Olefin insertion into Metal alkyl can be followed by hydride elimination or additional olefin insertions:

\[
\begin{align*}
R - RH & \rightarrow R - RH \\
R' - RH & \rightarrow R' - RH \\
R - RH & \rightarrow R - RH \\
R' - RH & \rightarrow R' - RH
\end{align*}
\]

-dimerization/oligomerization
-small molecules
-polymerization

Recall:

\[
\begin{align*}
\text{electron rich M (late transition metal) } K_{eq} < 1 & \rightarrow \text{dimerization, etc} \\
\text{electron poor M (early transition metal) } K_{eq} > 1 & \rightarrow \text{polymerization}
\end{align*}
\]

Shell Higher Olefin Process (SHOP)

- SHOP process operates on 1 MILLION TON scale
- One of the largest applications of homogeneous transition metal catalysis
- Explains Adrich prices:

\[
\begin{align*}
\text{Terminal Olefin} & \quad \text{Price (1000l)} \\
1\text{-Hexene} & \quad 813 \\
1\text{-Heptene} & \quad 191 \\
1\text{-Octene} & \quad 23 \\
1\text{-Nonene} & \quad 720 \\
1\text{-Decene} & \quad 19 \\
1\text{-Undecene} & \quad 640
\end{align*}
\]

Chauvin, Schrock, Grubbs: 2005 nobel prize in chemistry. For a history, see: http://nobelprize.org/chemistry/laureates/2005/chemadv05.pdf

See CHNF, Chapter 11, p593
Ligand change gives polymer instead of oligomer

note Ziegler-Natta catalysts (TiCl₄/AlCl₃) and cationic metalloocene catalysts not able to incorporate polar monomers. Late TM = functional group tolerant

Grubbs, Science, 2000, (287) 460
Ni-Catalyzed Dimerization aka hydrovinylation

Catalyst activation

1/2 \( \text{Ni} \cdot \text{Cl} \) \( \text{Cl} \) \( \text{PR}_3 \) \( \rightarrow \) \( \text{Ni} \cdot \text{Cl} \) \( \text{EtAlCl}_2 \) \( \text{PR}_3 \) \( \rightarrow \) \( \text{Ni} \cdot \text{Cl} \) \( \text{AlCl}_2 \text{Et} \) \( \text{PR}_3 \) \( \rightarrow \) minor product

rate = 60,000/sec at rt!!
Wilke, ACIEE, 1980, 622
ACIEE, 1988, 186
Historical account: ACIEE, 2003, 5000

Enantioselective Hydrovinylation

Ethylene (1 atm), [Ni(allyl)Cl]_2
NaBAR_4, CH_3Cl_2, low temp
Ligand

common side products

hydrovinylation of i-Bu-Styrene with 1: 74% ee
w/ 2: 68% ee

1: Rajanbue, JACS, 2001, 734
2: Leitner, JACS, 2001, 736
Metal-mediated dimerization:
- common use
- mild conditions
- many applications

Product distribution dependent on nature of ligand and L/Ni.

Houk, JACS, 1994, 330
Weinmann, AGEE, 1989, 569


Wender JACS, 1986, 4678; TL 1987, 2451
Synthetic Applications of [4+4]

Me\(\text{O}^*\) \(\text{Me}^*\) \(\text{Ni(COD)}_2(11 \text{ mol\%})\) \(\text{PPh}_3(33 \text{ mol\%})\) \(60^\circ\text{C}\) \(67\%\)

\(\text{Ni(COD)}_2(11 \text{ mol\%})\) \(\text{PPh}_3(33 \text{ mol\%})\)

\(110^\circ\text{C}\) \(52\%\)

But in the end...

\(\text{Ni(COD)}_2(11 \text{ mol\%})\)

\(\text{PPh}_3(33 \text{ mol\%})\)

\(T18^\circ\text{C}\) \(92\%\)

\(\text{DABCO (cat)}\)

\(\text{Me, TMS}\)

\(1:1 - 2:1\)

\(r, \text{NTs, NBoc, CH}_2\)

\(1 \text{ or 2}\)

\(\text{Ni(0)}; \text{Wender, TL, 1987, 2221}\)

\(\text{Taxol: Wender, JACS, 1997, 2755, 2757}\)

Catalytic [4+2] Cycloadditions

\(\text{Ni(COD)}_2(10 \text{ mol\%})\)

\(\text{P(O-Biphenyl)}_3(30 \text{ mol\%})\)

\(\text{Me, TMS}\)

\(1:1 - 2:1\)

\(r, \text{NTs, NBoc, CH}_2\)

\(1 \text{ or 2}\)

\(\text{Wender Jacs 1989, 6432}\)

\(\text{jacs 1995, 1843}\)

\(\text{Ni(0)}\) may prefer the less hindered olefin while \(\text{Rh(I)}\) prefers the more \(\epsilon\)-rich olefin
Ready; Catalysis

Isomerization/cyclization

Dissociation required for good alignment

Favored with big P, Small substrates

Ready; Catalysis

Intercepted hydrogenation

[5+2] Cycloaddition

**Alkenes/alkynes**

\[ \text{RhCl}(PPh_3)_3 (0.1 \text{ mol\%}-0.5 \text{ mol\%}) \]

\[ \text{AgOTf} (0.1 \text{ mol\%}-0.5 \text{ mol\%}) \]

\[ 110^\circ C \]

**Allenes**

\[ \text{RhCl}(PPh_3)_3 (0.1 \text{ mol\%}-0.5 \text{ mol\%}) \]

\[ 110^\circ C \]

