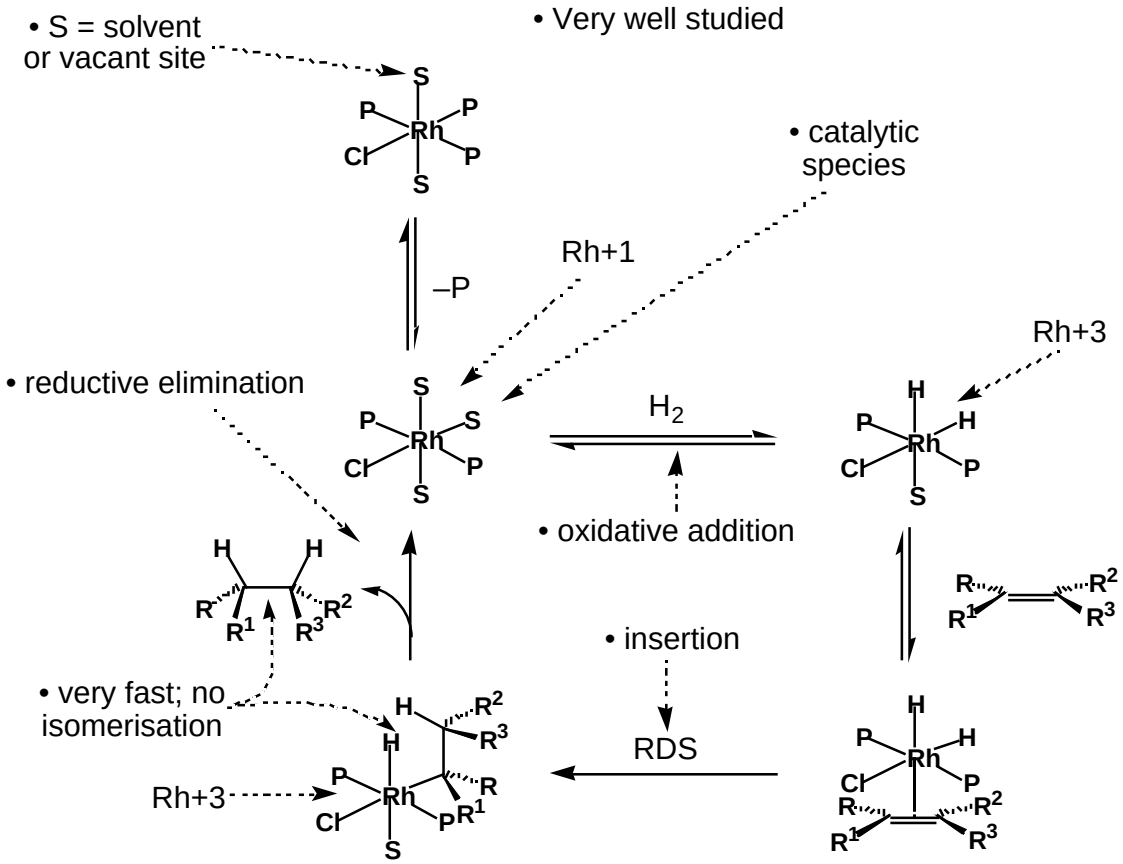


Monohydride Catalysts

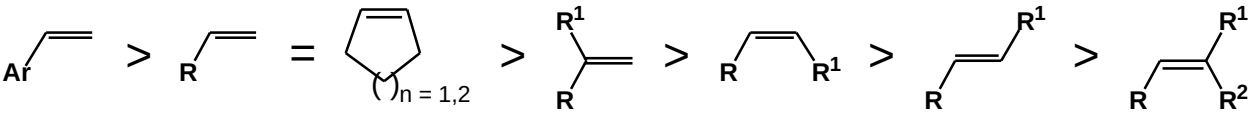
- $L_nM–H$
- Examples: $HRu(Cl)(PPh_3)_3$
  Cp_2TiH



