One reaction, many applications

- Oxidative addition is a key step in many transition-metal catalyzed reactions
  - Main exception: olefin polymerization
- The ease of addition (or elimination) can be tuned by the electronic and steric properties of the ancillary ligands
- The most common applications involve:
  a) Late transition metals (platinum metals)
  b) C-X, H-H or Si-H bonds

Many are not too sensitive to O₂ and H₂O and are now routinely used in organic synthesis.
The Heck reaction

ArX + \( \text{"Pd"} \) \( \rightarrow \) Ar\( \cdot \)R \( \rightarrow \) Ar\( \cdot \)R + HX

- Pd often added in the form of Pd\(_2\)(dba)\(_3\).
- Usually with phosphine ligands.
- Typical **catalyst loading**: 1-5%.
- But there are examples with turnovers of 10\(^6\) or more
- Heterogenous Pd precursors can also be used
- But the reaction itself happens in solution

dba, not quite an innocent ligand
The Heck reaction

- For most systems, we don't know the coordination environment of Pd during catalysis.

- At best, we can detect one or more *resting states*.

- The dramatic effects of ligand variation show that **at least one ligand** is bound to Pd for **at least part of** the cycle.
The Heck reaction

- Works well with aryl iodides, bromides
- Slow with chlorides
- Hardly any activity with acetates etc
- Challenges for "green chemistry"

- Pt is ineffective
  - Probably gets "stuck" somewhere in the cycle
Suzuki and Stille coupling

\[
\begin{align*}
RX + \text{ArB(OH)}_2 & \xrightarrow{\text{"Pd"}} \text{RAr} + \text{XB(OH)}_2 \\
RX + \text{ArSnR'}_3 & \xrightarrow{\text{"Pd"}} \text{RAr} + \text{XSnR'}_3
\end{align*}
\]

R = aryl or vinyl

- Glorified Wurtz coupling
- Many variations, mainly in the choice of electrophile
  - Instead of B(OH)_2 or SnMe_3, also MgCl, ZnBr, etc
- The Suzuki and Stille variations use convenient, air-stable starting materials
Suzuki and Stille coupling

- The oxidative addition and reductive elimination steps have been studied extensively.
- Much less is known about the mechanism of the substitution step.
  - The literature mentions "open" (3-center) and "closed" (4-center) mechanisms
- This may well be different for different electrophiles.
Reductive elimination

Rate depends strongly on types of groups to be eliminated.

Usually easy for:
- H + alkyl / aryl / acyl
  - H 1s orbital shape, c.f. insertion
- alkyl + acyl
  - participation of acyl $\pi$-system
- SiR$_3$ + alkyl etc

Often slow for:
- alkoxide + alkyl
- halide + alkyl
  - thermodynamic reasons?
Catalytic olefin hydrogenation (1)

- Usually with platinum metals.
  - e.g. Wilkinson's catalyst
- Many chiral variations available.
  - enantioselectivity mechanism can be very subtle
- For achiral hydrogenation, heterogeneous catalysts ("Pd black") are often a good alternative.
- Extremely high turnovers possible.
- For early transition metals, $\sigma$-bond metathesis instead of oxidative addition.
Catalytic olefin hydrogenation (2)

- Alternative mechanism for metals not forming a "stable" hydride.
- Requires oxidative addition, not observed for early transition metals.
Oxidative addition of MeI to (Acac)RhL₂


Generally thought to involve nucleophilic attack of the Rh lone pair on MeI (ionic mechanism).

What's going on?
Model complexes for cationic intermediates

• Independent synthesis of a cationic *trans* complex:

\[(\text{Acac})\text{RhL}_2(\text{Me})(\text{NCMe})^+ \xrightarrow{\text{AgBPh}_4/\text{MeCN}} (\text{Acac})\text{RhL}_2(\text{Me})(\text{I})\]

\[(\text{Xray})\]

\((1)\)

NMR spectra independent of temperature
Model complexes for cationic intermediates

- Trapping (?) of an ionic intermediate

\[
\begin{align*}
(Acac)RhL_2(Me)(NCMe) & \xrightarrow{\oplus} \text{Me, NaBPh}_4 \\
& \xrightarrow{\text{MeCN}} (Acac)RhL_2
\end{align*}
\]

\[
\begin{align*}
\text{Me} & \quad \text{L} \\
\text{O} & \quad \text{Rh} \\
\text{Me} & \quad \text{L} \\
\text{NCMe} & \\
\text{Xray} & \quad (2)
\end{align*}
\]

