# Electronic Supplementary Information

## DIFFERENTIAL SELECTIVITY MEASUREMENTS AND COMPETITIVE REACTION METHODS AS EFFECTIVE MEANS FOR MECHANISTIC STUDIES OF COMPLEX CATALYTIC REACTIONS

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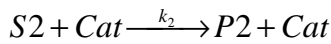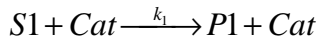
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**Chapter S1**

**Dependences of integral and differential selectivity on time in the competitive reaction of two competing substrates**

The reaction of two competing substrates $S1$ and $S2$ converting into two products $P1$ and $P2$ on the catalyst $Cat$ can be presented as follows:

$$S1 + Cat \xrightarrow{k_1} P1 + Cat$$

$$S2 + Cat \xrightarrow{k_2} P2 + Cat$$

Catalyst concentration ($[Cat]$) does not change, therefore competing reactions can be considered as the pseudo-first-order reaction described by the following rate equations:

$$r_{P1} = -\frac{d[S1]}{dt} = k_1[Cat][S1) = k_1'[S1] \text{ and } r_{P2} = -\frac{d[S1]}{dt} = k_2[Cat][S2] = k_2'[S2]$$

where $k_1' = k_1[Cat]$, $k_2' = k_2[Cat]$, $t$ - reaction time.

In this situation integral equations of the substrates consumption will be as:

$$[S1] = [S1]_0 \times e^{-k_1't} \text{ and } [S2] = [S2]_0 \times e^{-k_2't},$$

where $[S1]_0$ and $[S2]_0$ – initial concentrations of the substrates.

Integral equations for products:

$$[P1] = [S1]_0 - [S1] = [S1]_0(1 - e^{-k_1't}) \text{ и } [P2] = [S2]_0 - [S2] = [S2]_0(1 - e^{-k_2't})$$

So integral selectivity:

$$Sel_{int} = \frac{[P1]}{[P1] + [P2]} = \frac{[S1]_0(1 - e^{-k_1't})}{[S1]_0(1 - e^{-k_1't}) + [S2]_0(1 - e^{-k_2't})}$$

And differential selectivity:

$$Sel_{dif} = \frac{r_{P1}}{r_{P1} + r_{P2}} = \frac{k_1'[S1]}{k_1'[S1] + k_2'[S2]} = \frac{k_1'[S1]_0 e^{-k_1't}}{k_1'[S1]_0 e^{-k_1't} + k_2'[S2]_0 e^{-k_2't}}$$

It is obvious that differential and integral selectivities depend on time in different ways. It is illustrated by calculated dependences of the selectivities presented in Fig. S1.
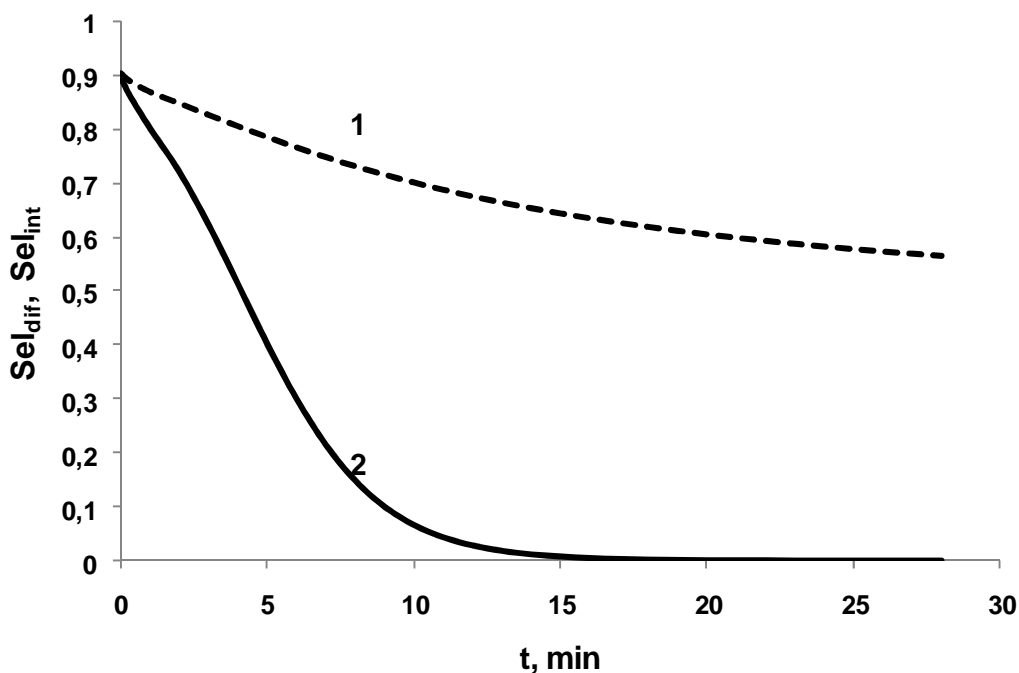
Fig. S1 Calculated dependences of integral (1) and differential (2) selectivities ($k'_1$=0.5 min$^{-1}$, $k'_2$=0.05 min$^{-1}$, $[S1]_0$=$[S2]_0$=100 M).

