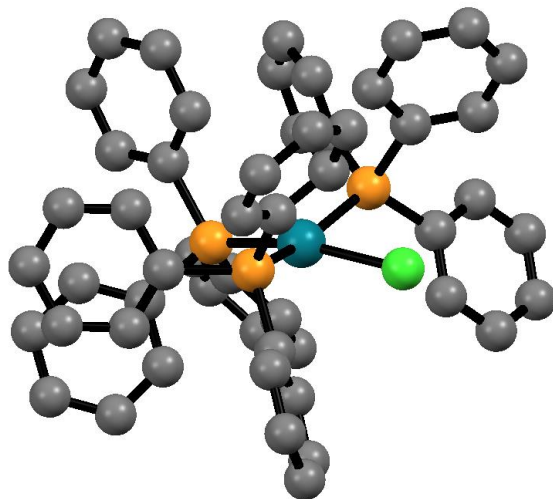


Chemistry of Molecular Systems



**Wilkinson's Catalyst,
 $\text{Rh}(\text{PPh}_3)_3\text{Cl}$**

Paradigm catalyst pioneered
by Geoffrey Wilkinson here
at Imperial College London

Fundamentals of catalysis – Lecture 12

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Intended learning outcomes

After the next four lectures you will be able to...

- classify the primary types of organometallic reactions.
- define what is meant by inert and labile TM complexes.
- explain the features that dictate inertness or lability of a complex.
- *understand the effects of catalyst on reaction pathways.*
- *define key terms in catalysis.*
- *analyse catalytic cycles and their respective data to infer key steps in the cycles.*
- rationalise the effectiveness of TM complexes in catalysis.
- understand key aspects of catalyst design to optimise performance.
- understand the importance of TM complexes in small molecule activation.
- recognise, explain and rationalise key catalytic cycles
- propose catalytic cycles for a given transformation.

Catalysis: Introduction

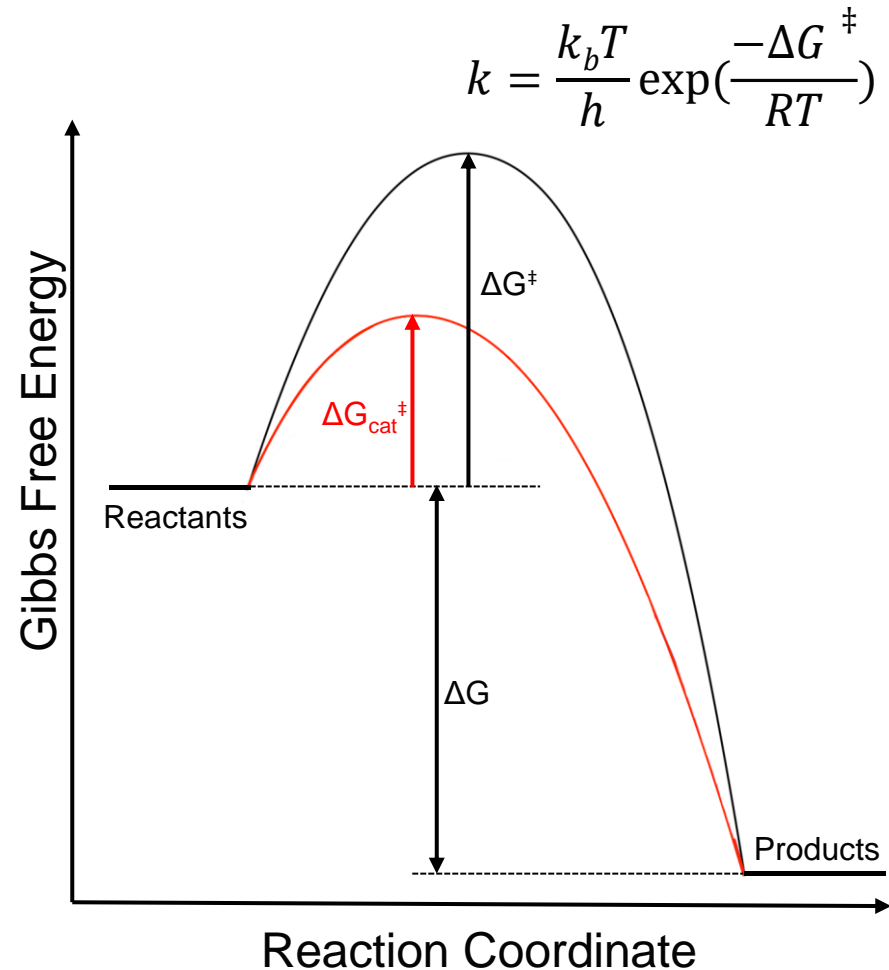
What is Catalysis?

“Catalysis is a means of accelerating chemical reactions by lowering the activation energy barrier (ΔG^\ddagger)” (Bochmann)

“A substance that increases the rate of a reaction without modifying the overall standard Gibbs energy change in the reaction” (IUPAC definition of Catalyst).

Not used up in reaction but appears in rate equation.

Doesn't alter position of equilibrium (i.e. ΔG stays the same)



Catalysis: Introduction

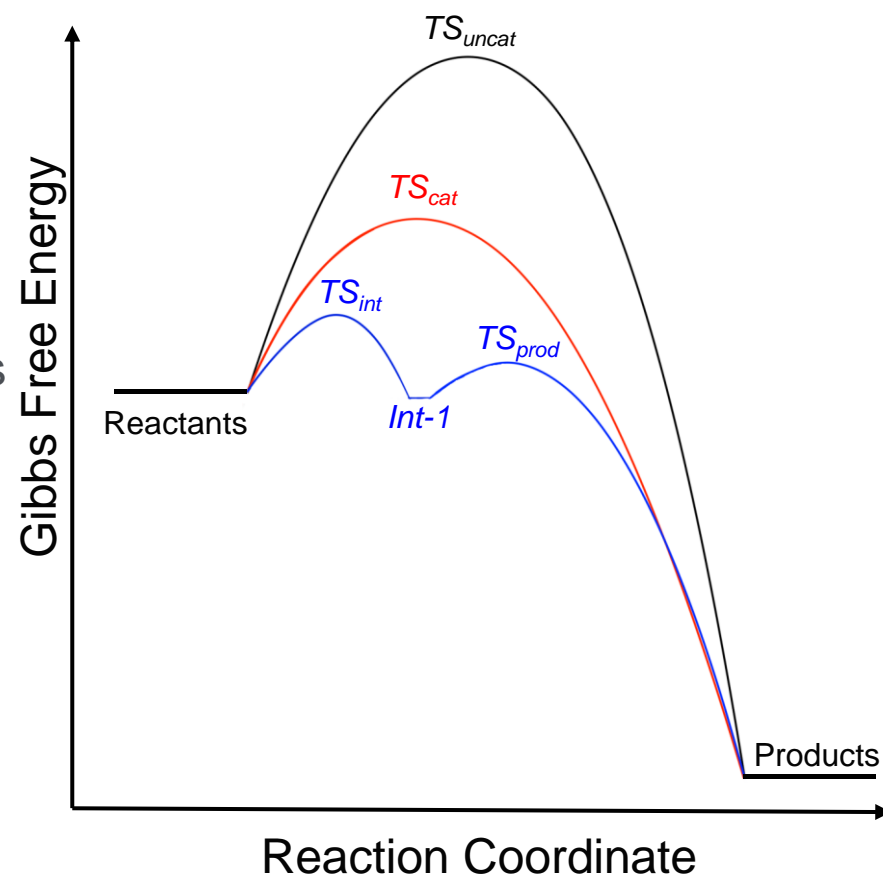
So catalysts lowers ΔG^\ddagger – how?

Can be by stabilising transition state (red)

More commonly by forming a pathway of accessible intermediates (blue)

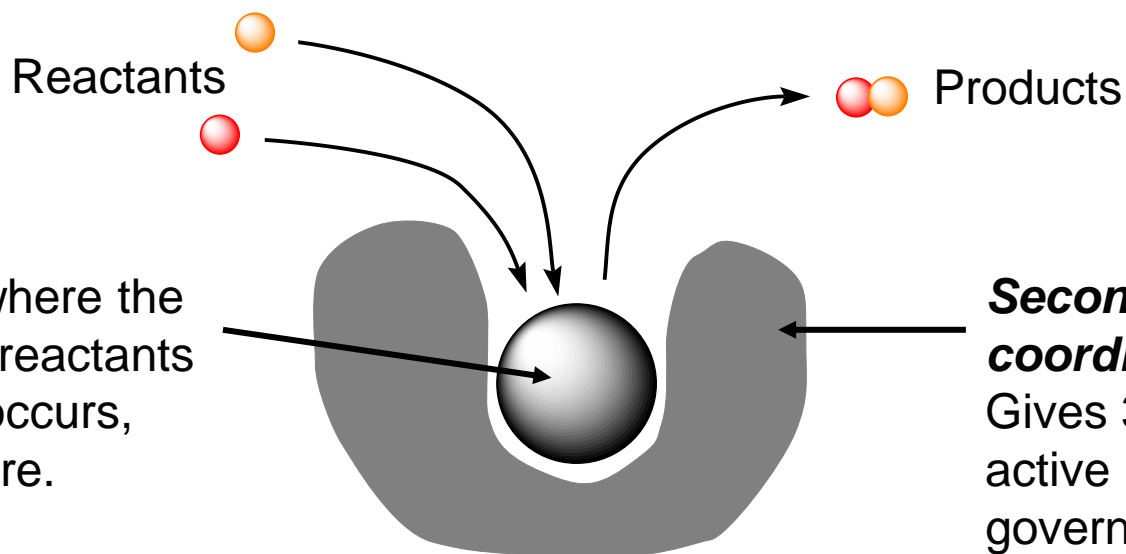
Transition State: “the state corresponding to the highest potential energy along this reaction coordinate – it cannot be observed.”

Intermediate: “is a molecular entity that is formed from the reactants and reacts further to give products with a lifetime appreciably longer than a molecular vibration –i.e. it is *theoretically* observable!”