*not clear if ring expansion or cyclization occurs first*

![Chemical structures and reactions]

*Wender, Jacs 1995, 4720; 1998, 10976; 1940; 1999, 5348*

---

**Synthetic Applications of [5+2] Cycloadditions**

![Chemical structures and reactions]

*Wender, OL, 2001, 2105*

*Wender, OL, 2000, 2323*
Metal-mediated trimerization:
Key early discoveries: Volhardt, ACIEE, 1984, 539

[4+2]/[4+1] retroinsertion

Volhardt, Bergman
JACS, 1974, 4996

Proposed Mechanism

Rovis, JACS, 2006, 12370

Ru-Catalyzed enyne isomerization

Can tune b:1 (better for b-selective)
Trost, JACS, 1995, 615; JACS, 2001, 12504

Intramolecular version:

X = O, NTs, C(ewg)2

Rxns also referred to as Alder-ene or metallo-ene reactions, but that is misleading given the most likely mechanism:

Trost, jacs 1995, 615; 2000, 714
Ready; Catalysis  
Isomerization/cyclization-16

Synthetic Examples:

\[
\text{Cp}^*/(\text{CH}_2\text{CN})_2\text{PF}_6 (10 \text{ mol\%}) 50^\circ \text{C}
\]

46%, 3.5:1 branched:linear

Bulky L (e.g., Cp*) disfavors linear product

Trost, JACS, 2002, 12421

---

Ready; Catalysis  
Isomerization/cyclization-16

Similar mechanism observed with Ti(II)...

\[\text{Cp}_2\text{Ti(CO)}_2 (10 \text{ mol\%})\]

note thorne-engold effect common
Only with E olefins

\[20 \text{ mol\%} \text{Cp}_2\text{Ti(CO)}_2\]

Buchwald, JACS, 1999, 1976

...and Rh(I)

\[(\pm)-\text{O} \rightarrow \text{O} \rightarrow \text{OH}\]

\[\text{[Rh(COD)Cl]}_2 (S)-\text{BINAP}\]

only with Z olefins

40% >99% ee

46% >99% ee

Zhang, TL, 2005, 1823
General mechanism with electron rich transition metals:
Catalytic Pauson-Khand type reactions (review: ACIEE, 2003, 1800)

Pd-H mechanism provides ene products:

enantioselective version

question: Why would a metallocycle mechanism be unlikely with (chelating ligand)Pd?
Isomerization/cyclization-17

Starting Materials:

\[
\text{\(...\)} \quad \text{\(...\)} \quad \text{\(...\)}
\]

Isomerization/Rxns

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Substrate</th>
<th>Products</th>
<th>ee(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{C}<em>{2} \text{TiCl}</em>{2}/\text{PhMgBr})</td>
<td>1</td>
<td>4 (100%)</td>
<td></td>
</tr>
<tr>
<td>(\text{C}<em>{3} \text{H}</em>{6}(\text{R})<em>{2}\text{PPPh}</em>{3})</td>
<td>1</td>
<td>3 (95%); 4 (15%)</td>
<td></td>
</tr>
<tr>
<td>(\text{[R} \text{h(PPPh}_{3}\text{COD)]}^{+})</td>
<td>1</td>
<td>3 (100%)</td>
<td></td>
</tr>
<tr>
<td>(\text{[R} \text{h(DiOP)(COD)]}^{+})</td>
<td>1</td>
<td>3 (100%)</td>
<td></td>
</tr>
<tr>
<td>(\text{[R} \text{h(R-BINAP)(COD)]}^{+})</td>
<td>1</td>
<td>S-3 (100%); 97</td>
<td></td>
</tr>
<tr>
<td>(\text{[R} \text{h(S-BINAP)(COD)]}^{+})</td>
<td>2</td>
<td>S-3 (100%); 96</td>
<td></td>
</tr>
</tbody>
</table>

Process Development

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Modification</th>
<th>Turnover number</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Rh(BINAP)(COD)}^{+})</td>
<td>none</td>
<td>100</td>
</tr>
<tr>
<td>(\text{Rh(BINAP)(COD)}^{+})</td>
<td>added Red-AL</td>
<td>1,000</td>
</tr>
<tr>
<td>(\text{Rh(BINAP)(COD)}^{+})</td>
<td>Substrate purification</td>
<td>8,000</td>
</tr>
<tr>
<td>(\text{Rh(BINAP)}_{2})</td>
<td>catalyst recycling</td>
<td>400,000</td>
</tr>
</tbody>
</table>

\(\text{Red-AL} = \text{Vitrine} = (\text{MeOCH}_{2}\text{CH}_{2}\text{O})_{2}\text{AlH}_{2}\text{Na}\)

<table>
<thead>
<tr>
<th>compound</th>
<th>ee (%)</th>
<th>Production (tons/yr)</th>
<th>use</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{CHO})</td>
<td>97</td>
<td>1,500</td>
<td>synthetic intermediate; those stinky candles</td>
</tr>
<tr>
<td>(\text{CHO})</td>
<td>98</td>
<td>10</td>
<td>insect growth regulator</td>
</tr>
<tr>
<td>(\text{OMe})</td>
<td>98</td>
<td>1,000</td>
<td>pharmaceuticals; tabacco; household products</td>
</tr>
<tr>
<td>(\text{OH})</td>
<td>100</td>
<td>1,000</td>
<td></td>
</tr>
</tbody>
</table>
Axial chirality results in gearing of Ph. It is the location of the Ph’s that gives a good "chiral environment" near the metal.