**Chapter S2**

**Quantitative measurements of selectivity by integration of equations corresponding to different mechanism hypotheses**

1. If the rate ratio of competing reactions is expressed by the equation:

$$\frac{r_{P2}}{r_{P1}} = \frac{k_2[X_{com}]}{k_1[X_{com}]} = \frac{k_2}{k_1}$$

then

$$\frac{r_{P2}}{r_{P1}} = \frac{d[P2]/dt}{d[P1]/dt} = \frac{d[S2]/dt}{d[S1]/dt} = \frac{k_2[X_{com}]}{k_1[X_{com}]} = \frac{k_2}{k_1}$$

$$\frac{d[S2]}{d[S1]} = \frac{k_2}{k_1}$$

$$k_1 \int_{[S2]_0}^{[S2]} d[S2] = k_2 \int_{[S1]_0}^{[S1]} d[S1]$$

$$k_1([S2] - [S2]_0) = k_2([S1] - [S1]_0)$$

Integral dependence of [S1] on [S2] will be as:

$$[S1] = \left([S1]_0 - \frac{k_1}{k_2}[S2]_0\right) + \frac{k_1}{k_2}[S2]$$

The slope of tangent to any point of the linear dependence [S1]=f [S2] is the ratio of the rate constants of competing reactions determining the differential selectivity.

2.  If the rate ratio of competing reactions is expressed by the equation:

$$\frac{r_{P2}}{r_{P1}} = \frac{k_2[X_{com}][S2]}{k_1[X_{com}][S1]} = \frac{k_2}{k_1}\frac{[S2]}{[S1]}$$

then

$$\frac{r_{P2}}{r_{P1}} = \frac{d[P2]/dt}{d[P1]/dt} = \frac{d[S2]/dt}{d[S1]/dt} = \frac{k_2[X_{com}][S2]}{k_1[X_{com}][S1]} = \frac{k_2}{k_1}\frac{[S2]}{[S1]}$$

$$\frac{d[S2]}{d[S1]} = \frac{k_2}{k_1}\frac{[S2]}{[S1]}$$

$$\int_{[S2]_0}^{[S2]} \frac{d[S2]}{[S2]} = \frac{k_2}{k_1}\int_{[S1]_0}^{[S1]} \frac{d[S1]}{[S1]}$$

$$Ln\left(\frac{[S2]}{[S2]_0}\right) = \frac{k_2}{k_1}Ln\left(\frac{[S1]}{[S1]_0}\right)$$

Integral dependence of [S1] on [S2] will be as:

$$Ln[S1] = \left(Ln[S1]_0 - \frac{k_1}{k_2}Ln[S2]_0\right) + \frac{k_1}{k_2}Ln[S2]$$

The slope of tangent to any point of the linear dependence $Ln[S1]=f(Ln[S2])$ is the ratio of the rate constants of competing reactions determining the differential selectivity.

3.  If the rate ratio of competing reactions is expressed by the equation (for competing reaction of two competing substrates and common reagent R):

$$\frac{r_{P2}}{r_{P1}} = \frac{d[P2]/dt}{d[P1]/dt} = \frac{d[S2]/dt}{d[S1]/dt} = \left(\frac{k'_{S2}k_{S2}}{k'_{S1}k_{S1}}\right)\left(\frac{k'_{-S1} + k_{S1}[R]}{k'_{-S2} + k_{S2}[R]}\right)\frac{[S2]}{[S1]}$$

$$\frac{d[S2]}{d[S1]} = \left(\frac{k'_{S2}k_{S2}}{k'_{S1}k_{S1}}\right)\left(\frac{k'_{-S1} + k_{S1}[R]}{k'_{-S2} + k_{S2}[R]}\right)\frac{[S2]}{[S1]}$$

As this equation is too complex integral dependence of [S1] on [S2] can be obtained by appropriate methods of numerical integration. Calculation of the rate constants can be performed by nonlinear fitting the experimental data to selectivity equation (typically a PC with a spreadsheet program, perhaps supplemented by a commercial curve-fitting package).

