Projects

- Organosilicon cross-coupling: mechanistic studies

- New approaches to the enantioselective synthesis of quaternary stereocenters

- Use of the Water-Gas Shift Reaction to drive reductive processes in organic synthesis
### Catalytic cycle for cross-coupling reactions

The catalytic cycle for cross-coupling reactions involves several key steps:

1. **Oxidative addition**
2. **Reductive elimination**
3. **Transmetalation**

The transmetalation step, which differentiates the various cross-coupling processes and is more difficult to study, involves the reaction of different metal ligands with palladium complexes.

- **M = Mg (Kumada)**
- **Zn (Negishi)**
- **Sn (Stille)**
- **B (Suzuki-Miyaura)**
- **Si (Hiyama-Denmark)**

### Modes of transmetalation of organosilanes

**Fluoride-activated transmetalation (Hiyama-Hatanaka, 1988)**

Fröjd and colleagues observed that fluoride-activated transmetalation of organosilanes can be facilitated by certain metal complexes.

- **Brønsted base-activated transmetalation (Denmark, 2001)**

Thermal transmetalation and pre-equilibrium conditions can also be used to study transmetalation processes.

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Denmark, S. E.; Sweis, R. F. J. Am. Chem. Soc. 2001, 123, 6439

Tymonko, S. A.; Smith, R. C.; Ambrosi, A.; Denmark, S. E. J. Am. Chem. Soc. 2015, 137, 6192

Tymonko, S. A.; Smith, R. C.; Ambrosi, A.; Ober, M. H.; Wang, H.; Denmark, S. E. J. Am. Chem. Soc. 2015, 137, 6200
Are both modes of transmetalation viable?
Which one is preferred?

J. Am. Chem. Soc. 2015, 137, 6192
J. Am. Chem. Soc. 2015, 137, 6200

Alkenylsilanolate arylpalladium complexes

Tymonko, S. A.; Smith, R. C.
Alkenylsilanolate arylpalladium complexes

- Species with a Si-O-Pd linkage are competent intermediates
- Alkenylsilanlates are capable of direct, thermal transmetalation

What is the preferred transmetalation mode in the CATALYTIC reaction?

Kinetic studies – potassium silanolate

rate = \( k_{\text{obs}} \) \([\text{K^+ silanolate}]^{0} \) \([\text{Ar-I}]^{0} \) \([\text{dppp(O)_{2}}]^{0} \) with \( k_{\text{obs}} = k \) [Pd]

0\(^{th}\) order in silanolate is consistent with:
- Turnover-limiting thermal transmetalation
- Turnover-limiting activated transmetalation from a saturated 10-Si-5 intermediate
Kinetic studies – cesium silanolate

rate = $k_{\text{obs}} [\text{Cs' silanolate}]^{0.55} [\text{Ar-I}]^0 [\text{dppp(O)$_2$}]^0$ with $k_{\text{obs}} = k [\text{Pd}]

- Partial order in silanolate indicates rapid equilibration of 8-Si-4 and 10-Si-5 intermediates. Both modes of transmetalation are operative.
- 0th order in silanolate at higher concentrations is consistent with complete saturation as the 10-Si-5 species. Only activated transmetalation is operative.

Alkenylsilanlates – summary

- **POTASSIUM ALKENYL SILANOLATES**

  The preferred transmetalation pathway is thermal

- **CESIUM ALKENYL SILANOLATES**

  Both thermal and activated transmetalation are operative

These conclusions are in contrast with the reigning paradigm that organosilicon cross-coupling must be anionically activated (Hiyama-Hatanaka paradigm)
Arylsilanolate arylpalladium complexes

Tymonko, S. A.; Smith, R. C.
Arylpalladium arylsilanolate complexes

- Arylsilanolates are capable of direct, thermal transmetalation
- CuTC facilitates transmetalation by decomplexation of phosphine ligands

**What is the preferred transmetalation mode in the CATALYTIC reaction?**

<table>
<thead>
<tr>
<th>ligand</th>
<th>rate (10⁻² mM/s)</th>
<th>rate with CuTC</th>
<th>increase</th>
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<tr>
<td>dppbz</td>
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<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