Catalysis: Active Site Model

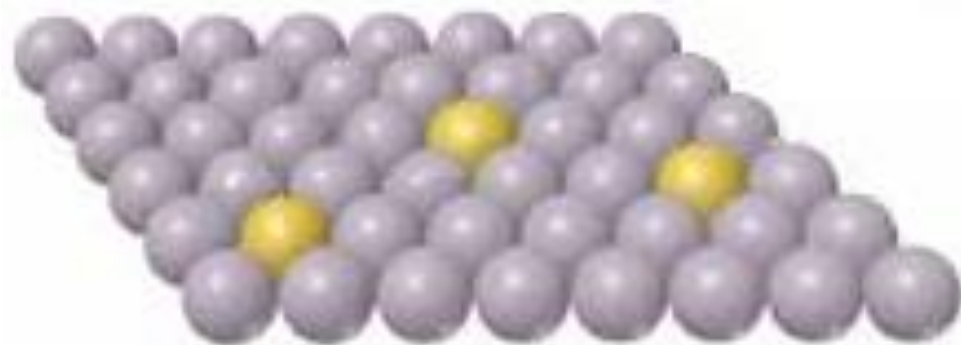
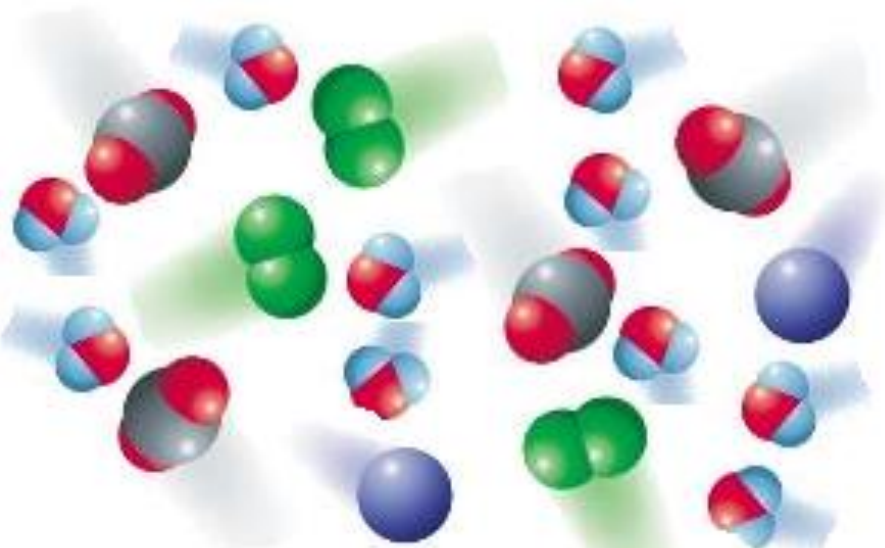
Mass Transport: For the reactants to form products they must get to, and interact with, active site – may be rate limiting (especially in heterogeneous catalysis).



Active site: site where the actual reaction of reactants to form products occurs, often a metal centre.

Secondary coordination sphere: Gives 3D shape around active site and will govern selectivity.

Catalysis: Homogenous vs Heterogenous



Homogeneous catalysis: Reactants, products and catalysts all in the same phase.

Pros: Well defined active site and secondary coordination sphere – high selectivity.

Same phase gives easy mass transport – high activity.

Solution phase means easy to study.

Cons: Solvent interaction gives deleterious side reactivity – low longevity.

Separation of catalyst and products.

Heterogeneous catalysis: Reactants, products in different phase to catalyst.

Pros: Catalyst recyclability/regeneration.

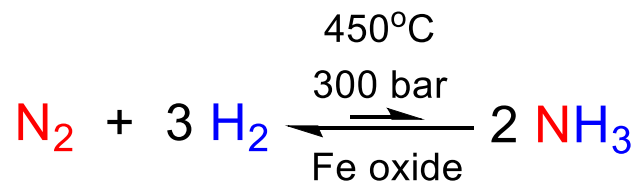
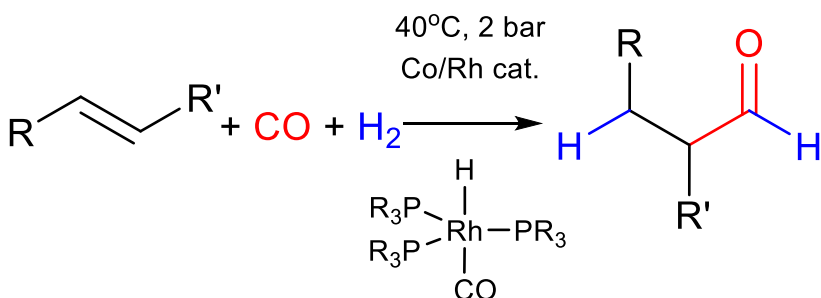
Lack of poisoning of products.

High catalyst longevity.

work at extreme temperatures and pressures.

Cons: Generally poorer selectivity and activity. Difficult to study active site.

Catalysis: Homogenous vs Heterogenous



Homogeneous catalysis examples:

Simple acid/base catalysis (e.g. ester hydrolysis), enzymes, organometallic complexes.

e.g. 'Oxo process' (hydroformylation)

Heterogeneous catalysis examples:

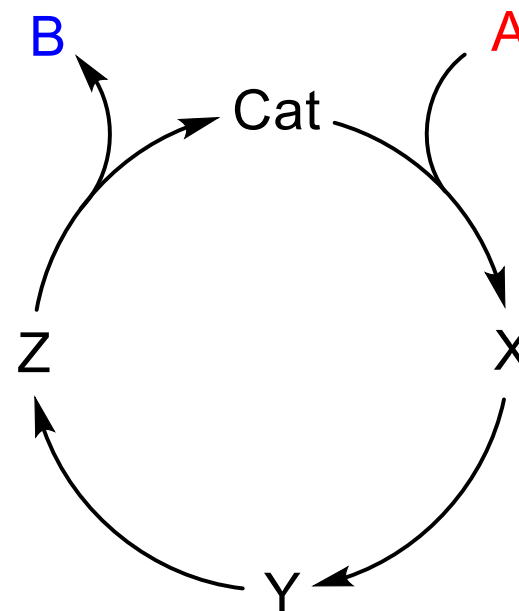
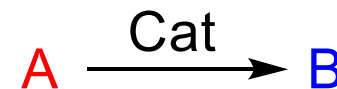
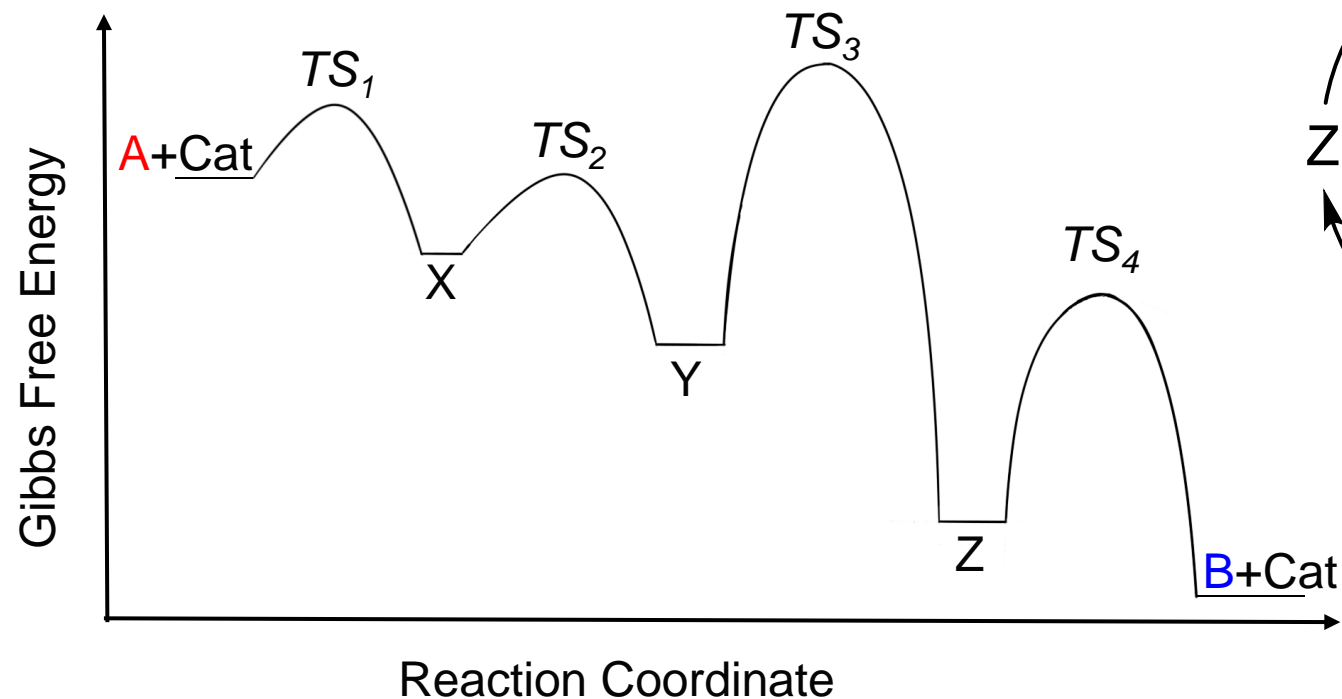
Clays, zeolites, nanoparticles, metal oxides, MOFs (metal organic frameworks), complexes affixed to surfaces (silica/alumina/polymers).

e.g. Haber-Bosch process

Catalysis: Introduction to catalytic cycles

Practically a catalytic cycle often made up of multiple steps with multiple intermediates.

Represented as energy span over all these intermediates, or as a catalytic cycle – you should be able to read both.

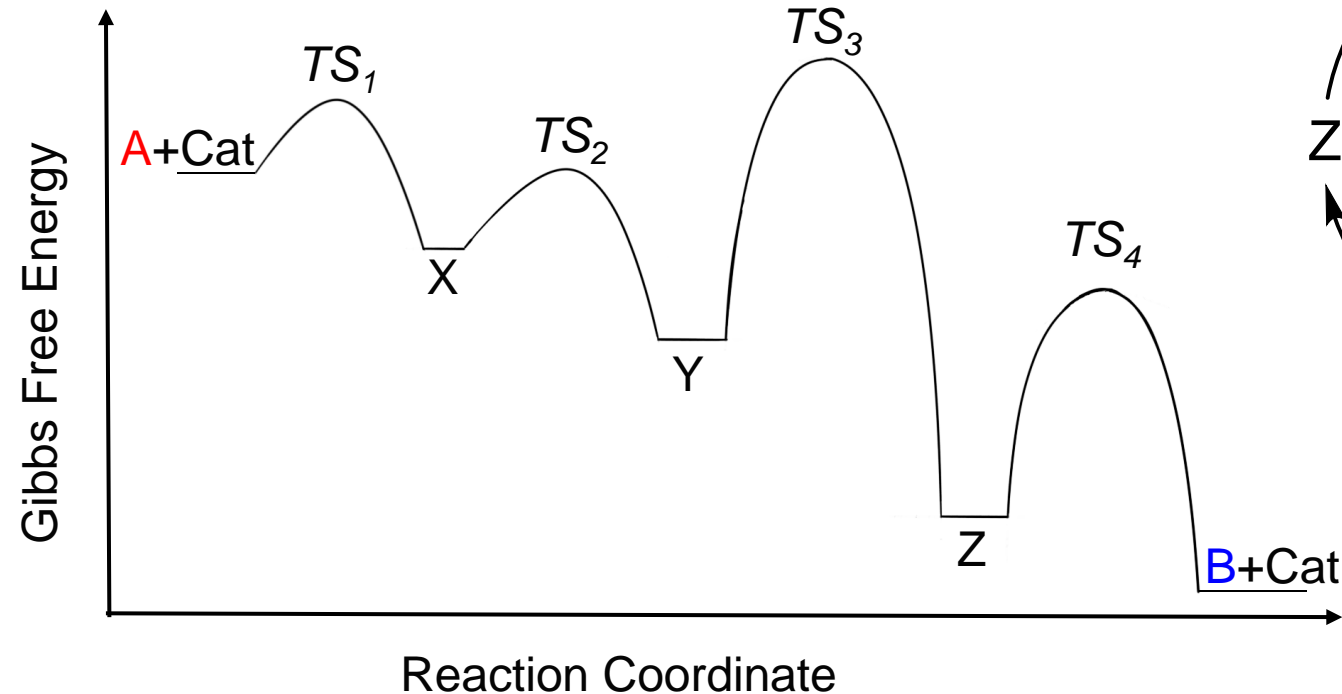
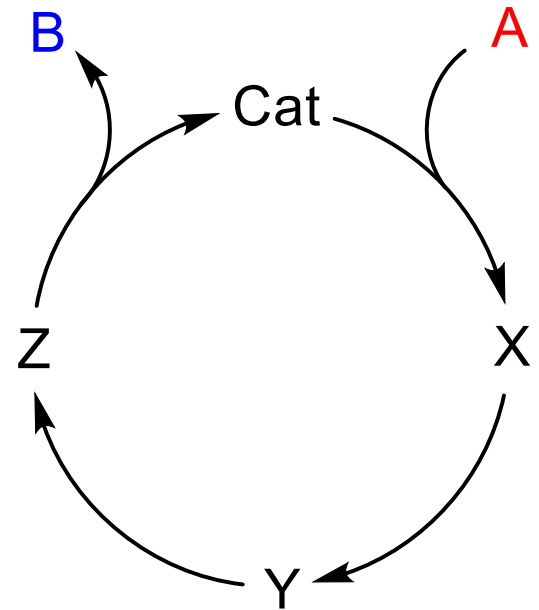
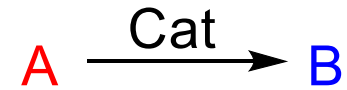