**Chapter S3**

**Differential selectivity measurements using to investigate active species nature in cross-coupling reactions**

3.1.Mizoroki-Heck reaction

To study the differential selectivity competitive experiments were carried out. Styrene (5 mmol) and two competing aryl halides (S1 and S2) (2.5 mmol of each), NaOAc (6.5 mmol) as base, Pd/support or PdCl$_2$ (0.08 mmol of Pd, i.e. 1.6 mol% with respect to styrene), naphthalene (1 mmol) as internal standard for GC analysis were added to 5 ml of DMF in a glass reactor, equipped with a magnetic stirring bar and a septum inlet. The reactor was placed into a pre-heated oil bath (140$^0$C) and the reaction mixture was stirred. Each run was repeated three times to make sure that it is reproducible. Samples for GC analyses were collected at different moments of the reaction.

When alkenes were used as competing substrates 1-bromo-4-chlorobenzene (5 mmol) and two competing alkenes (S1 and S2) (2.5 mmol of each), NaOAc (6.5 mmol) as base, Pd/C or PdCl$_2$ (0.08 mmol of Pd, i.e. 1.6 mol% with respect to aryl bromide), naphthalene (1 mmol) as internal standard for GC analysis were added to 5 ml of DMF in a glass reactor, equipped with a magnetic stirring bar and a septum inlet. The experimental procedure was analogous to mentioned above.
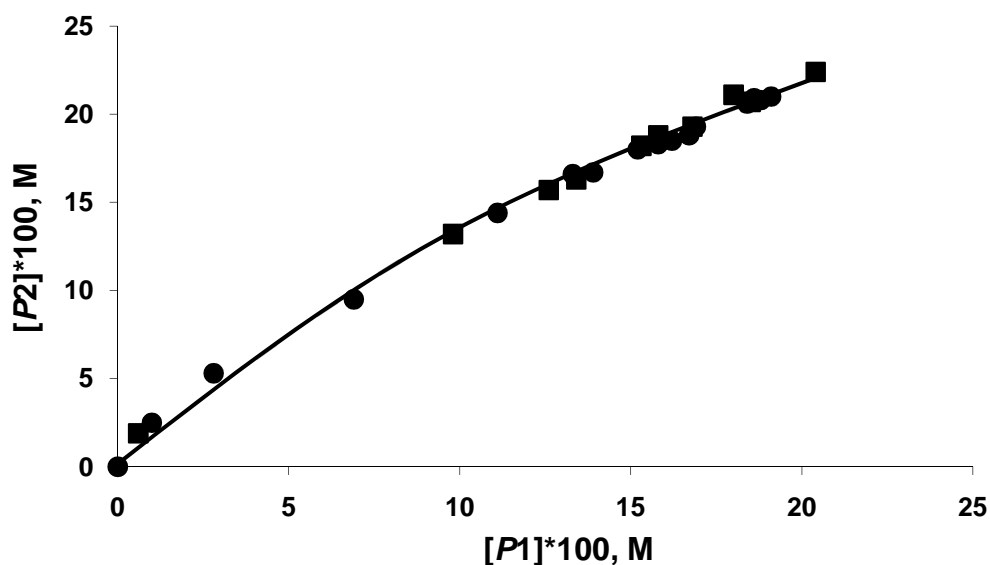


