Organometallic Catalysis in Industry

Figure 9-1
Reaction Coordinates for a Catalyzed and Uncatalyzed Chemical Reaction

$\Delta G^\ddagger$

S: Substrate  P: Product  C: Catalyst
S-C: Substrate-Catalyst Complex  P-C: Product-Catalyst Complex
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Homogeneous</th>
<th>Heterogenous</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Catalyst composition and</td>
<td>Discrete molecules with well-defined</td>
<td>Nondiscrete molecular entities;</td>
</tr>
<tr>
<td>nature of active site</td>
<td>active site</td>
<td>active site not well-defined</td>
</tr>
<tr>
<td>2. Determination of reaction</td>
<td>Relatively straightforward using standard</td>
<td>Very difficult</td>
</tr>
<tr>
<td>mechanism</td>
<td>techniques</td>
<td></td>
</tr>
<tr>
<td>3. Catalyst properties</td>
<td>Easily modified, often highly selectiv,</td>
<td>Difficult to modify, relatively</td>
</tr>
<tr>
<td></td>
<td>poor thermal stability, mild reaction</td>
<td>unselective, thermally robust,</td>
</tr>
<tr>
<td></td>
<td>conditions</td>
<td>vigorous reaction conditions</td>
</tr>
<tr>
<td>4. Ease of separation from product</td>
<td>Often difficult</td>
<td>Relatively easy</td>
</tr>
</tbody>
</table>
Some terminology:

**Catalytic cycles:** a circular path meant to show *productive reactions*, in order, that lead from the catalytically active species and its reaction with a substrate through to product elimination and regeneration of the catalyst.

**Turnover number:** number of times a cycle is completed before the catalyst dies. Typically this is > 1000; a stoichiometric reaction has a TON of 1.

**Turnover rate or frequency:** the rate at which a cycle is completed. This can be reported in many ways but it is usually in mol product per mol catalyst per time. Eg. a good ethylene polymerization catalyst might have a turnover rate of 5000 kg polyethylene per mol of catalyst per hour.

**Resting State:** this is the stable, and usually inactive, form of the catalyst when no substrate is provided or when it has been used up. Eg. with a coordinated solvent molecule occupying the active coordination site.

**Pre-catalyst:** the stable compound put into the reactor; it must be transformed *in situ* into the active species. Eg. Cp₂ZrCl₂ in Z-N polymerizations where MAO is the *activator*. 
So why transition metals?

- **wide range of bonding modes**
  - $\sigma$ and $\pi$ bonds
  - many valence electrons

- **wide choice of ligands**
  - ionic or neutral

- **tunable properties**
  - choice of metal
  - electronic and steric effects of ancillary ligands

- **variable coordination numbers**
  - 4 and 5 or 5 and 6 coordinate geometries accessible for same metal

- **variable oxidation states**
  - ox. states separated by 2 units facilitate oxidative addition and reductive elimination reactions
**Tolman’s rules:** (really only apply to middle and late T.M.)

- Diamagnetic organometallic complexes may exist in *significant concentration* only if the metal’s valence shell contains 16 or 18 electrons. A significant concentration is one that can be detected spectroscopically or kinetically.

- Organometallic reactions, including catalytic ones, *proceed by elementary steps* involving only intermediates with 16 or 18 valence electrons.

As a corollary, there is an old saying in catalysis that says:

> ‘If you can isolate it, then it isn’t the active catalyst’

This statement has been shown to be untrue in many catalytic systems in more recent work.
## Industrial Importance of Homogeneous Catalysis

<table>
<thead>
<tr>
<th>Reaction and Products</th>
<th>Ann. Production World (2015)</th>
<th>10^3 metric tons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Olefin additions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adiponitrile (for nylon)</td>
<td></td>
<td>1,200</td>
</tr>
<tr>
<td><strong>Olefin polymerizations</strong> (all types)</td>
<td></td>
<td>100,000+</td>
</tr>
<tr>
<td><strong>Carbonylations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxo alcohols (hydroformylation)</td>
<td></td>
<td>2,000</td>
</tr>
<tr>
<td>Acetic acid/anhydride (from MeOH)</td>
<td></td>
<td>2,500</td>
</tr>
<tr>
<td><strong>Olefin oxidation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td></td>
<td>1,250+</td>
</tr>
<tr>
<td>Propylene oxide</td>
<td></td>
<td>7,500</td>
</tr>
<tr>
<td><strong>Alkane and arene oxidations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terephthalic acid and esters</td>
<td></td>
<td>5,000+</td>
</tr>
<tr>
<td>Adipic acid (for nylon)</td>
<td></td>
<td>1,200+</td>
</tr>
</tbody>
</table>
1. Isomerization of Alkenes

- often unwanted side reaction but can be useful in some cases
- most metal hydride species will do this to some extent
2. Hydrogenation

Most important for alkenes: *usually* oxidative addition / reductive elimination sequences

Wilkinson’s catalyst is the original system and most famous but many are now known

- selective for $\text{C}=$C over C=O and CN
- does not scramble H and D
- exclusively syn $\text{H}_2$ addition (see e.g. below)
- commercially available
Wilkinson’s catalyst:
Insertion is turnover limiting

Scheme 9.7
Mechanism of Hydrogenation
with Wilkinson’s Catalyst

Key Steps: a, b, c, d, e
L = PPH₃; Solv: EtOH, THF
Many cationic hydride complexes are also used: one example is $[\text{Rh}(\text{dppe})(L)_2]^+$.
Asymmetric hydrogenation:

Chiral chelating ligands result in preferential delivery of H₂ to one enantiotopic face of the alkene

Chiral chelating phosphines are among the most popular
Some examples of asymmetric hydrogenation of alkenes using a related Ir catalyst:

\[
\text{L} = \text{ligand in Figure 15.12}
\]
Asymmetric transfer hydrogenation of ketones: asymmetric Meerwein-Pondorff-Verley reduction

Reaction occurs with Lewis acids too: alumina, lanthanide and group 4 metal complexes

No oxidation state change for the metal
3. Hydroformylation (Oxo process)

- Formally addition of formaldehyde across a double bond
- Discovered by BASF by Otto Roelen using Co catalysts
- Worldwide scale: about 7 BILLION kgs per year
- **HCo(CO)_4** catalyst:
  conditions 110-180 °C / 200-300 atm

- **linear/branched** ratio is about 3:1
- internal alkenes isomerize to terminal so only α or β aldehydes formed
- **problem**: catalyst loss due to volatility of HCo(CO)_4 and Co_2(CO)_8
- HRh(CO)(PPh₃)₂ allows lower T (100 °C) and P (6 atm)
- linear to branched ratio: > 10:1
- hydrogenation is much slower under the conditions used and does not compete as a side reaction.
4. Monsanto Acetic Acid Process (carbonylation of MeOH)

- acetic acid for industrial uses: vinyl acetate, cellulose acetate, pharmaceuticals, dyes and pesticides.
- Monsanto process dominates the market but older methods such as the oxidation of ethylene via acetaldehyde are still practiced.
- conditions: 180 °C / 30-40 atm / 10⁻³ M catalyst
5. Alkene Oxidations: the **Wacker** process

- used to prepare acetaldehyde for conversion to acetic acid
- replaced dangerous hydration of acetylene in 1950's
- now largely superceded by Monsanto process
- ultimate oxygen source is air although the reaction chemistry occurs solely at Pd
Some debate over whether inter- or intramolecular attack occurs.
Evidence for intramolecular attack from labelling studies:

\[
Pd(MeCN)_2(BF_4)_2 \text{ (5 mol %)} \quad (S,S)-\text{ip-boxax} \quad [\text{Pd/L = 1/2}] \\
\text{Benzoquinone (4 equiv.)} \\
\text{MeOH, 20 °C, 4 h} \\
82\% \text{ yield} \\
A/B/C/D = 33/33/23/11
\]

\[
\text{Pd(II) syn-oxypalladation} \\
\text{β-H elimination} \\
\text{H-Pd addition}
\]

Scheme 16.32
Oxidative Amination: closely related to Wacker Chemistry
6. Hydrofunctionalization of Alkenes

- **Hydroamination**  \( H-NR_2 \) (covered earlier)
- **Hydrozirconation**  \( H-ZrX_3 \) (covered earlier)
- **Hydrocyanation**  \( H-CN \)
- **Hydrosilylation**  \( H-SiX_3 \)
- **Hydroboration**  \( H-B(OR)_2 \)
**General mechanism** is pretty much the same for all later transition metals:
Hydrocyanation

- By far the most common catalysts are Ni⁰ complexes like NiL₄ or chiral variants, Ni(L₂*)₂
- Used industrially to produce adiponitrile for nylon synthesis and one route to Naproxen (tradename: Alleve)
Hydrosilylation

- Usual catalysts are Pt\(^0\) complexes like Speier’s and Karsted’s catalysts (below).
- Catalyst loadings are incredibly low (highly active catalysts): \(10^{-5}\) mol\% common.
- Still controversy over whether it is actually colloidal Pt that is the catalyst (induction period?)
- **Industrial uses**: polysiloxanes for caulks, gaskets, coatings, etc.

**Speier’s catalyst**: \(\text{H}_2\text{PtCl}_6\)

**Karsted’s catalyst**: widely used Pt\(^0\) but still induction period
Asymmetric variants used in organic synthesis

\[
\ce{R = C=CHCH2R \ + \ HSiCl3 \xrightarrow{[Pt]} \ Cl_3SiCH=CHCH2R \xrightarrow{i) \ EtOH / NEt3} \ HOCH=CHCH2R} \xrightarrow{ii) \ H_2O_2, KF, KHCO_3} \ %ee > 95%
\]

+ PtL₄
σ-bond metathesis alternative: no oxidative-addn / red. elim
Hydroboration

- Late transition metal catalysts (Rh, Ir, Pd, Pt, Ni) by oxid. add. / red. elim. AND early transition metals and lanthanides by σ-bond metathesis
- Mostly used in organic synthesis for regio- and stereoselective alcohol formation

\[
\begin{align*}
\text{ArCH} = \text{CH}_2 & \xrightarrow{1. \text{ HBcat. catalyst}} \text{ArCH}_3 + \text{ArCH} \text{CH}_3 \\
& \xrightarrow{2. \text{ H}_2\text{O}_2/\text{OH}^0} \text{ArCH}_3 + \text{ArCH} \text{CH}_3
\end{align*}
\]

Catalyst

- \(\text{RhCl(PPh}_3)_3\) (in argon) > 99 < 1
- \(\text{RhCl(PPh}_3)_3\) (in air) 24 76
- \([\text{Rh(COD)}_2]\text{BF}_4/\text{dppb}\) 99 1
- \(\text{Cp}_2\text{TiMe}_2\) (in benzene) 0 100