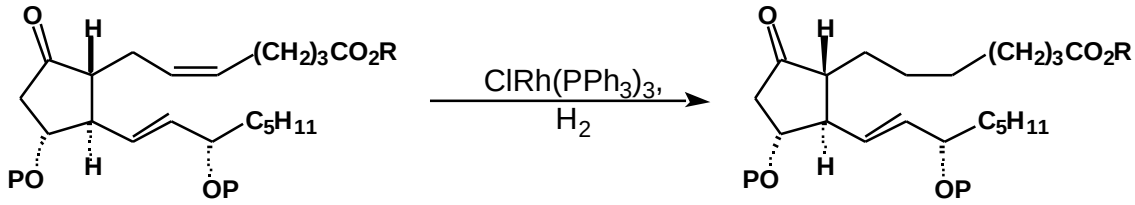
Wilkinson's Catalysis



Selectivity

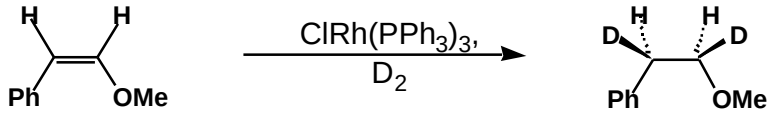


• Like heterogeneous catalysts there is a strong steric selectivity for the least hindered alkenes



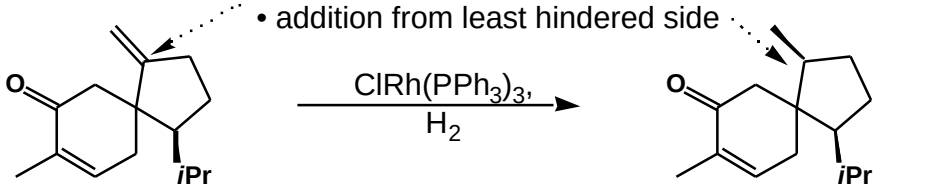
Stereoselectivity

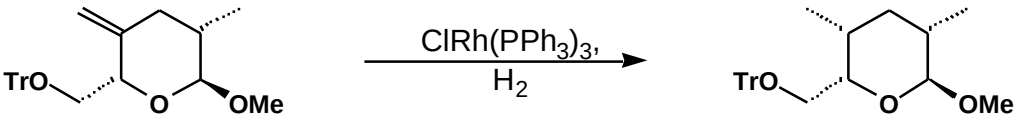
• As indicated in the mechanism reductive elimination is fast so no isomerisation can occur and ***syn addition*** results



• Like heterogeneous catalysts, hydrogenation occurs from the ***least hindered face***

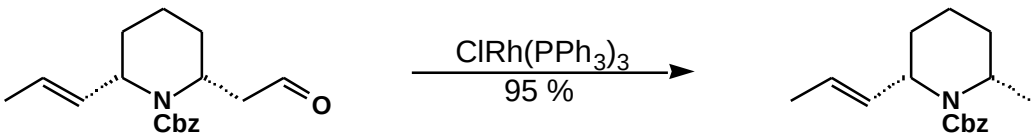
• less substituted alkene
• addition from least hindered side





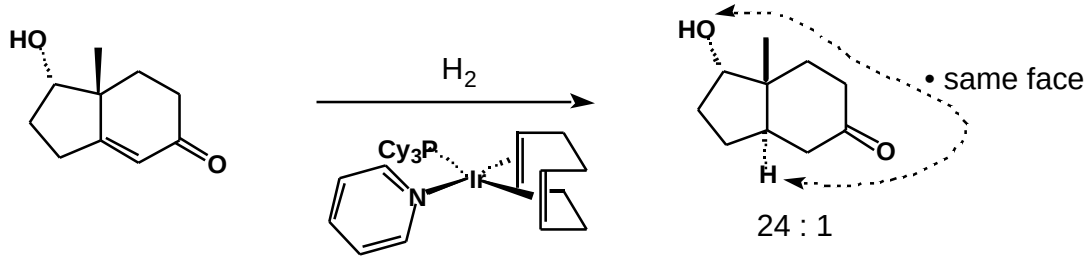
Functional Group Compatibilty

• Compatible with most functional groups
• ***Aldehydes*** often undergo ***decarbonylation***