Fig. S2 The phase trajectories of Mizoroki-Heck reaction of competing aryl iodides (iodobenzene and 4-iodotoluene) with styrene using PdCl$_2$ (■) and Pd/C (●)as catalyst precursors, where [$P$1] - [stilbene], [$P$2] - [4-methylstilbene].
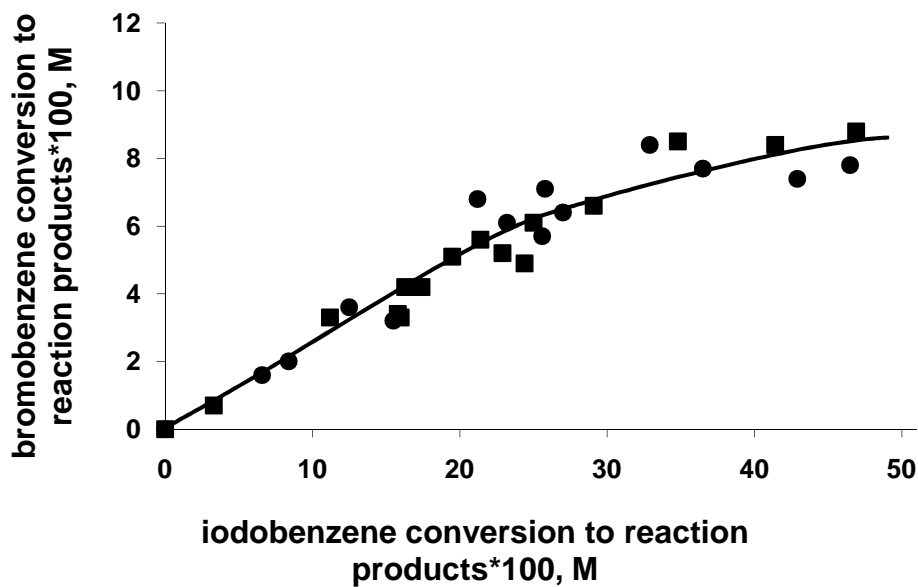
Fig. S3 The phase trajectories of Mizoroki-Heck reaction with styrene and competing iodobenzene and bromobenzene using PdCl$_2$ (■) and Pd/C (●) as catalyst precursors.
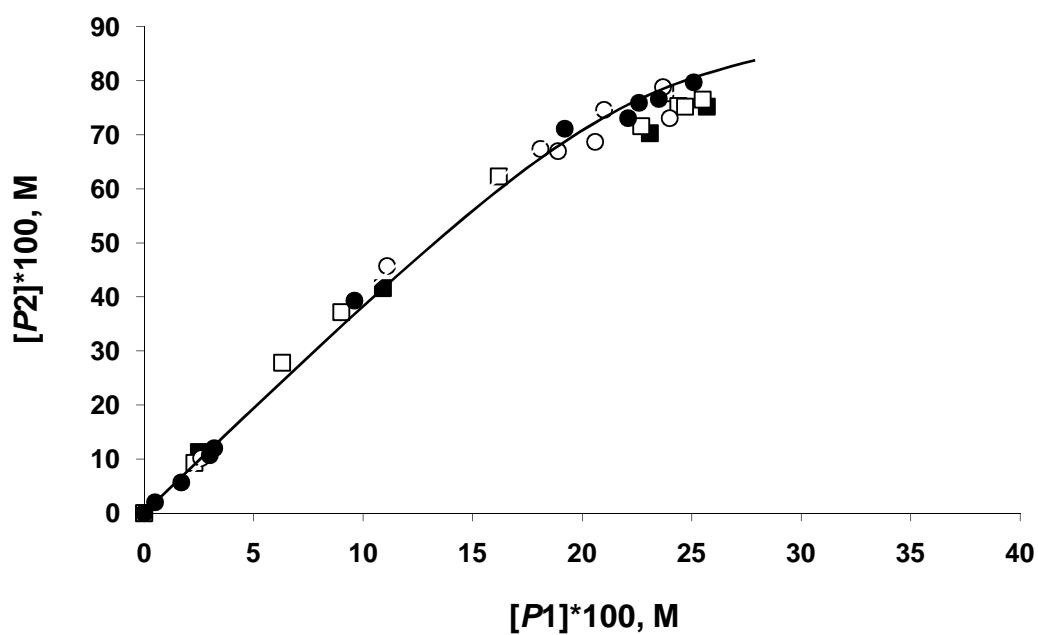


