Chapter 3
Chemical Reactivity

CHEMICAL REACTIVITY

STABILITY OF ORGANIC COMPOUNDS AND COMPLEXES

The **HSAB** principle is extremely helpful in assessing the relative stability of organic species.
RCO^+ is a hard Lewis acid, its combination with hard bases forms thermodynamically stable molecules, e.g., acids **RCOOH**, esters **RCOOR´**, amides **$RCONR_2$´**

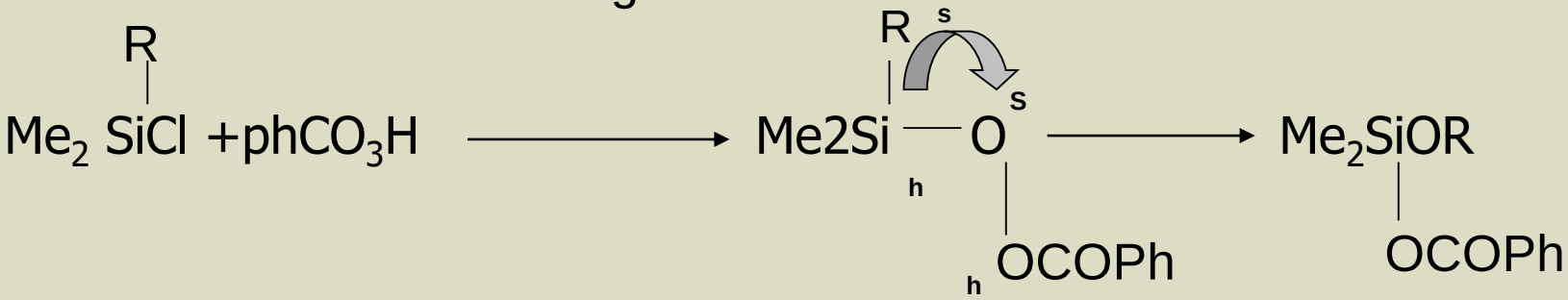
In contrast with soft bases such as thioester **RCOSR´**, selenoesters **RCOSeR´**, acyl iodide **RCOI** is highly reactive or labile species.

RO^+ act as an soft acceptor, therefore peroxycarboxylic acids are thermodynamically unstable and reactive molecules. A wider “softness gap” exist between **OH^+** and **$RCOO^-$** with electron attractive group.
Trifluoroperacetic acid is a more potent oxidant than peracetic acid and triazole-1-peroxycarboxylic acid is about two hundred times more reactive than perbenzoic acid toward olefins.

RCOOX acyloxyhalides = $RCOO^-$ (Hard) + X^+ (Soft)

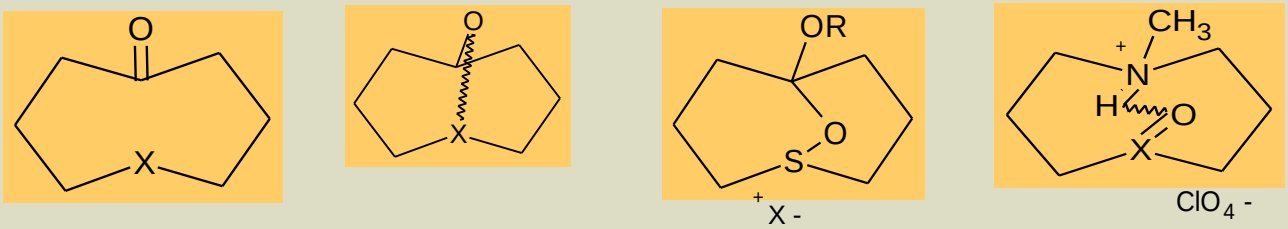
They are extremely labile and exist as transient intermediate in the Hunsdiecker and Simonini reactions.

$$RCOO^- Ag^+ + x_2 \xrightarrow[-AgX]{} RCOOX \longrightarrow RX + CO_2$$



(Cannot be isolated)

Strong transannular N….C=O interaction in following systems has been shown.



(1) X = N (Strong) (2) X = S (Weaker) (3) (Strong) (4) (Strong)

Hard-Hard Interaction

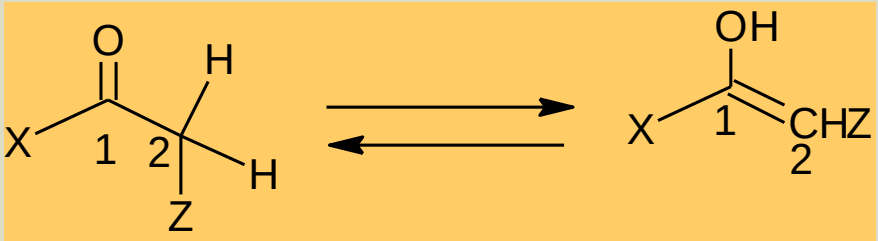
In 2- halocyclohexanones axial position is prefer for halogen as it becomes more polarizable.