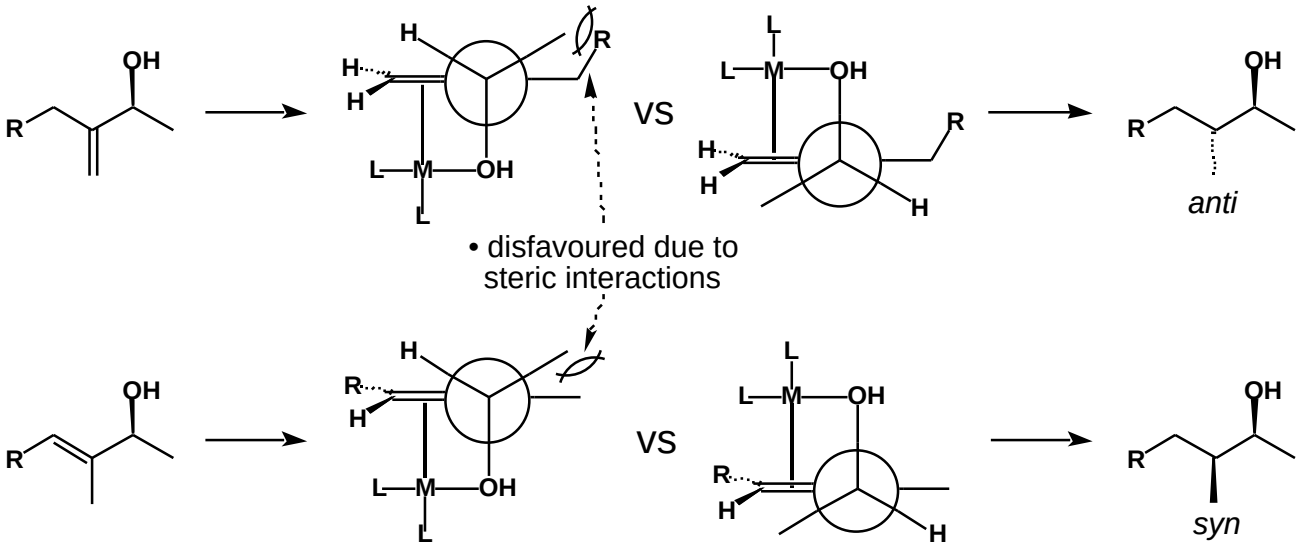
Directed Hydrogenation

• A *hydroxyl* group in the substrate can ***displace*** a ligand from the catalyst resulting in ***directed hydrogenation***
• This can reverse normal selectivity



Crabtree's catalyst

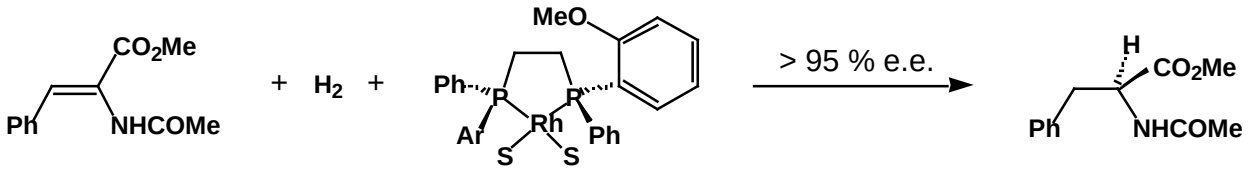
• Crabtree's catalyst much more reactive than Wilkinson's; so good for *hindered alkenes*
• Crabtree's catalyst gives *superior* directing effect for ***cyclic substrates***
• For ***acyclic substrates*** use Wilkinson's catalyst
• If *alkene isomerisation* a problem use Wilkinson's catalyst at elevated pressure