Fig. S4 The phase trajectories of Mizoroki-Heck reaction of competing aryl bromides (bromobenzene and 1-bromo-4-chlorobenzene) with styrene using 1,6 mol.% (■), 0,32 mol.% (□), 0,16 mol.% (○), 0,016 mol.% (●) of PdCl$_2$ as catalyst precursor, where [P1] - [stilbene], [P2] - [4-chlorostilbene].
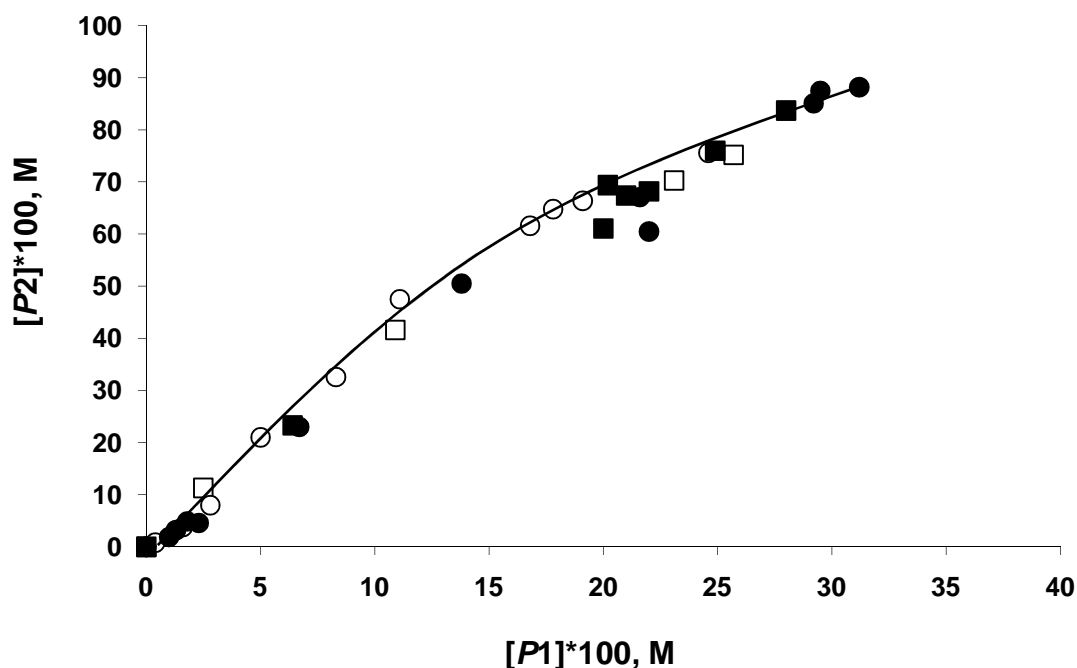
Fig. S5 The phase trajectories of Mizoroki-Heck reaction of competing aryl bromides (bromobenzene and 1-bromo-4-chlorobenzene) with styrene using $NBu_4Br$ (Pd/C + $NBu_4Br$, ●), HCOONa ($PdCl_2$ + HCOONa, ■), $PdCl_2$ (□) and Pd/C (○) as catalyst precursors, where [$P1$] - [stilbene], [$P2$] - [4-chlorostilbene].
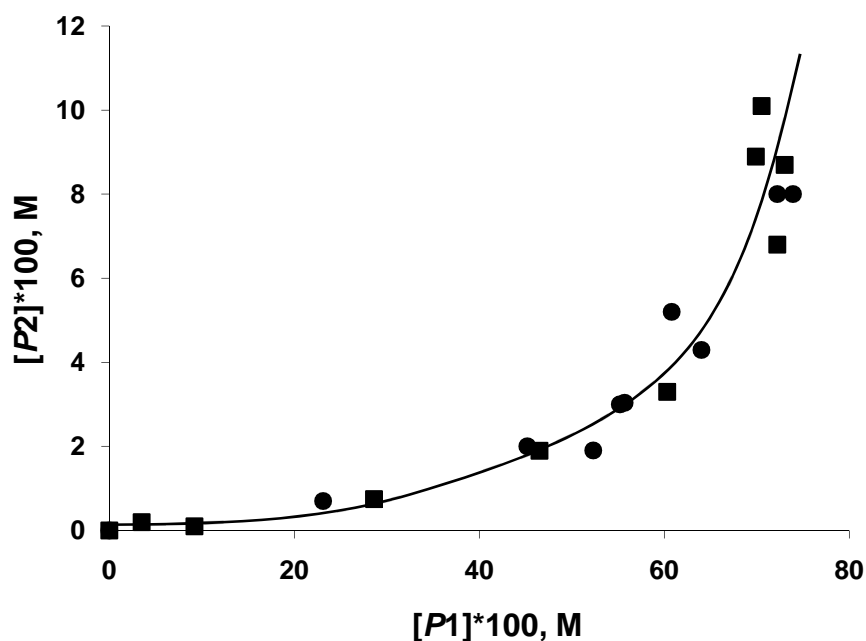


Fig. S6 The phase trajectories of Mizoroki-Heck reaction of 1-bromo-4-chlorobenzene with competing alkenes (styrene and $n$-butyl acrylate) using $PdCl_2$ (●) and Pd/C (■) as catalyst precursors, where [$P1$] - [4-chlorobutylcinnamate], [$P2$] - [stilbene].