Catalysis: Introduction to catalytic cycles

At equilibrium **EVERY STEP** occurs at the same rate – ‘steady state’ approximation.

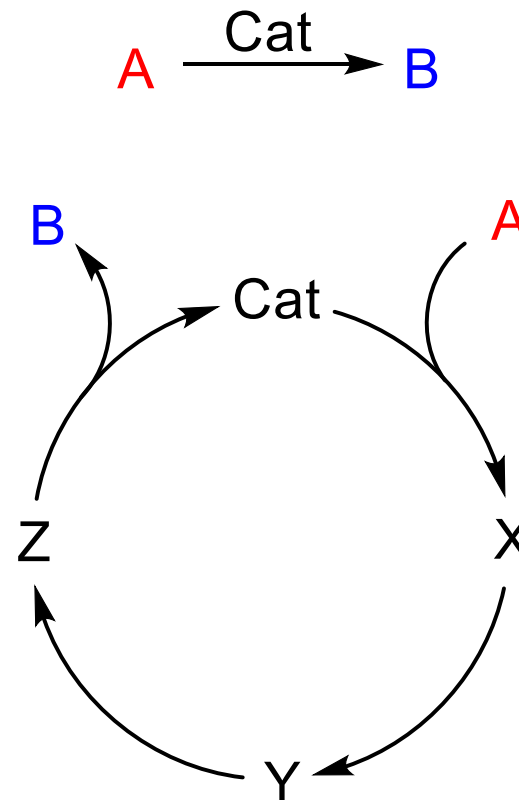
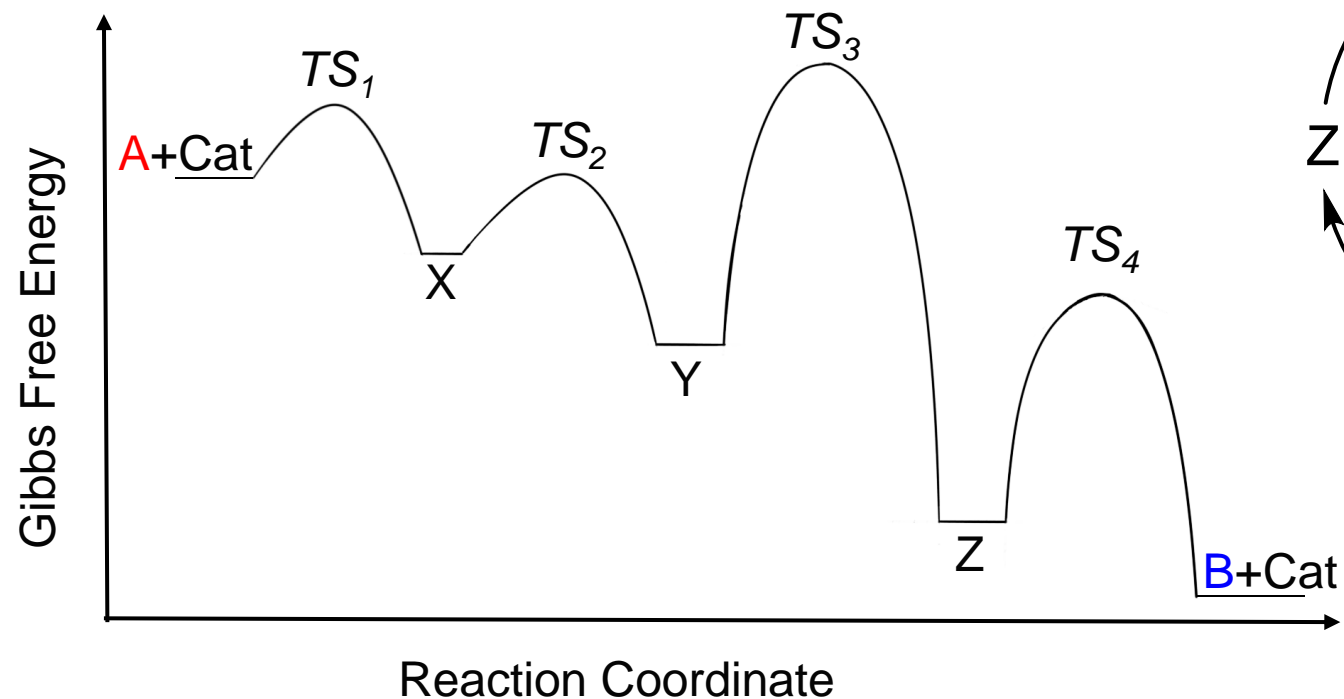
But each step has different $\Delta G^\ddagger \rightarrow$ different k
 $\rightarrow [X], [Y], [Z], [Cat]$ are **CONSTANT** but **DIFFERENT**.

i.e. $k_1[Cat][A] = k_2[X] = k_3[Y] = k_4[Z] = d[B]/dt$



Catalysis: Introduction to catalytic cycles

The **RATE LIMITING STEP** (also called **Rate Determining Step** or **Turnover Limiting Step**) is the step with the smallest k , or largest ΔG^\ddagger , measured from the *most stable prior intermediate*.



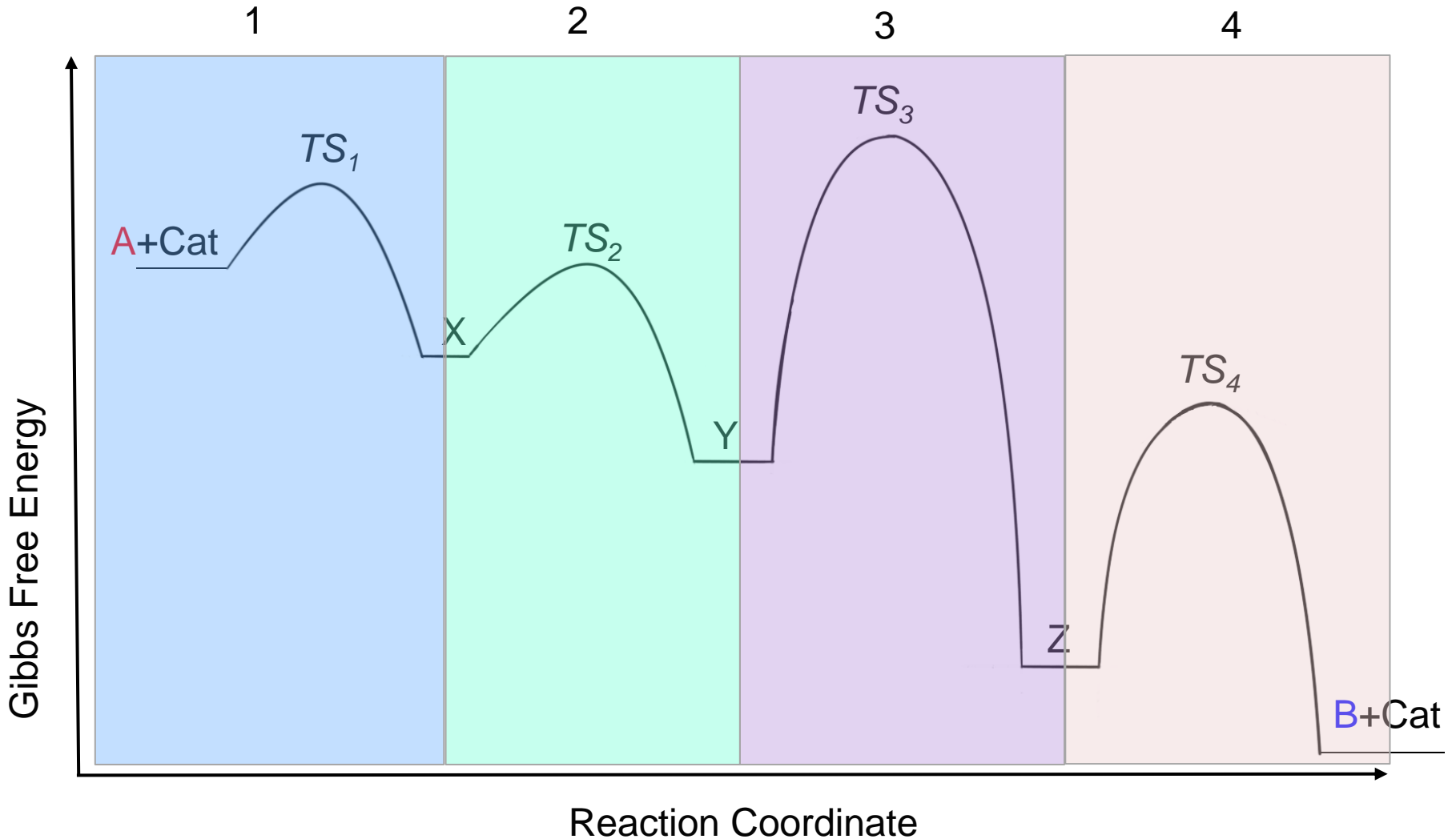
Identifying Rate Limiting Step in Energy Profile

Measurement of ΔG^\ddagger must come from most stable prior intermediate.