T-shaped arylsilanolate complexes

- (t-Bu3P)₂Pd + \( \text{Br} \)Br(t-Bu3P)HBr (3 mol %) 2-butanone, 70 °C 45 min (82%)
- (t-Bu3P)₂Pd + (t-Bu3P)₂HBr (3 mol %) toluene, rt (82%)
- (t-Bu3P)₂Pd + C₆H₄CF₂, 50 °C (rate = 2.45×10⁻³ mM/s)
Kinetic studies – potassium silanolate

- $K^+4^- \leq 1$ equiv (with respect to $3^-$): slow reaction, thermal transmetalation
- $1$ equiv $< K^+4^- < 5$ equiv: sudden increase in rate, activated transmetalation
- $K^+4^- > 5$ equiv: no increase in rate, activated transmetalation (saturated)

Kinetic studies – cesium silanolate

- $Cs^+4^- = 1$ equiv (with respect to $3^-$): same rate as with $K^+4^-$, thermal transmetalation
- $1$ equiv $< Cs^+4^- < 5$ equiv: sudden increase in rate, activated transmetalation
- $Cs^+4^- > 5$ equiv: no increase in rate, activated transmetalation (saturated)
Saturation point

- Cs-silanolate reacts much faster than the K-silanolate; kinetics had to be run at room temperature (vs. 50 °C for the K-silanolate)
- **Initial hypothesis:** higher nucleophilicity of the Cs-silanolate accounts for the increased rate
- However, saturation points for K and Cs-silanolates are identical
- **Rates at 25 °C are different**

![Chemical structure]

- **New hypothesis:** in toluene, ion pairs are not separated; higher reactivity of the Cs-silanolate arises from the greater negative charge localized on the 10-Si-5 intermediate

Arylsilanolates – summary

- Regardless of the cation employed (K⁺ or Cs⁺), arylsilanolates undergo **activated** transmetalation under catalytic conditions

![Chemical structure]

Transmetalation proceeds via S⁻Ar mechanism (requires interruption of aromaticity)

Denmark, S. E.; Smith, R. C.; Chang, W. T. T. *Tetrahedron* 2011, 67, 4391
Computational studies – thermal transmetalation

Extrusion of Me₂Si=O is supported!

Isomerization of the silanolate complex provides a lower energy pathway

Wang, H.

Computational studies – activated transmetalation

10-Si-S intermediate located as a stationary point

(ΔG°_thermal - ΔG°_activated) = 1.8 kcal/mol

Wang, H.
Summary of transmetalation modes

- Intermediates containing the critical Si-O-Pd linkage were isolated and shown to be kinetically competent

\[
\begin{align*}
\text{Me} & \quad \text{Me} \\
\text{Si} & \quad \text{O} \\
\text{Pd-L} & \quad \text{L}
\end{align*}
\]

- Both thermal and activated transmetalation are viable, depending on the conditions (stoichiometric or catalytic) and the organic moiety used (alkenyl or aryl)

\[
\begin{align*}
\text{Me} & \quad \text{Me} \\
\text{Si} & \quad \text{O} \\
\text{Pd-L} & \quad \text{L} \\
\text{8-Si-4} & \quad \text{thermal} \\
\text{Me} & \quad \text{Me} \\
\text{Si} & \quad \text{O} \\
\text{Pd-L} & \quad \text{L} \\
\text{10-Si-5} & \quad \text{activated}
\end{align*}
\]

- The understanding of the mechanism of cross-coupling of organosilanolates can guide the design and optimization of synthetic methods

- Stimulated similar studies for the transmetalation step in the Suzuki coupling

\[\text{J. Am. Chem. Soc. 2015, 137, 6192}\]
\[\text{J. Am. Chem. Soc. 2015, 137, 6200}\]

Quaternary stereocenters in organic synthesis

- Among the drugs currently on the market, nearly 300 contain a quaternary stereocenter

- Among the drugs on the market containing quaternary stereocenters, no instances are found where the stereocenter is forged via asymmetric synthesis!