The O:X_{eq} interaction would be more highly destabilizing if the hardness difference of the heteroatoms is more pronounced.

Lewis acid coordination with carbonyl compounds C=O lowers the stretching frequency in the infrared. More stable complexes are formed between C=O and hard Lewis acid.

	$FeCl_3$	$AlCl_3$	$TiCl_4$	BF_3	$ZnCl_2$	$CdCl_2$	$HgCl_2$
$\Delta\nu_{co}(cm^{-1})$	130	120	118	107	47	38	31

Enolization of carbonyl compound:

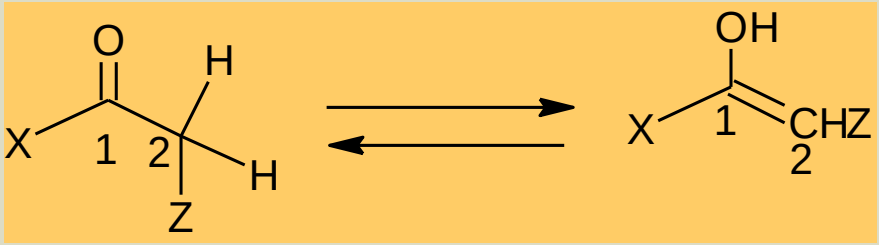


(5) (6)

When X = H, C-1 is softened and enolization is favored. The C-1 of the enol form (6) is probably softer since it is doubly bonded to another carbon instead of to oxygen as in the ketone form.

Aldol condensation is proceeds much more readily with aldehydes than with ketone.

When X= Cl, OH, OR and other electronegative groups, C-1 became harder and enolization is thereby discouraged.



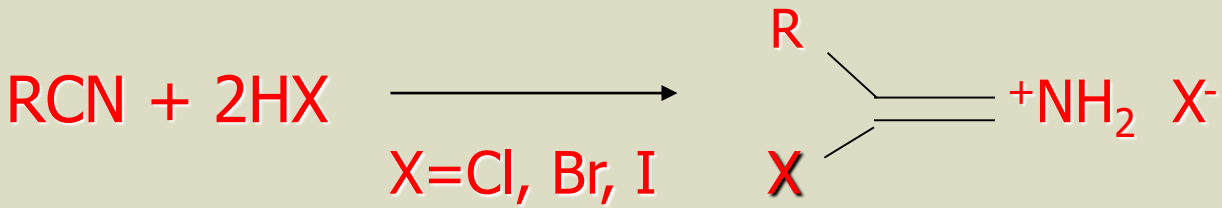
(5) (6)

α- Substitutent (z) effect:

Electronegative groups such as halogen or carbonyl prefer direct bonding to a harder center which is available in the enol form. The enol content of several 2-substituted ethyl acetoacetate increased with the hardness of the substituent, except for those capable of π-π conjugation.

% Enol: H (8), Me (5), Et (~1), Ph (15), Br (5), CF_3 (89), CN (93)

The thermodynamic stability of these imidyl halide salt adducts increases with acidity of HX. The nitrile hydrogen fluoride adducts are particularly stable because interaction of hard bases with the hard nitrile carbon.



Thermal reorganization of isonitriles to nitriles can be expected on the basis of the HSAB concept, although isomerization of some compouds proceed via a free radical mechanism. Equilibrium of thiocyanates yields a partition ratio of $k_S/K_N \approx 5$, indicating that the thiocyanate is more stable than the isothiocyanate. The soft sulfur atom prefers bonding singly rather than doubly to the carbon.

Thiocyanates form more stable complexes with phenol (through hydrogen bonding) than with iodine (by charge transfer), whereas exactly opposite results are observed with isothiocyanates.

The strength of the interaction between phenol and dialkyl chalcogenides (R_2X) falls off as X=O» S > Se

A **chalcogenide** is a chemical compound consisting of at least one chalcogen anion and at least one more electropositive element.