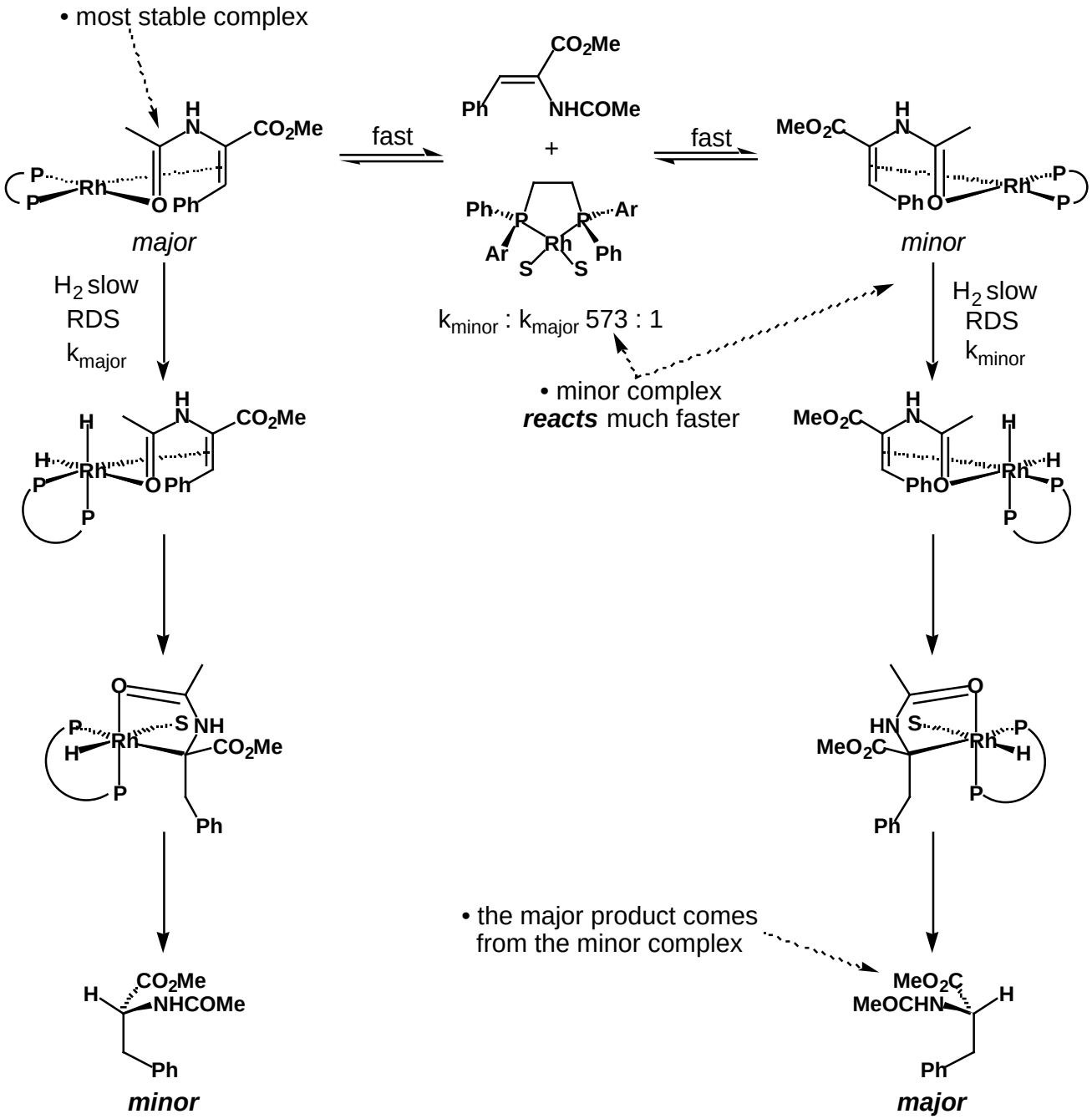
• **Note:** only get stereocontrol if ***isomerisation is surpressed***