- Stereoselective synthesis is made difficult by the steric repulsion between the substituents

- Existing methods lack generality

\[\text{de Vries, J. G., Important Pharmaceuticals and Intermediates. In Quaternary Stereocenters, Wiley-VCH Verlag GmbH & Co. KGaA: 2006; 25-50.}\]
\[\text{Kleeman, A.; Engel, J.; Kutscher, B.; Reichert, D., Pharmaceutical Substances - Syntheses, Patents and Applications of the Most Relevant APIs. Thieme.}\]
Enantioselective synthesis of quaternary stereocenters

- **Ongoing challenge** in organic synthesis
- The majority of the methods target **cyclic structures**
- **Acyclic structures** are more challenging due to the increased degrees of freedom
- **Limitation of existing methods:**
  - Limited to very specific substitution patterns in the starting material/product
  - Cannot generate isolated stereocenters
  - Are not catalytic (rely on a chiral auxiliary, a stoichiometric chiral reagent, or a resolution process as the source of the stereocenter)
  - Are overengineered
  - Utilize expensive and/or sensitive reagents/catalysts, therefore not scalable

Cross-coupling of allenylsilanolates

- **Advantages of silanol cross-coupling**
  - Stereocontrol imparted by the **chirality of the substrate**
  (no chiral reagent/catalyst needed)
  - The resulting **alkyne** is a **versatile intermediate**
Synthesis of allenylsilanolates: retrosynthetic analysis

Is the route amenable to an enantioselective synthesis?

Synthesis of allenylsilanolates

1. MsCl, Et3N, DCM
2. BnMgCl, CuCN, LiCl, THF, -78°C

(89%)

1. BuLi, THF, -78°C
2. DMOP-SiEt2Cl
3. BuLi

(72%)

1. HCl/Et2O, DCM, 0°C
2. acetate buffer (pH = 5)

(92%)

base

(NaH, KH, iBuLi)
Synthesis of allenylsilanlates

Enantioselective synthesis of allenylsilanols:
- Oxidation/stereoselective reduction
- Asymmetric reverse Brook rearrangement

- A synthesis of allenylsilanols/silanlates was developed (4 steps, 59% overall yield, potentially enantioselective)
- Flexible enough to accommodate structural variations
- Introduction of a new protecting group for sterically encumbered silanes

Cross-coupling optimization

Optimization with respect to:
- Pd source
- Ligand
- Electrophile
- R group (Et, iPr)
- M (Li, Na, K, Cs)
- Temperature
- Solvent
### Survey of Pd sources

<table>
<thead>
<tr>
<th>Pd source</th>
<th>time</th>
<th>α-product (%)</th>
<th>γ-product (%)</th>
<th>silanol (%)</th>
<th>halide (%)</th>
<th>allene (%)</th>
<th>α:γ ratio</th>
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<tbody>
<tr>
<td>Pd$_2$(dba)$_3$</td>
<td>1 h</td>
<td>36</td>
<td>-</td>
<td>46</td>
<td>54</td>
<td>3</td>
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<tr>
<td></td>
<td>18 h</td>
<td>37</td>
<td>5</td>
<td>20</td>
<td>37</td>
<td>5</td>
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<tr>
<td>Pd(4,4'-CF$_3$-dba)$_2$</td>
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<td>-</td>
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<td>61</td>
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<td>18 h</td>
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<td>4</td>
<td>27</td>
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<td>18 h</td>
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<td>5</td>
<td>4</td>
<td>-</td>
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<td>82:18</td>
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<td>15</td>
<td>-</td>
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<td></td>
<td>18 h</td>
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<td>12</td>
<td>49</td>
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<td>58:42</td>
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<td>Pd(acac)$_2$</td>
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<td>15</td>
<td>-</td>
<td>57</td>
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</tr>
<tr>
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<td>18 h</td>
<td>15</td>
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<td>51</td>
<td>6</td>
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<td>28</td>
<td>73</td>
<td>2</td>
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</tr>
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<td>7</td>
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<td>34</td>
<td>2</td>
<td>62:38</td>
</tr>
<tr>
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<td>10</td>
<td>2</td>
<td>50</td>
<td>82</td>
<td>6</td>
<td>83:17</td>
</tr>
<tr>
<td></td>
<td>18 h</td>
<td>10</td>
<td>10</td>
<td>14</td>
<td>61</td>
<td>9</td>
<td>49:51</td>
</tr>
<tr>
<td>Pd(OCOCF$_3$)$_2$</td>
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<td>85</td>
<td>3</td>
<td>90:10</td>
</tr>
<tr>
<td></td>
<td>18 h</td>
<td>10</td>
<td>11</td>
<td>10</td>
<td>53</td>
<td>6</td>
<td>47:53</td>
</tr>
</tbody>
</table>