### 3.2. Suzuki-Miyaura reaction

To study the differential selectivity competitive experiments were carried out. Phenylboronic acid (5 mmol) and two competing aryl halides ($S1$ and $S2$) (2.5 mmol of each), NaOAc (6.5 mmol) as base, Pd/support or $PdCl_2$ (0.08 mmol of Pd, i.e. 1.6 mol% with respect to

phenylboronic acid), naphthalene (1 mmol) as internal standard for GC analysis were added to 5 ml of DMF in a glass reactor, equipped with a magnetic stirring bar and a septum inlet. The reactor was placed into a pre-heated oil bath ($140^0$C) and the reaction mixture was stirred. Each run was repeated three times to make sure that it is reproducible. Samples for GC analyses were collected at different moments of the reaction.
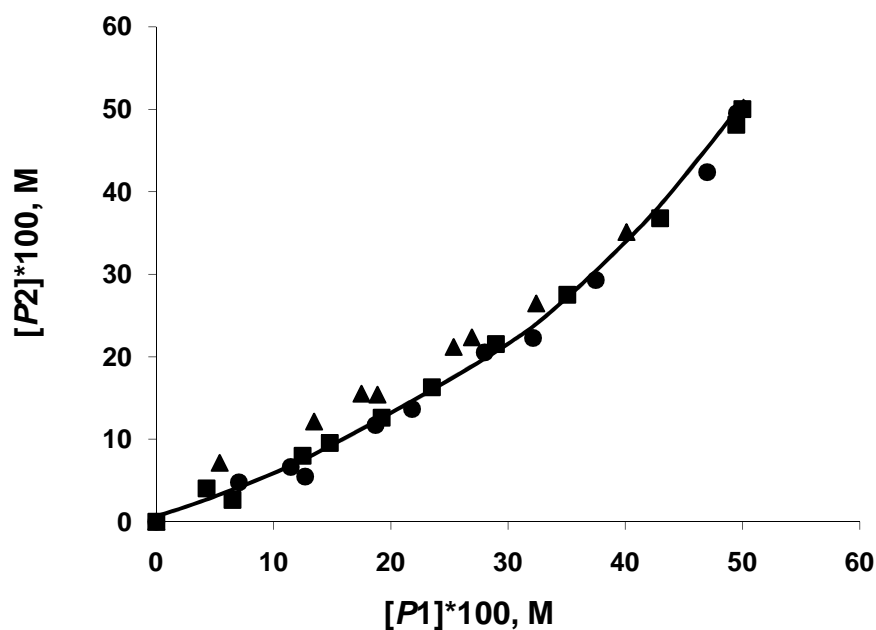