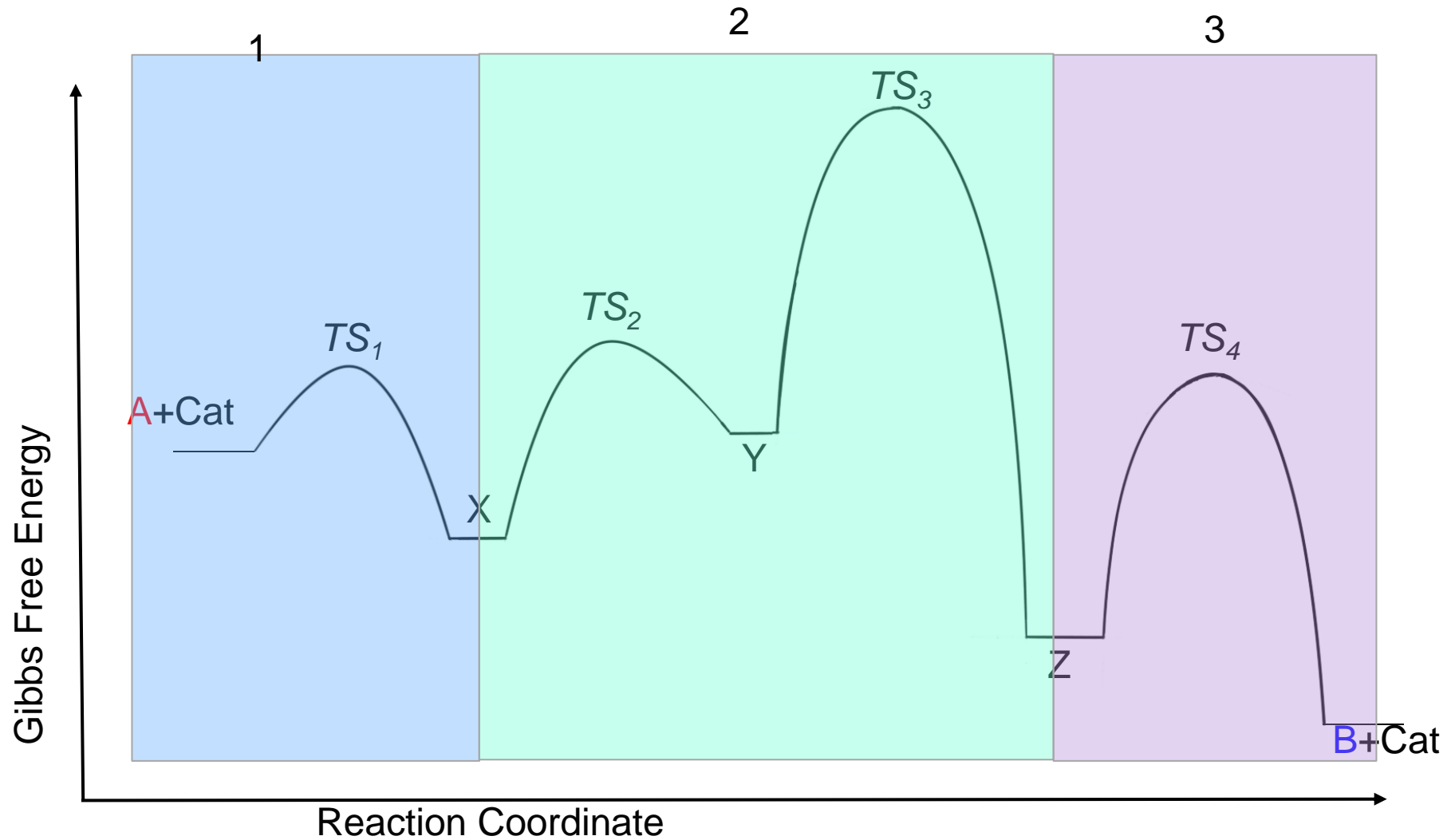
How do we do this?

- 1) Starting at substrate find the next intermediate that is more stable (i.e. below it). This is first section.
- 2) From this intermediate continue onwards until you find the next more stable intermediate. This is the next section.
- 3) Continue this process until you are at your products.
- 4) The section that has the biggest difference between its starting intermediate and highest transition state is the rate-determining step

Identifying Rate Limiting Step in Energy Profile



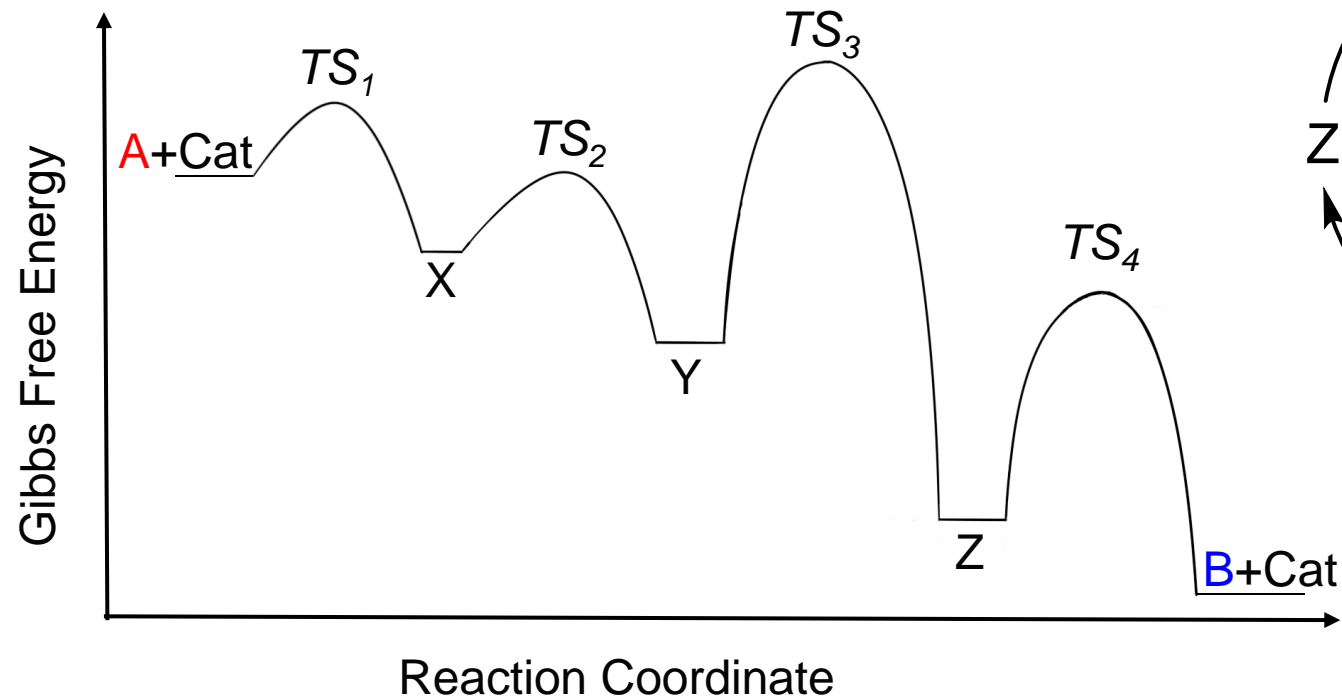
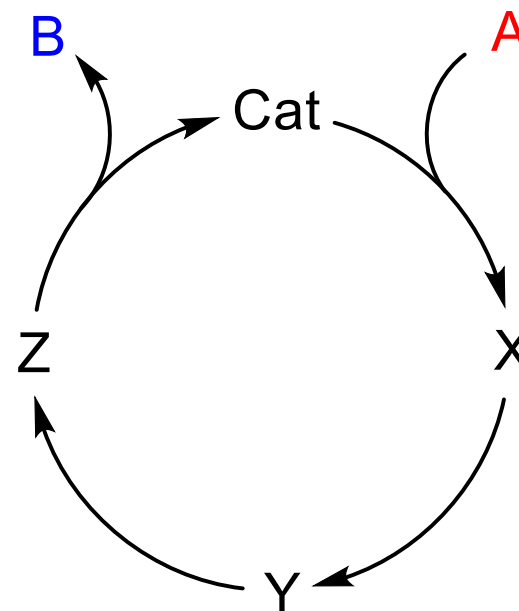
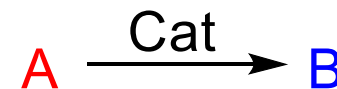
Identifying Rate Limiting Step in Energy Profile



Catalysis: Introduction to catalytic cycles

The **RESTING STATE** in catalysis is the intermediate that has the highest concentration.

It will be the intermediate at the beginning of the section that has the rate-determining step.



Identifying Rate Limiting Step Experimentally

However we not be able to experimentally observe intermediates. So how do we experimentally establish the rate determining step.

- 1) Using kinetic measurements to establish a rate law (but watch out for dangers...)
- 2) Computationally model the catalytic cycle
- 3) Kinetic Isotope Effect

Kinetic Isotope Effect

C-H and C-D bonds are not the same strength!

Zero-point bond energy is related to the reduced mass by:

$$\nu = \frac{1}{2\pi} \sqrt{\frac{k}{m_r}} \text{ where } m_r = \frac{m_1 m_2}{m_1 + m_2}$$

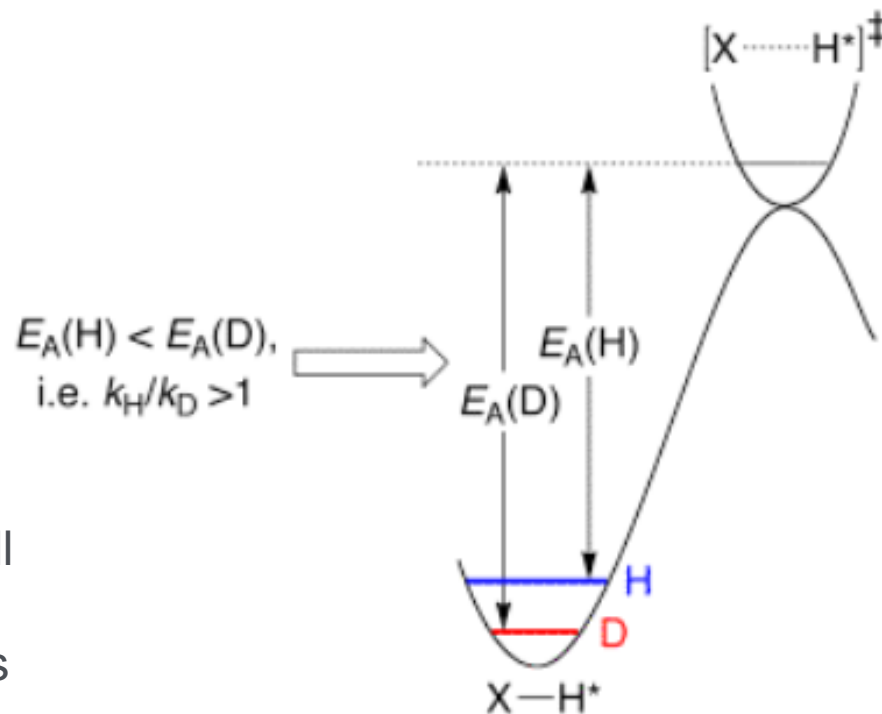
$$e_n = \left(n + \frac{1}{2} \right) h\nu \text{ where } n = 0$$

So the energy difference will cause a small difference in rate.