NMR spectra temperature-dependent
VT-NMR of (2)

\(^{31}\text{P}\{^1\text{H}\} \text{ NMR}

At RT: 1 broadened doublet at 29.8 ppm
At -50°C: sharp, intense doublet at 29.7 ppm; two much less intense "dd" at 27.3, 23.6 ppm
Equilibrium between a symmetric and an asymmetric species, \textit{neither} of which is (1)! The symmetric one probably corresponds to the X-ray structure.

The benzoylacetonate complex shows similar behaviour, but now at low T \textit{both} species have inequivalent P atoms.
Reaction of (2) with NH$_3$

Equilibration presumably via:

But why doesn't it go on to:

Oxidative addition, reductive elimination
Heating of (2)

\[
\text{Oxidative addition, reductive elimination}
\]

\[
\begin{align*}
\text{Heating of (2)} & \quad \Delta \\
\text{(2)} & \quad \rightarrow \\
\text{(1)} & \quad + \text{MePPh}_3 + \ldots
\end{align*}
\]
Reaction with iodide

Rate difference caused by trans effect of Me group in (2)?
Conclusions?

• Oxidative addition *probably* begins with attack of Rh $d_{z2}$ at Me group of MeI leading to an ionic *cis* intermediate.

• The initial ionic product can be trapped, but would otherwise react further to the neutral *trans* final product.

• The ionic *cis* acetonitrile complex is labile at RT, equilibrates rapidly between *two isomeric cis forms*, but will only go to the *trans* product at higher temperature.

• It seems *likely* that the *trans* ionic complex is thermodynamically favoured, but the key experiment to prove that is not reported.
Carbenes and Olefin Metathesis

\[
\begin{align*}
M &= C \\
C &= C
\end{align*}
\]

\[
\begin{align*}
M &= C \\
C &= C
\end{align*}
\]

\[
\begin{align*}
M &= C \\
C &= C
\end{align*}
\]

\[
\begin{align*}
M &= C \\
C &= C
\end{align*}
\]
Metal-carbon multiple bonds

- Many transition metals form not only M-C single bonds but also M=C and (more rare) even M≡C bonds.
- Complexes containing an M=C bond are called carbene complexes
  - The ligand without the metal would be a free carbene
- Complexes with M≡C bonds are called carbyne complexes

- Both types of complexes tend to be reactive, and useful in catalysis

- We distinguish between Fischer-type and Schrock-type carbene (and carbyne) complexes
Schrock-type carbene complexes

- "Standard" M=C bond: normal σ and π bonds, both polarized as in M^{δ^+}-C{δ^-}
- Carbene not particularly stabilized, has a triplet ground state
- Early/middle transition metal, high oxidation state
  - count carbene as 2-
- Carbene carbon is nucleophilic
- Prototype:
  - formed by "α-elimination"
σ and π bonds

TaMe$_3$(=CH$_2$)
Real $M=C$ double bonds

$TaBz_5$

$2.17-2.22 \, \text{Å}$

$TaBz_2(CHPh)(amide-carbene)$

$1.94$

$2.25$
Synthesis of Schrock carbenes

Usually from decomposition of alkyls ($\alpha$-elimination)

Variations:

$$\text{Cp}_2\text{TaMe}_3 \xrightarrow{E^+} \text{Cp}_2\text{TaMe}_2^+ \xrightarrow{B^-} \text{Cp}_2\text{Ta} = \text{CH}_2$$

$$\text{Cp}_2\text{Ta}\text{Me} \xrightarrow{?} \left[ \text{Cp}_2\text{Ta} \right] \xrightarrow{?} \text{Cp}_2\text{Ta} = \text{CH}_2$$
Reactivity of Schrock carbenes

- With ketones: "Wittig" $\text{M} = \text{C}$
  \[ \text{M} = \text{C} + \text{O} = \text{C} \rightarrow \text{M} \text{O} + \text{C} \text{C} \]

- With electrophiles: attack on carbene carbon
  Unhindered carbenes dimerize: $\text{M} = \text{C}$
  \[ \text{M} = \text{C} + \text{C} = \text{M} \rightarrow \text{M} - \text{C} \text{C} - \text{M} \]