Fig. S7 The phase trajectories of Suzuki-Miyaura reaction of competing aryl iodides (iodobenzene and 4-iodotoluene) with phenylboronic acid using $PdCl_2$ (■), $Pd/Al_2O_3$ (▲) and Pd/C (●) as catalyst precursors where [$P$1] - [biphenyl], [$P$2] - [4-methylbiphenyl].
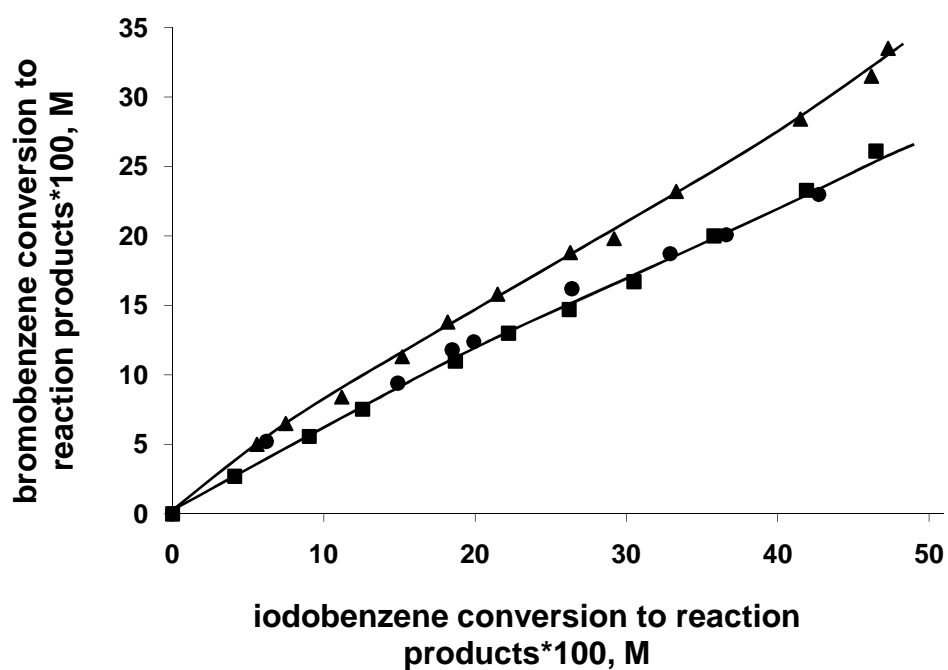
Fig. S8 The phase trajectories of Suzuki-Miyaura reaction with phenylboronic acid and competing iodobenzene and bromobenzene using PdCl$_2$ (■), Pd/C (▲) and Pd/C + NBu$_4$Br (●) as catalyst precursors.

### 3.3. Comparative study of Mizoroki-Heck and Suzuki-Miyaura reactions

To compare differential selectivities Mizoroki-Heck and Suzuki-Miyaura reactions the reactions between two competing aryl halides and styrene or phenylboronic acid in Mizoroki-Heck and Suzuki-Miyaura reactions respectively were carried out according to the procedures mentioned above.
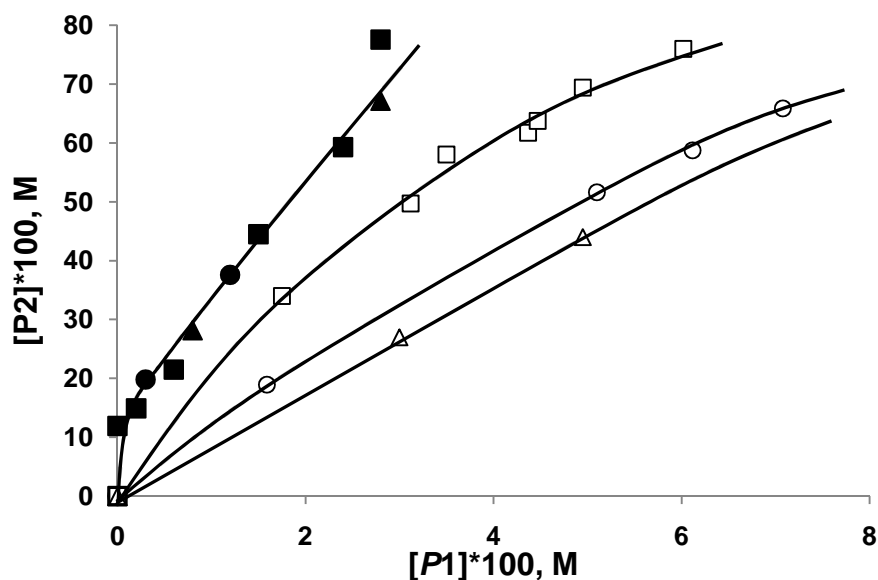


Fig. S9 The phase trajectories of Suzuki-Miyaura reaction with phenylboronic acid and Mizoroki-Heck reaction with styrene and competing aryl bromides (bromobenzene and 4-bromoacetophenone) using (□) Pd/SiO$_2$ (Suzuki-Miyaura reaction), (○) Pd/Al$_2$O$_3$ (Suzuki-Miyaura reaction), (Δ) PdCl$_2$ (Suzuki-Miyaura reaction), (■) Pd/SiO$_2$ (Mizoroki-Heck reaction), (●) Pd/Al$_2$O$_3$ (Mizoroki-Heck reaction) and (▲) PdCl$_2$ (Mizoroki-Heck reaction) as catalyst precursors where [$P$1] - [product of bromobenzene coupling], [$P$2] - [product of 4-bromoacetophenone coupling].