$K_H/K_D = 1 \rightarrow$ No difference, this bond is not changed in the RLS.

$K_H/K_D > 1 \rightarrow$ This bond breaks in the RLS.

$K_H/K_D < 1 \rightarrow$ This bond changes hybridization in the RLS.



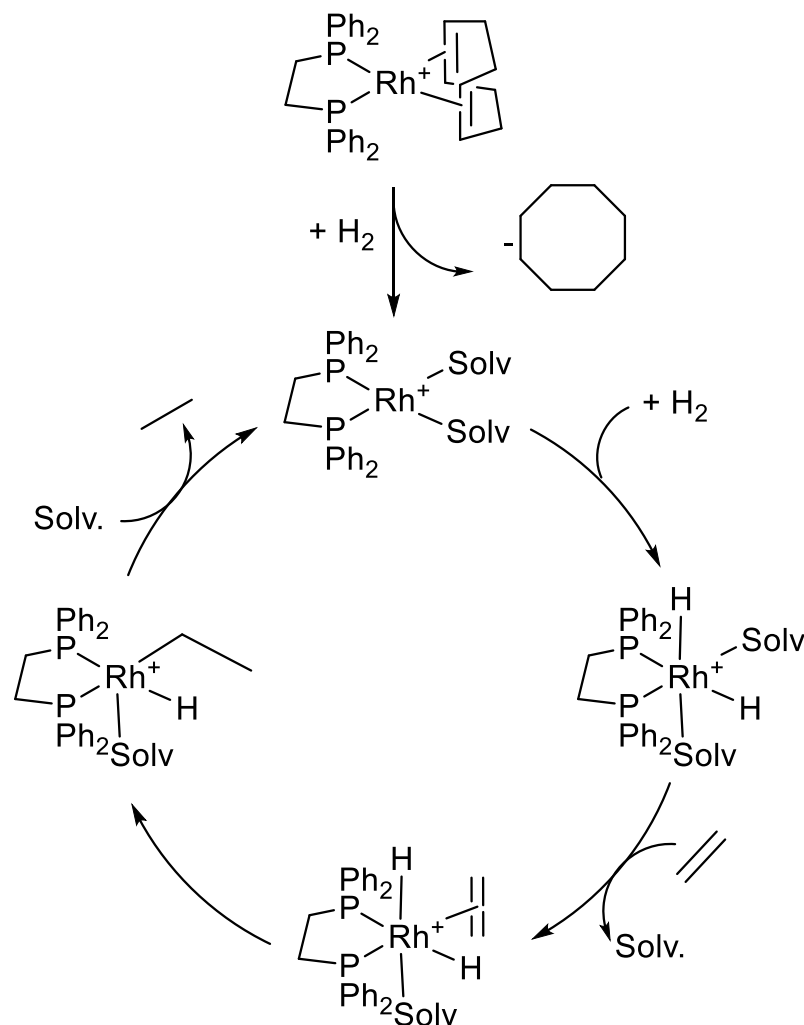
Catalysis: Activation Processes

Often the 'catalyst' we add to a mixture is not actually on the catalytic cycle, but a precursor.

In this case the catalyst may need **ACTIVATING**

Common Activation Routes:
 Hydrogenation of an olefin
 Photoejection of CO
 Loss of a labile ligand

If such an activating process is slow this may cause a lag in the rate at the beginning of the reaction – **Induction Period**



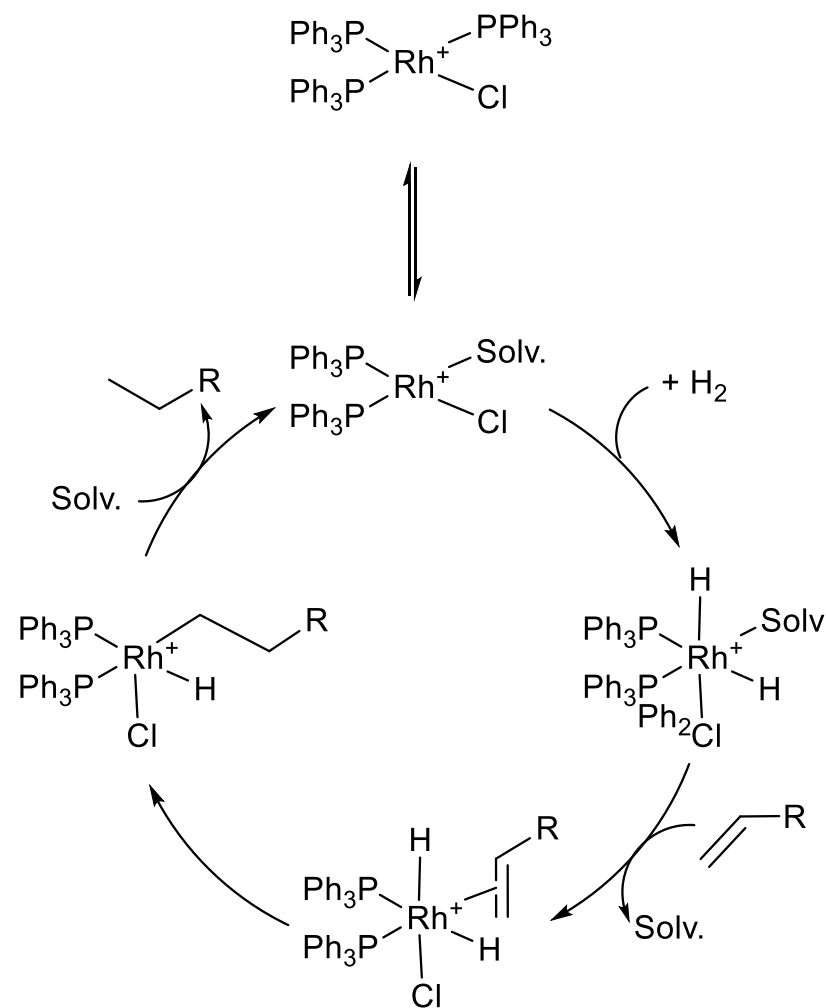
Catalysis: Activation Processes

Often the 'catalyst' we add to a mixture is not actually on the catalytic cycle, but a precursor.

Other activation process may set up a **PRE-EQUILIBRIUM** which will affect catalyst concentration.

The position of the equilibrium will affect rate of catalysis. Could give unexpected things in the rate equation!

For example additional PPh_3 hinders Wilkinson's catalyst.



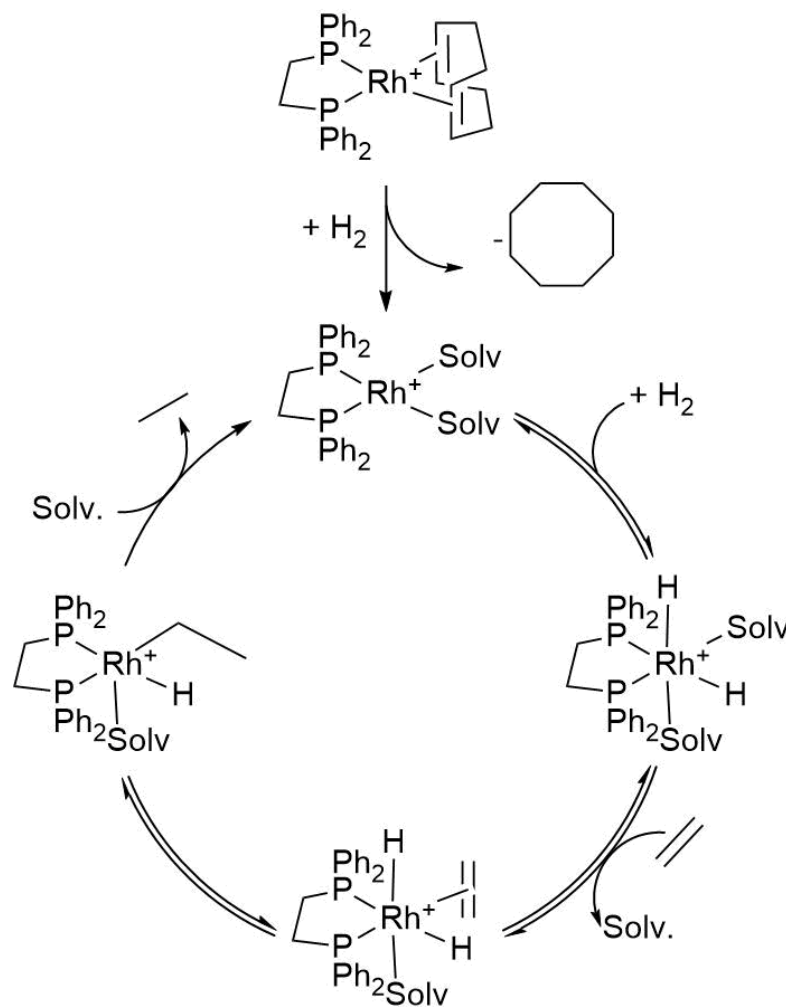
DANGER 1: Principle of Microscopic Reversibility

Often steps between intermediates are drawn irreversible – often not the case!

PRINCIPLE OF MICROSCOPIC REVERSIBILITY:

The mechanism of the reverse reaction is identical to the forward reaction, and the transition state is identical.

The catalyst will just make the system adopt equilibrium positions. Need an absolute thermodynamic driving force to push a cycle round (loss of gas, product more stable)



DANGER 2: Vacant Sites

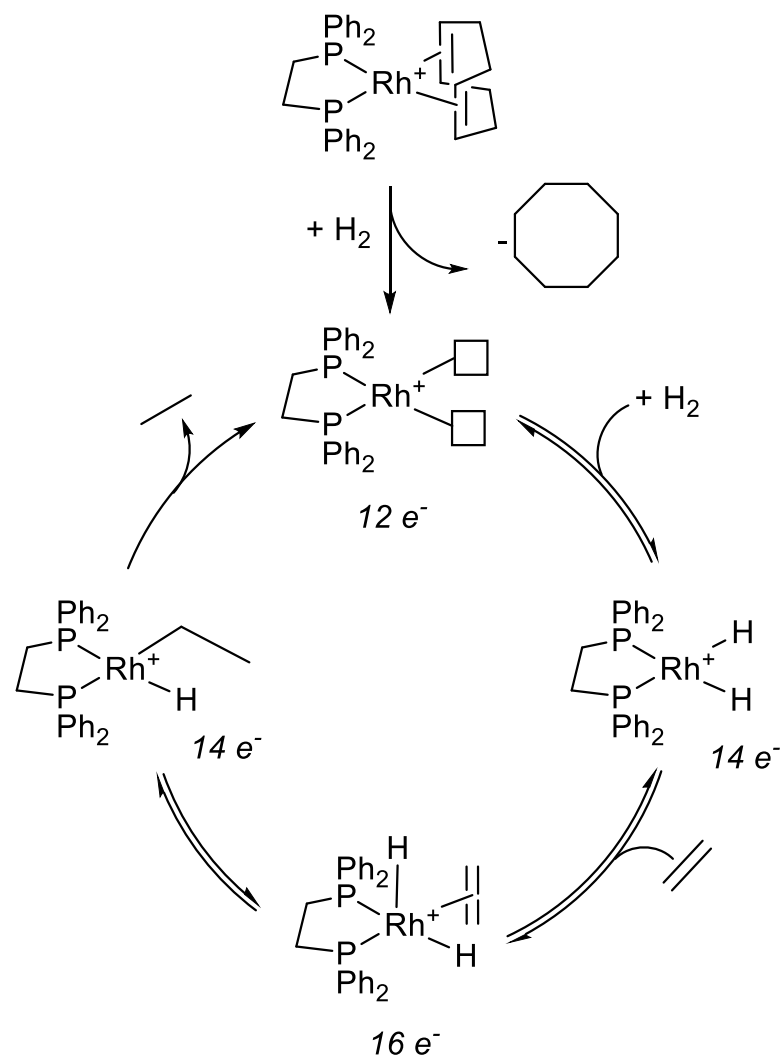
Catalytic cycles are sometimes drawn with vacant sites: □

Inaccurate representation:

Implies very electron deficient cycles

Implies solvent isn't a competing ligand!