### Mechanistic hypothesis

- The \( \alpha:\gamma \) ratio decreases over the course of the reaction.
- Products/byproducts are not responsible for a change in the mechanism (tested by addition of NaI, arsine-oxide, product).
- **Thermal transmetalation** for the \( \gamma \)-product / **Activated transmetalation** for the \( \alpha \)-product?
Catalytic cycle

Implications

Activated transmetalation favored by:
- High concentration of silanolate
- Poorly coordinating cations (K⁺, Cs⁺)
- Small R groups (Me)
- Ethereal solvents
- Additives that loosen the ion pair

Thermal transmetalation favored by:
- Low concentration of silanolate
- Tightly coordinating cations (Li⁺)
- Large R groups (iPr)
- Non-coordinating solvents
- Bulky electrophiles
## Effect of the cation

<table>
<thead>
<tr>
<th>conditions</th>
<th>time</th>
<th>α-product (%)</th>
<th>γ-product (%)</th>
<th>silanol (%)</th>
<th>halide (%)</th>
<th>allene (%)</th>
<th>α:γ ratio</th>
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<td>Li-silanolate</td>
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<td>55</td>
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<td>18 h</td>
<td>10</td>
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<td>10</td>
<td>53</td>
<td>6</td>
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<td>K-silanolate</td>
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<td>-</td>
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<tr>
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<td>45</td>
<td>1</td>
<td>18</td>
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<td>K-silanolate</td>
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<td>1</td>
<td>22</td>
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<tr>
<td>80 °C</td>
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<td>2</td>
<td>-</td>
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<td>Silanol + Cs₂CO₃</td>
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Tight ion pair $\rightarrow$ γ-selectivity (but lower reactivity)

## Effect of the R groups on silicon

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<th>conditions</th>
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<th>α-product (%)</th>
<th>γ-product (%)</th>
<th>silanol (%)</th>
<th>halide (%)</th>
<th>allene (%)</th>
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</tr>
<tr>
<td>40 °C</td>
<td>18 h</td>
<td>10</td>
<td>11</td>
<td>10</td>
<td>53</td>
<td>6</td>
<td>47:53</td>
</tr>
<tr>
<td>Na / iPr₂</td>
<td>18 h</td>
<td>-</td>
<td>-</td>
<td>52</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>40 °C</td>
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<td></td>
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</tr>
<tr>
<td>Na / iPr₂</td>
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<td>74</td>
<td>76</td>
<td>1</td>
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<tr>
<td>80 °C</td>
<td>18 h</td>
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<td>6</td>
<td>14</td>
<td>11</td>
<td>1</td>
<td>8:92</td>
</tr>
<tr>
<td>K / Et₂</td>
<td>1 h</td>
<td>57</td>
<td>1</td>
<td>22</td>
<td>42</td>
<td>12</td>
<td>98:2</td>
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<tr>
<td>80 °C</td>
<td>18 h</td>
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<td>7</td>
<td>2</td>
<td>-</td>
<td>20</td>
<td>93:7</td>
</tr>
<tr>
<td>K / iPr₂</td>
<td>1 h</td>
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<td>1</td>
<td>61</td>
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<td>Et₂ + Cs₂CO₃</td>
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<td>29</td>
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<td>iPr₂ + Cs₂CO₃</td>
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<td>84</td>
<td>76</td>
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<td>80 °C</td>
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<td>3</td>
<td>23</td>
<td>9</td>
<td>-</td>
<td>1</td>
<td>11:89</td>
</tr>
</tbody>
</table>

Bulky R group $\rightarrow$ γ-selectivity (but lower reactivity)
Optimized cross-coupling reaction

- Optimization of **α-selective cross-coupling** conditions

  \[
  \text{Bn} \rightleftharpoons \text{Me} \rightleftharpoons \text{SiEt} \rightleftharpoons \text{OK}^+ \quad (1.3 \text{ equiv}) + \quad \text{Ph}_{\text{F}} \rightleftharpoons \text{Ph} \rightleftharpoons \text{I} \quad \text{Pd(OOCF}_3\text{)}_2 \left(5 \text{ mol} \%ight) \quad \text{PPh}_3 \left(10 \text{ mol} \%ight) \quad \text{toluene, 80 °C, 18 h} \]

  \[\text{Bn} \rightleftharpoons \text{Me} \rightleftharpoons \text{CF}_3 \quad 82\%, \alpha/\gamma = 93:7\]