- With olefins: metallacycles
  - Metathesis catalysis !
  \[ \text{M} = \text{C} + \text{C} = \text{C} \rightarrow \text{M} - \text{C} \text{C} - \text{C} \]
  - "intermediate" carbenes are better for this
**Fischer-type carbene complexes**

- Ligand best described as strong $\sigma$-donor, medium-weak $\pi$-acceptor
- Carbene has singlet ground state
  - because of $\pi$-donor substituents
- Metal: late, low oxidation state
  - count carbene as neutral ligand
- Carbene carbon is **electrophilic**

Prototype:
- nucleophilic attack at coordinated CO

\[
\begin{align*}
(CO)_5W=Me & \quad \text{1) MeLi} \\
\text{OMe} & \quad \text{2) MeI} \\
Me &\quad W(CO)_6
\end{align*}
\]
**σ donation, π backdonation**

- **C-O π**
- **C→Mo σ-donation**
- **Mo→C π-backdonation**
- **LUMO**
Good ligands, but no "real" M=C bond
Synthesis of Fischer carbenes

- Usually from CO or RNC complexes via
  1) Nucleophilic attack on C
  2) Electrophilic attack on O/N

- Also: spontaneous isomerization of vinyl, olefin of acetylene complexes (Ru)
Reactivity of Fischer carbenes

- Decomposition:
  - a) Dimer of carbene (C=C)
  - b) Olefin, via isomerization of carbene
- Oxidation to ketone
- Nucleophilic substitution on carbene carbon
Arduengo carbenes

- Free, stable carbenes

- Good ligands, strong σ-donors
- More reluctant to dissociate than phosphines
- Shape very different from that of typical phosphines

- Easy and convenient synthesis from imidazolium salts
Olefin metathesis catalysis

Schrock catalyst.
Highly active but sensitive to functional groups.

Grubbs catalyst.
Stable, but $\text{PCy}_3$ must dissociate for the reaction to start.
Tolerates many functional groups.
Olefin metathesis catalysis

\[ \text{M} = \text{C} \quad + \quad \text{C} = \text{C} \quad \overset{\rightleftharpoons}{\text{M} - \text{C}} \quad \overset{\rightleftharpoons}{\text{C} - \text{C}} \quad \overset{\rightleftharpoons}{\text{M} \quad + \quad \text{C} \quad + \quad \text{C}} \]

Driving force:

- Escape of gaseous products
- Decrease of ring strain

"ADMET"

"ROMP"
For Schrock catalysts, the equilibrium between carbene and metallacyclobutane can be tuned by the choice of substituents (OR groups).
Carbyne complexes

- Fischer: 
  \[
  \text{OMe} \quad \text{Me} \xrightarrow{\text{BX}_3} \quad \text{Me} \quad \text{Me}^+ \]

- Schrock: synthesis mostly ad-hoc 
  \[
  \text{Cp}^*\text{TaBr}_2 \xrightarrow{\text{Na/Hg}} \quad \text{Na/Hg} \quad \text{dmpe} \quad \text{Cp}^*\text{Ta} \quad \text{H} \]

\[
\begin{align*}
\text{P} & \quad \text{P} \\
\text{P} & \quad \text{P}
\end{align*}
\]
**Alkyne metathesis catalysis**

e.g. with \((t\text{BuO})_3\text{W}≡\)

\[
\begin{align*}
\text{M}≡\text{C} & \quad + \quad \text{C}≡\text{C} \\
\leftrightarrow & \quad \text{M} & \quad \leftrightarrow \quad \text{M} & \quad \leftrightarrow \quad \text{M} \quad + \quad \text{C} \quad + \quad \text{C}
\end{align*}
\]

Very sensitive to functional groups.

Not (yet) very useful in organic synthesis.
Carbene and carbenoid chemistry

• Both main group metals and transition metals can be used to transfer carbenes to e.g. double bonds ("cyclopropanation").

• Main group metals: carbenoid reagents
  – Simmons-Smith: IZnCH₂I, EtZnCH₂I

• Transition metals: with diazo compounds
  – (RCOO)₄Cu₂ and (RCOO)₄Rh₂
  – Mode of action obscure