Bad practice – don't do it.

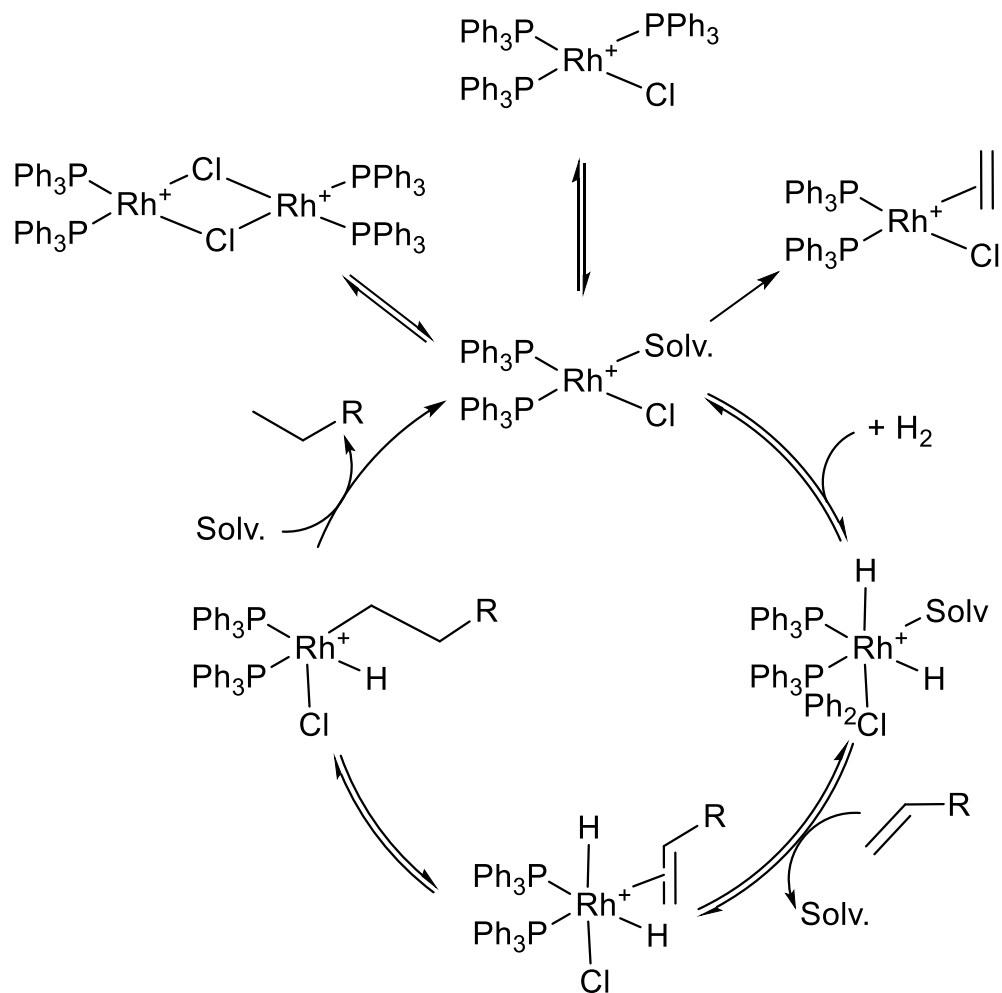


Catalysis: Off-cycle intermediates

Sometimes a catalyst can interact with something to form an inactive species.

If this interaction is reversible this species can be considered an **OFF-CYCLE INTERMEDIATE**

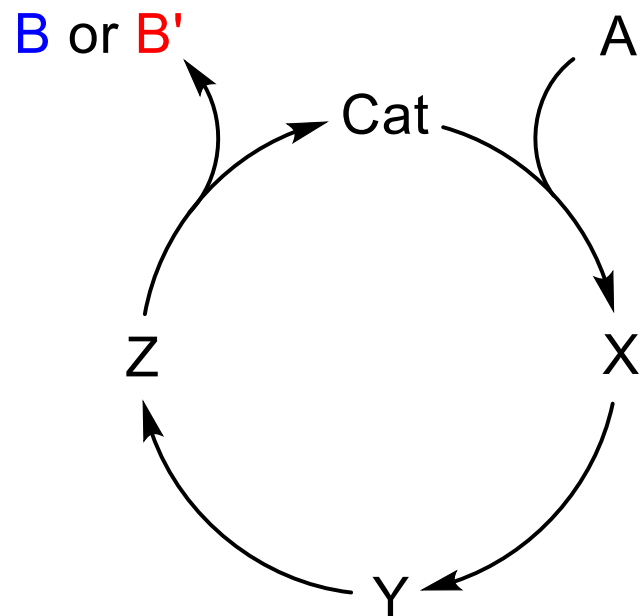
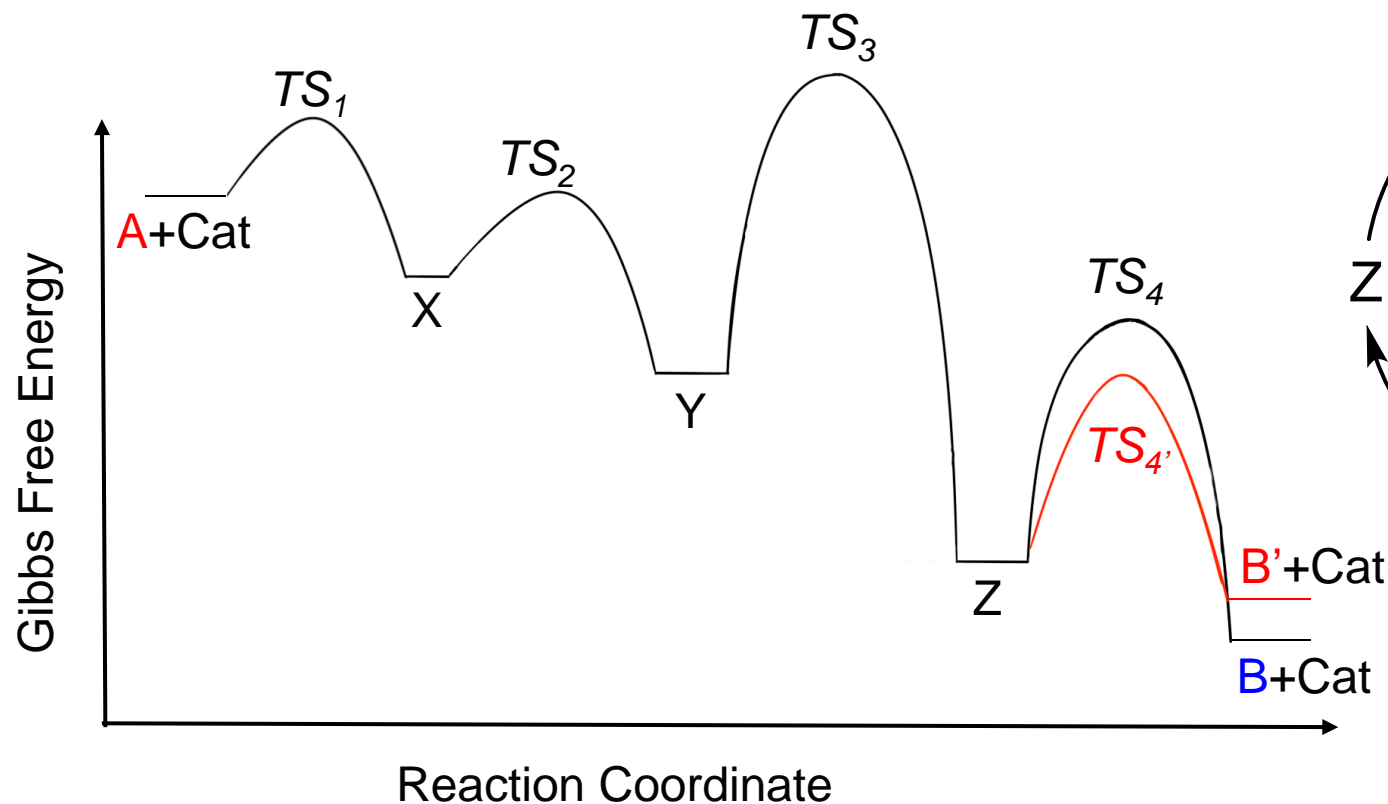
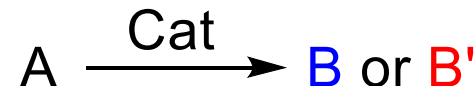
If this interaction is irreversible this removed our catalyst from the system and it is a **DEACTIVATION PATHWAY**