- Unsuccessful optimization of **γ-selective cross-coupling** conditions (α-coupling is preferred, unless Si bears bulky substituents)

  \[
  \text{Bn} \rightleftharpoons \text{Me} \rightleftharpoons \text{SiPh}_3 \rightleftharpoons \text{OH} \quad (1.3 \text{ equiv}) + \quad \text{Ph}_{\text{F}} \rightleftharpoons \text{Ph} \rightleftharpoons \text{I} \quad \text{Pd(OOCF}_3\text{)}_2 \left(5 \text{ mol} \%ight) \quad \text{PPh}_3 \left(10 \text{ mol} \%ight) \quad \text{Cs}_2\text{CO}_3 \left(1.3 \text{ equiv}\right) \quad \text{toluene, 80 °C, 18 h} \]

  \[\text{Bn} \rightleftharpoons \text{Me} \rightleftharpoons \text{CF}_3 \quad 23\%, \gamma/\alpha = 89:11\]

Conclusions

- The enantioselective synthesis of quaternary stereocenters could not be achieved through the proposed methods
- Allenylsilanolates prefer to undergo cross-coupling at the α-position
- The **enantioretentive α-selective cross-coupling** of allenylsilanolates is open to further exploration
- C-C activation of 3,3-disubstituted cyclobutanones is challenging and complicated by several competing processes
Reductive processes in organic synthesis

- A large number of organic reactions are **overall reductive** and rely on a pre-reduced starting material.
- **Issues:** waste stream, poor atom economy

**Grignard**

\[ \text{R} = \text{Br} \quad \text{Mg}(0) \rightarrow [\text{R} - \text{Mg}(II)\text{Br}] \rightarrow 1. \text{R}' - \text{CHO} + 2. \text{H}_2\text{O} \rightarrow \text{R} - \text{R}' + \text{Mg}(II)\text{Br}\text{OH} \]

**Stannane allylation**

\[ \text{Sn}(IV)\text{Bu}_3 \rightarrow \text{R} - \text{Mg}(II)\text{Br} \rightarrow \text{OH} \rightarrow \text{Bu}_3\text{Sn}(IV)\text{OH} \]

**Nozaki-Hiyama-Kishi**

\[ \text{R} = \text{Br} \quad \text{Ni}(0) \rightarrow \text{R} - \text{Ni}(II)\text{Br}_2 \]

**Wittig**

\[ \text{R} - \text{Br} \rightarrow \text{PPh}_3 \rightarrow \text{R} - \text{P}+\text{Ph}_3\text{Br} \rightarrow \text{R} - \text{Ph}_3\text{P}=\text{O} \]

Catalytic variants

- **Solution:** use of a terminal reducing agent
- This approach does not solve the problem of waste generation – it just replaces a reducing agent with another (perhaps more tractable) stoichiometric reducing agent

**Nozaki-Hiyama-Kishi**

\[ \text{Me} - \text{I} \rightarrow \text{CHO} \rightarrow \text{CrCl}_2/\text{NiCl}_2 (15 \text{ mol}\%) \rightarrow \text{Mn powder (1.7 equiv)} \rightarrow \text{TMSCl (2.4 equiv)} \rightarrow \text{DMF/DME, 50 °C} \rightarrow \text{MeO} \rightarrow \text{Me} \rightarrow \text{OH} \rightarrow (75\%) \]


**Halide coupling**

\[ \text{Me}_{2}\text{N} - \text{Br} \rightarrow \text{Br} - \text{COOEt} \rightarrow \text{Nil}_2 (5 \text{ mol}\%) \rightarrow \text{bipy (5 mol\%)} \rightarrow \text{pyridine (5 mol\%)} \rightarrow \text{Nal (25 mol\%)} \rightarrow \text{Zn (2 equiv)} \rightarrow \text{DMAPU, 60 °C} \rightarrow \text{Me}_{2}\text{N} \rightarrow \text{COOEt} \rightarrow (72\%) \]


**Wittig reaction**

\[ \text{O} \rightarrow \text{Ph} \rightarrow \text{Me} \rightarrow \text{O} \rightarrow \text{Pb}_2\text{SiH}_2 (1.5 \text{ equiv}) \rightarrow \text{Na}_2\text{CO}_3 (1.5 \text{ equiv}) \rightarrow \text{toluene, 100 °C} \rightarrow \text{Me} \rightarrow \text{COOEt} \rightarrow (73\%, E/Z > 95:5) \]

**Truly catalytic variants**

**Grand Challenge:**
Discover ways to carry out fundamentally new chemical transformations utilizing green and sustainable chemistry and engineering, based on the ultimate premise that it is better to prevent waste than to clean it up after it is formed.