ASYMMETRIC HYDROGENATION

• Many asymmetric variants have now been developed
• ***Diphosphine*** ligands are very common



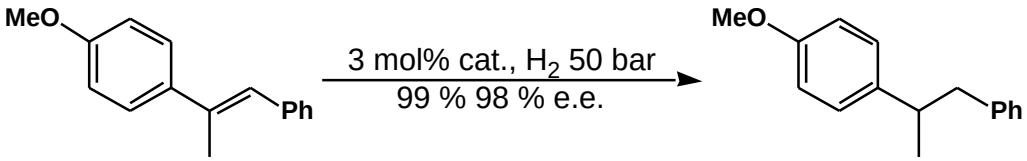
Mechanism

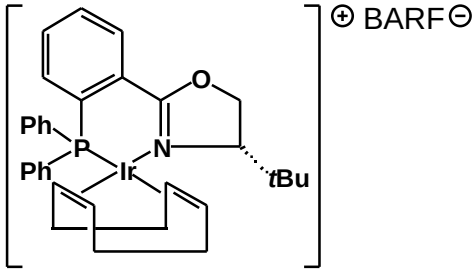


• **Note:** Substrate and metal ***must*** be complexed to get good e.e.

Non-Co-ordinated Asymmetric Catalysts

- Catalysts that do ***not*** require co-ordination to the substrate to give good e.e.s still uncommon
- They offer the advantage of greater structural variety
- One example is:

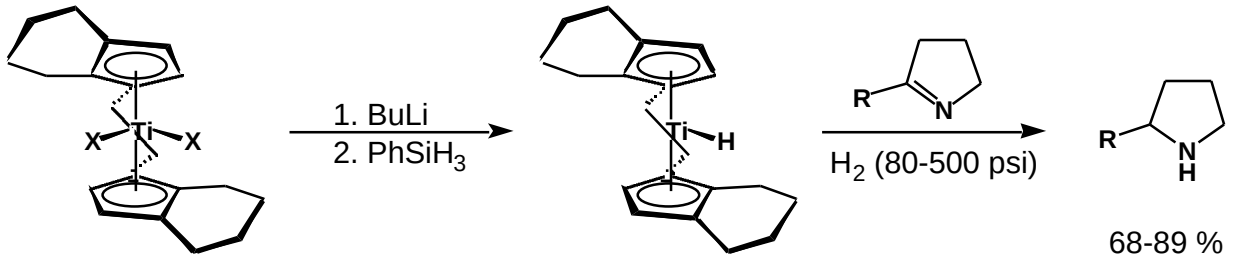




BARF = tetrakis{3,5-trifluoromethyl}phenyl borate

Monohydride Catalyst

- Provides a second example

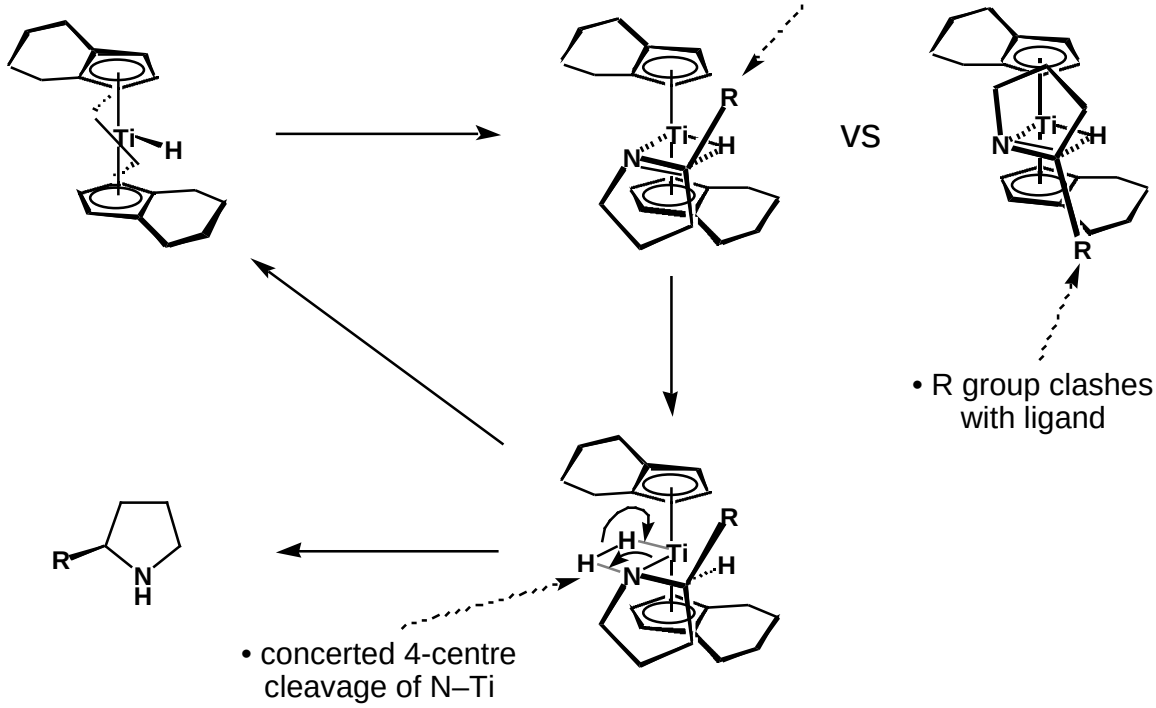


68-89 %
95-99 % e.e.