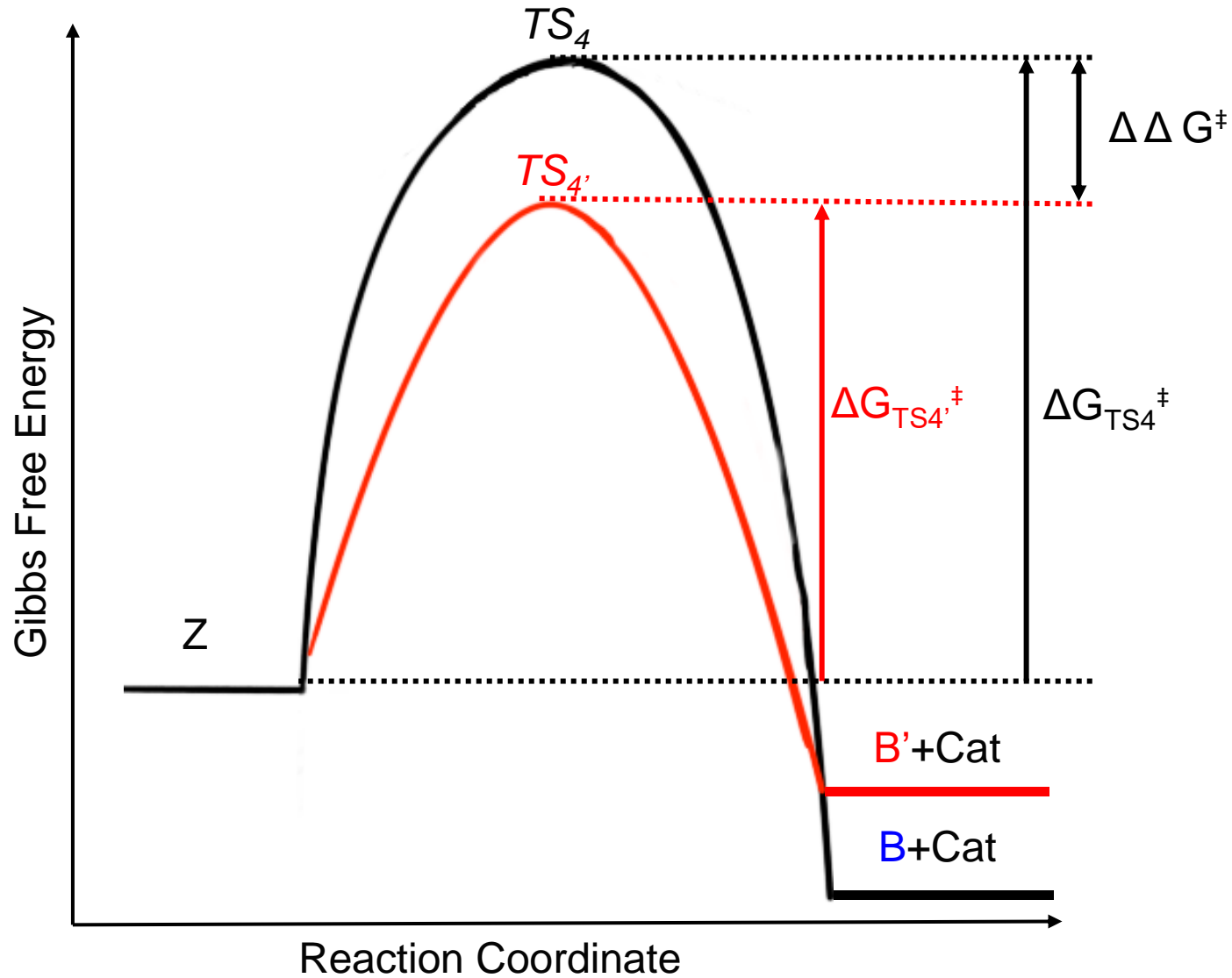
Catalysis: Selectivity Determining Step

Often our substrates will have regioselective and stereoselective options.

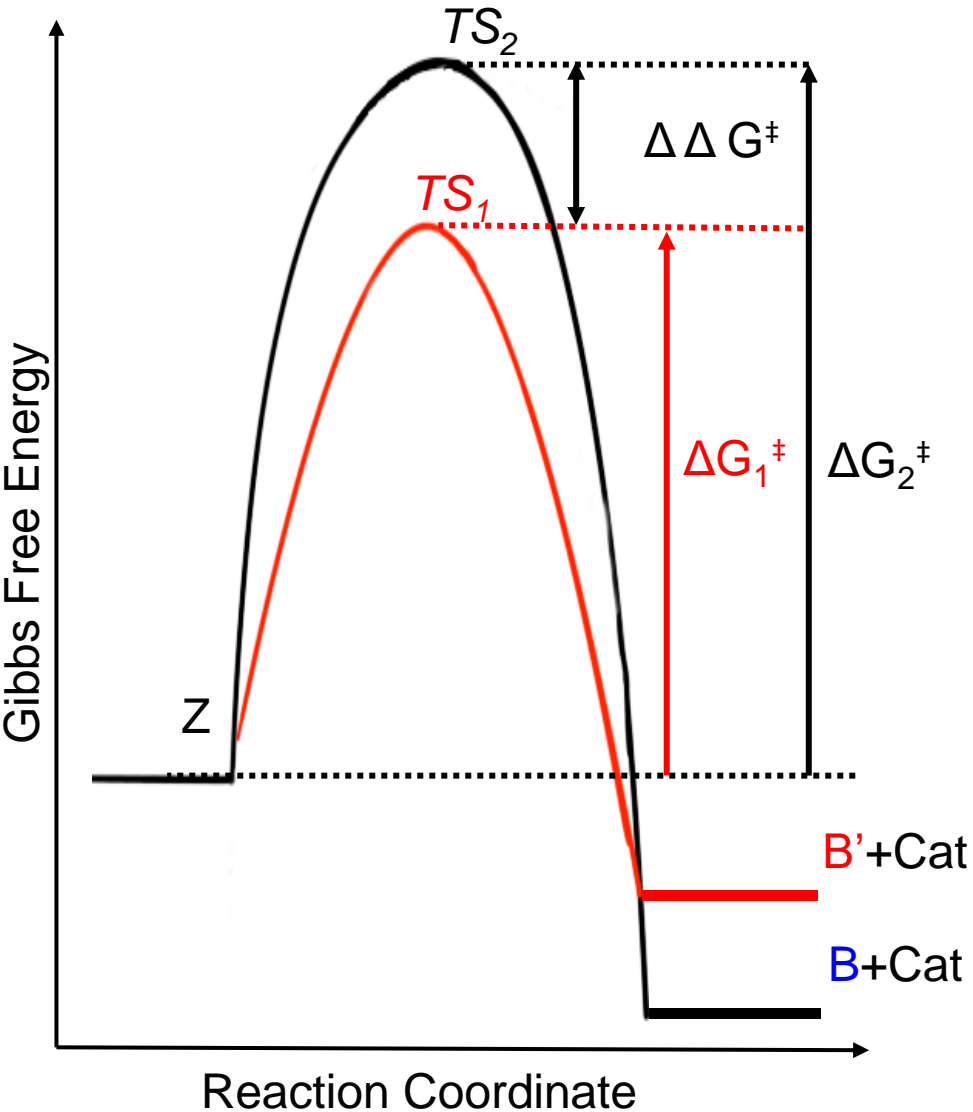
The selectivity will be determined by the ***SELECTIVITY DETERMINING STEP***. This is often different from the rate determining step.



Catalysis: Selectivity Determining Step



Catalysis: Selectivity Determining Step



Product ratio:

$$\left(\frac{d[B']}{dt}\right) / \left(\frac{d[B]}{dt}\right) = \frac{k_1[Z]}{k_2[Z]}$$

$$\frac{k_1}{k_2} = \frac{Ae^{-\frac{\Delta G_1}{RT}}}{Ae^{-\frac{\Delta G_2}{RT}}} = e^{-\frac{\Delta \Delta G^\ddagger}{RT}}$$

$$\Delta \Delta G^\ddagger = -RT \ln k^\ddagger$$

$$s = \frac{k_1[Z]}{k_1[Z] + k_2[Z]}$$

$$s = \frac{1}{1 + e^{-\frac{\Delta \Delta G^\ddagger}{RT}}}$$

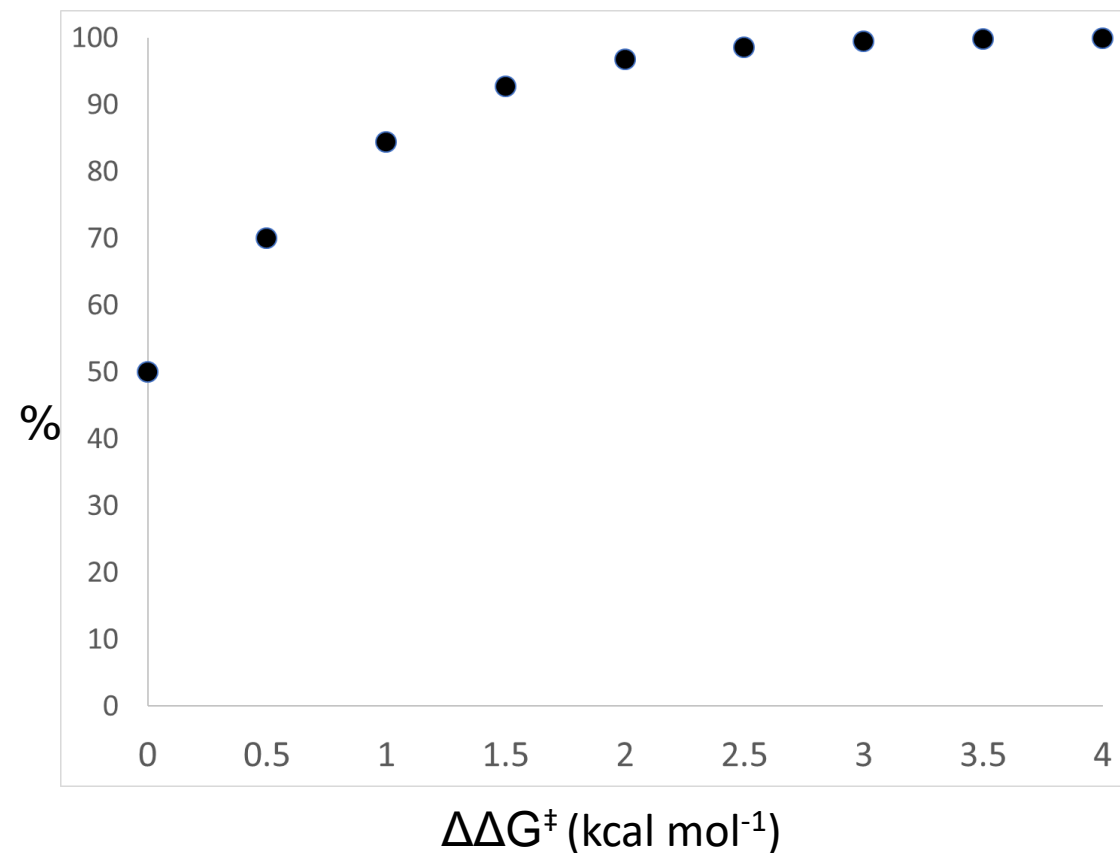
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$$\Delta\Delta G^\ddagger = -RT \ln k^\ddagger$$



$\Delta\Delta G^\ddagger$	K^\ddagger	Product		% yield
		B	B'	
0.0	1.0	1.0	1	50.0
0.5	2.3	2.3	1	69.9
1.0	5.4	5.4	1	84.4
1.5	12.6	12.6	1	92.6
2.0	29.3	29.3	1	96.7
2.5	68.2	68.2	1	98.6
3.0	158.6	158.6	1	99.4
3.5	369.0	369.0	1	99.7
4.0	858.6	858.6	1	99.9