- **Better solution: redox-neutral transformations**

  **Hydrogen-transfer allylation**

  ![Chemical reaction](image)

  ![Chemical structure](image)

  (62%, er = 96.5:3.5)


  **Hydrogen-transfer alkylation**

  ![Chemical reaction](image)

  ![Chemical structure](image)

  (71%)


**Our solution**

Use of CO as the terminal reducing agent exploiting the reducing potential of the Water-Gas Shift Reaction

\[
\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2
\]

- **Cheap, traceless reducing agent**
- **CO**₂ and acetic acid are the only byproducts


1. Addition of organometallic reagents to carbonyls

- WGSR reduces the metal that accomplishes the transformation
- Studied using DoE approaches with Cr, Mn, Ru, Pd, Ni
- Turnover was never observed
- Issues: Compatibility with water

Cleavage of the alkoxide

Electrochemical limitations

\[
\begin{align*}
\text{CO} + \text{H}_2\text{O} & \rightarrow \text{CO}_2 + 2\text{H}^+ + 2e^- & E_{\text{ox}}^* = +0.53 \text{ V} \\
\text{M}^{n+} + 2e^- & \rightarrow \text{M}^0 & E_{\text{red}}^* = x \\
\text{M}^{n+} + \text{CO} + \text{H}_2\text{O} & \rightarrow \text{M}^0 + \text{CO}_2 + 2\text{H}^+ & \Delta E^* = (x + 0.53) \text{ V}
\end{align*}
\]

If \( E_{\text{red}}^* > -0.53 \text{ V} \), the reaction can be driven by the WGSR.
Electrochemical requirements

\[ M^{2+} + 2e^- \rightarrow M^0 \]
\[ M^{2+} + CO + H_2O \rightarrow M^0 + CO_2 + 2H^+ \]

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2. Catalytic Wittig olefination

- WGSR turns over an organocatalyst
- The metal is NOT involved in the transformation being accomplished
3. Reductive alkylation

- WGSR and C-C bond forming event happen in **two separate steps**
- WGSR acts as a **source of H2**
- **Benefits**: tandem reaction; higher functional group compatibility vs standard hydrogenation
- Previous reports: user-unfriendly protocol, high T and P

![Diagram]


### Substrate scope

- Works at **room temperature**!
- Good functional group compatibility
- Significant impact of the **alkene’s Lewis basicity**
- Being extended to ketones and other active-methylene compounds

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<th>Substrate</th>
<th>Yield (%)</th>
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<tbody>
<tr>
<td>NC COOEt + R-CHO</td>
<td>RhCl3 2 mol%, H2O 2 equiv, 18 h</td>
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<tr>
<td>Me CHO</td>
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**WGSR summary**

- The WGSR can be successfully used in organic synthesis to provide reducing power
- Different strategies can be envisioned:
  - *Reduction of a metal catalyst*
  - *Reduction of an organocatalyst*
  - *Incorporation of H₂ in the substrate*
- The first two approaches are more challenging and need to take into account:
  -  *Electrochemical limits*
  -  *Ease of reduction (BDEs)*
  -  *Compatibility with water*

**References**

- **Organosilanolate cross-coupling**
  
  *Cross-Coupling with Organosilicon Compounds*
  
  
  *Why You Really Should Consider Using Palladium-Catalyzed Cross-Coupling of Silanols and Silanolates*
  

- **Allene chemistry**
  
  *Modern Allene Chemistry*
  

- **Quaternary stereocenters**
  
  *Catalytic enantioselective synthesis of quaternary carbon stereocentres*
  

- **C-C activation**
  
  *C-C Bond Activation*
  
  
  *Catalytic C-C Bond Activations via Oxidative Addition to Transition Metals*
  

- **WGSR in organic synthesis**
  
  *ACIE review coming soon... stay tuned*