X_2 = 1,1'-binaphth-2,2'-diolate

Mechanism

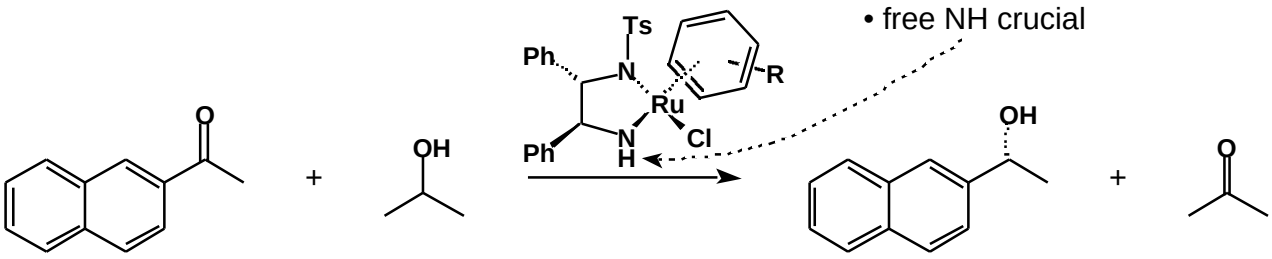
- R group in space



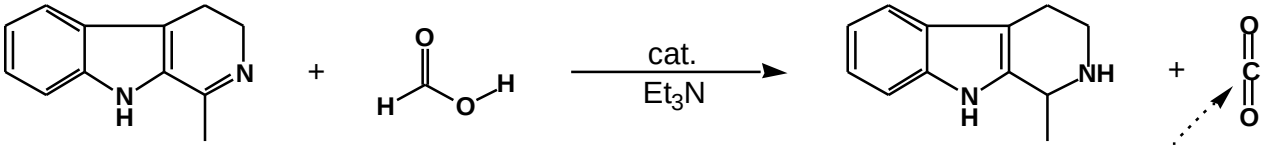
- R group clashes with ligand

- concerted 4-centre cleavage of N–Ti

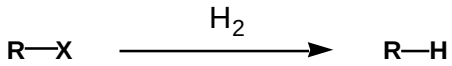
Transfer Hydrogenation



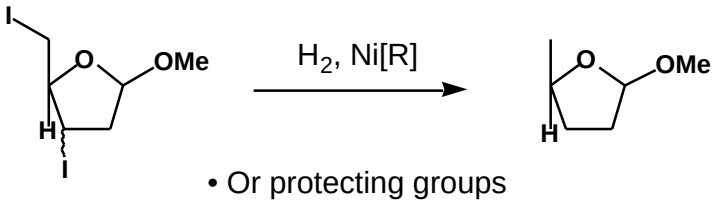
- Mechanism is given in the *Oxidation Section of this course*
- **Problem:** the reaction is reversible (*hence the oxidation*)
- If ***formic acid / triethyl amine*** is used as the reductant reaction ***irreversible***



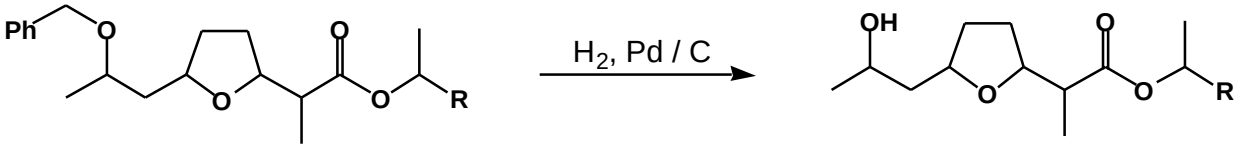
Hydrogenolysis



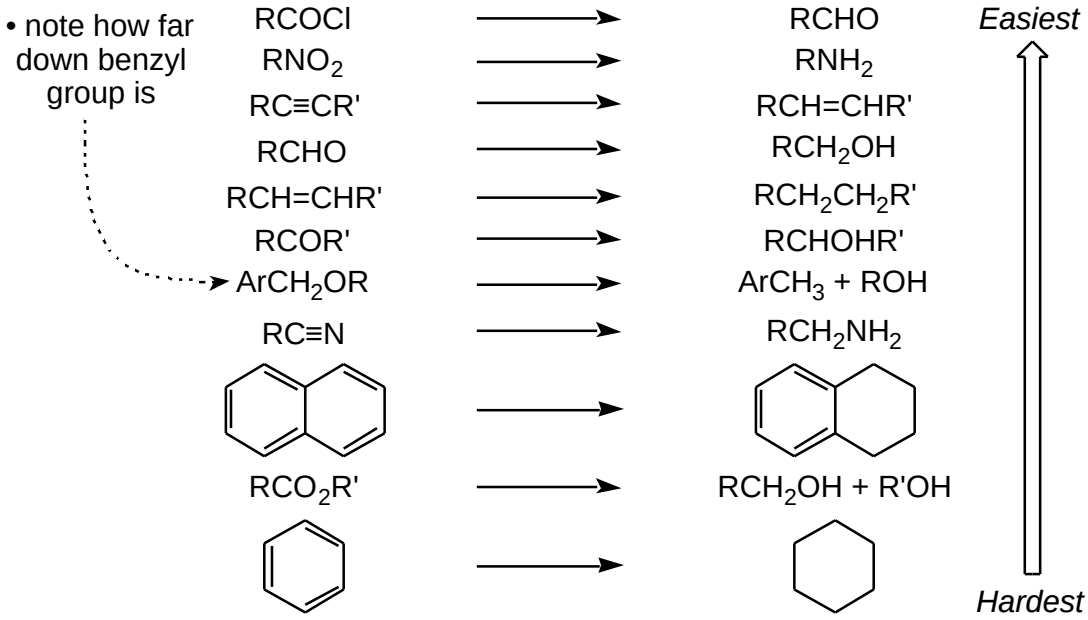
- Used to remove various functional groups



- Or protecting groups



Ease of reduction of functional groups towards catalytic hydrogenation



- **Note:** different catalysts have different propensities for functional groups so this is only a ***rough*** order