Catalysis: Selectivity Determining Step

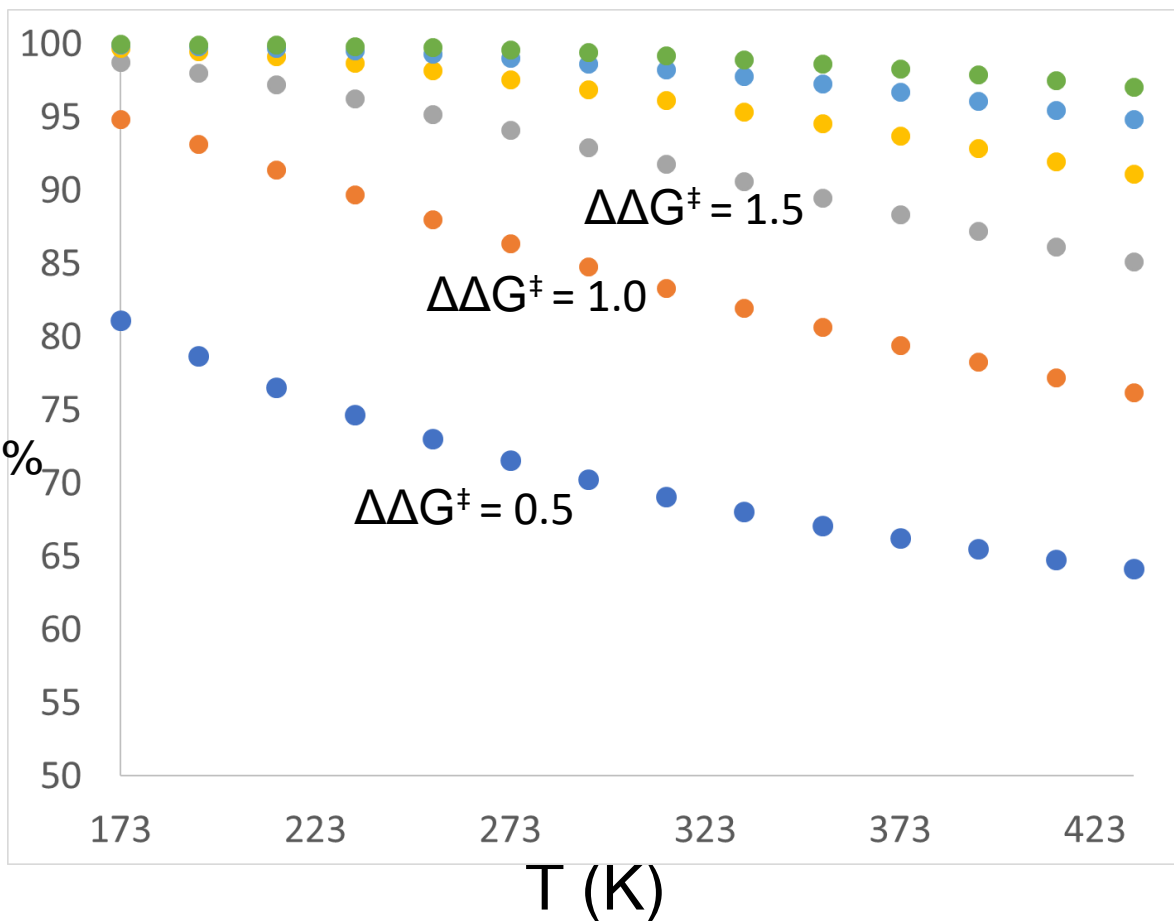
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$$\Delta\Delta G^\ddagger = -RT \ln k^\ddagger$$

T (K)	S (%)
173	94.8
193	93.2
213	91.4
233	89.7
253	88.0
273	86.4
293	84.8
313	83.3
333	81.9
353	80.6
373	79.4
393	78.3
413	77.2
433	76.2



Catalysis: Overall Catalyst Efficiency

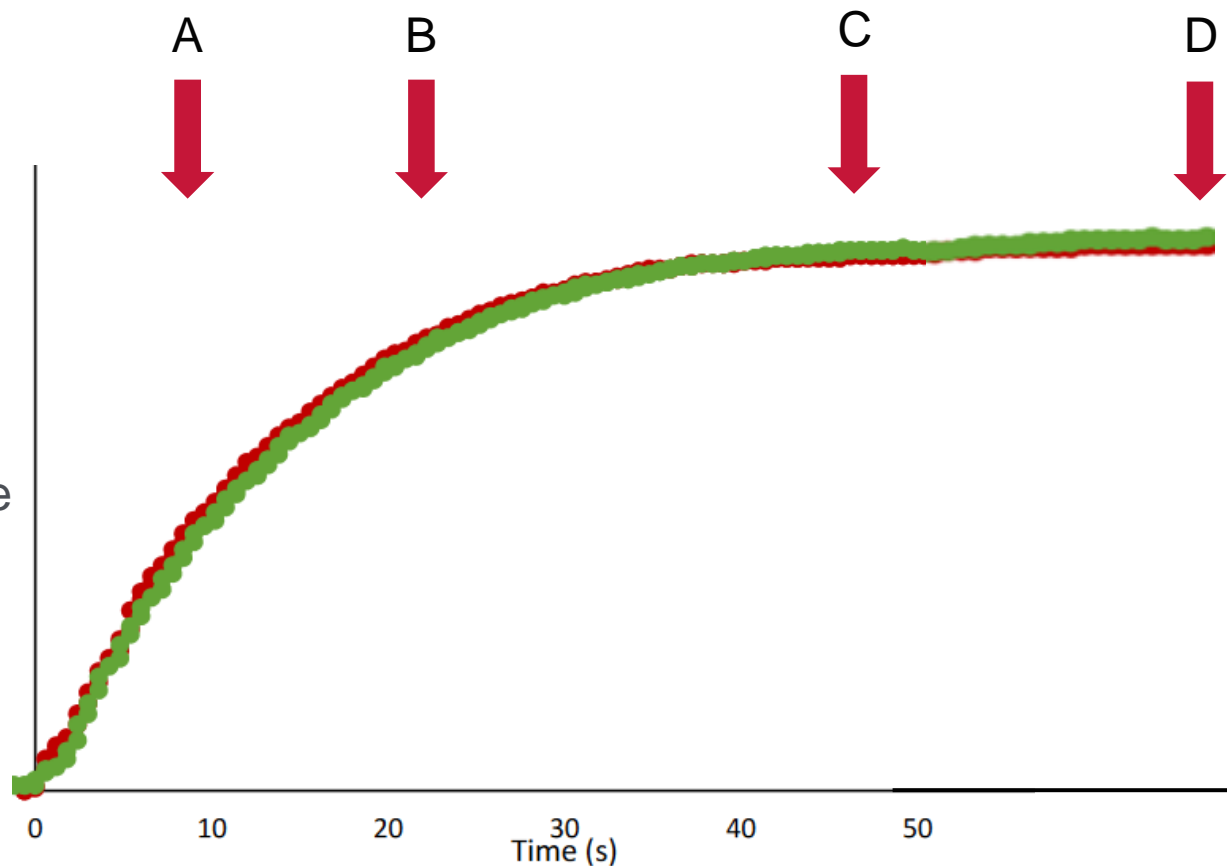
Catalyst efficiency can be measured in a number of ways. Each has limitation.

Most common:

Activity – amount of product, per catalyst, per hour.

TON – TurnOver Number. The number of times a catalyst goes round the cycle.

TOF – TurnOver frequency. The number of times a catalyst goes round the cycle divided by time catalyst has been on cycle.



Catalysis: Overall Catalyst Efficiency

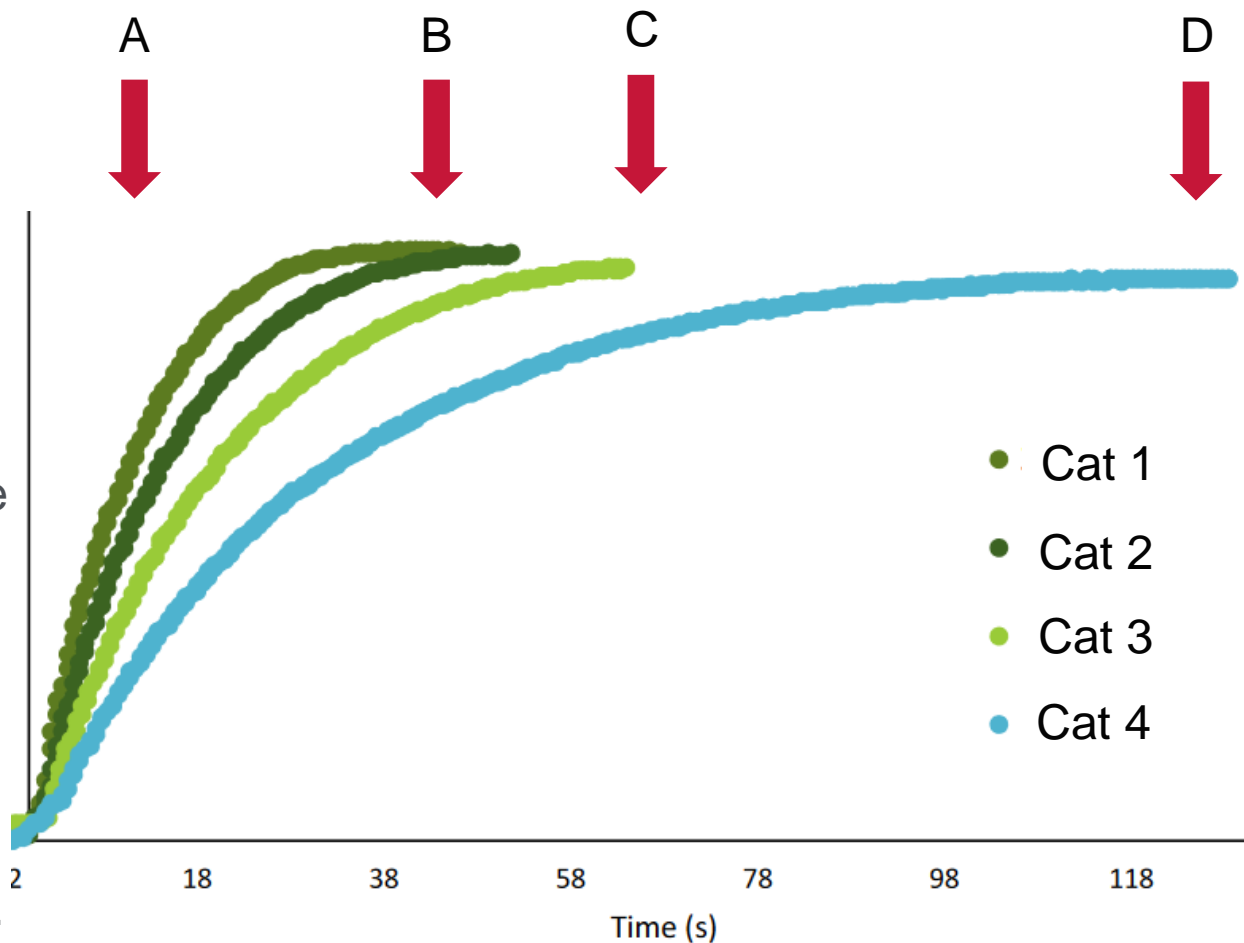
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Catalysis: Other considerations

Experimental Set-up: Batch vs. Flow.

Recyclability of the catalysts.

Toxicity of catalysts.

Colour of catalysts.

Stability of catalysts/pre-catalysts.

Availability of catalysts.