Phenol with alkyl halides as: RF > RCl > RBr >RI

The stability of silver complexes (AgL, $AgHL^+$, AgL_2^-) with $ArXCHCOO^-$ is a function of X = Se > S > O

The complex formation of BF_3 are $Me_2O > Me_2S > Me_2Se$

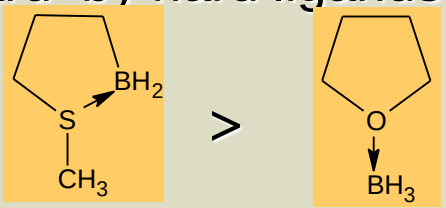
With BH_3 and BMe_3 an almost reverse trend is observed

$Me_2S > Me_2Se \sim Me_2O$

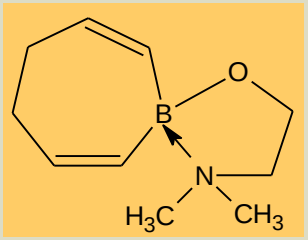
For X= S or Se: $Me_2X.\ BH_3 > Me_2X.\ BF_3$

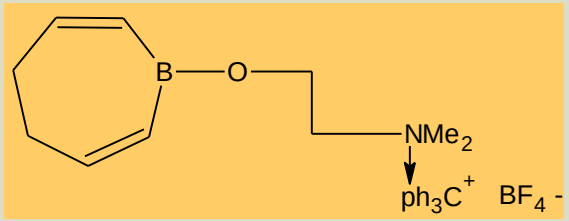
BX_3 coordinates better with amines than with ethers and sulfides.

Boron is a borderline accepter which becomes hard by hard ligands and becomes soft with soft ligands (such as H^-)



The Boron atom in dihydroborepine is internally coordinated by the amino borate, this chelation is removed by addition of trityl fluoroborate. This may indicate that the boron atom in the borinic esters is harder, but not as hard as the trityl cation.





$$Me_3NBH_3 + Me_3P \xrightleftharpoons{20:80} Me_3PBH_3 + Me_3N$$

$$Me_2PNMe_2 + Me_2PH \xrightleftharpoons{11:89} Me_2PPMe_2 + Me_2NH$$

Following example illustrate competition between nitrogen and phosphorus atoms for alkylation.

$$R_2NPR'_2 + R''X \longrightarrow R_2NP^+R'_2\,R''\;X^-$$

Silanes containing harder halogens prefer complexation with harder bases.

Stability is:

$X_4Si\text{-}NMe_3 > X_4Si\text{-}PH_3$

Alkyl hypohalites are very reactive molecules and liberate positive halogens with toward nucleophiles.

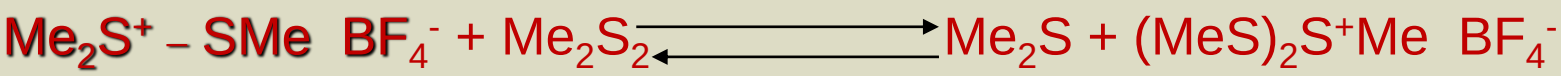
Hard-Soft interactions

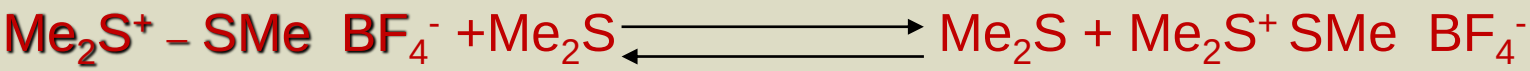
ROI > ROBr > ROCl

Triorganosilyl hypohalites are even more reactive and unstable. Oxygen in these compounds is further hardened by the neighboring silicon.

Sulfenate esters RSOR' have soft–hard make-up and more reactive and less stable than disulfides RSSR'.

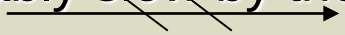
Following equilibriums involve soft–soft acid–base interactions.





soft-soft acid-base interactions

Mixed soft-hard interactions are so unfavorable in the equilibria portrayed below that either they are biased completely to one side or they are immeasurably slow by the nmr time scale.



$$Me_2S^+SMe + Me_2O \rightleftharpoons Me_2S + Me_2O^+SMe$$

slow

$$(CH_3)_2S^+OCH_3 + Me_2S \rightleftharpoons (CH_3)_2S + CH_3O^+SMe_2$$

Compounds $R_3M{=}X$ (M = P, As; X = S, Se) are excellent ligands for soft metal ions, but not for hard acceptors. This behavior is at variance with compounds $R_3M{=}O$ (M = P, As) which display metal ion affinity in the opposite sense.

The lanthanide cations are hard Lewis acids and form complex with functional groups that basis of lanthanide–induced shifts in nuclear magnetic resonance of organic molecules. Larger shifts of the nearby hydrogen atoms are associated with tighter coordination of the functional group with the metal ion.

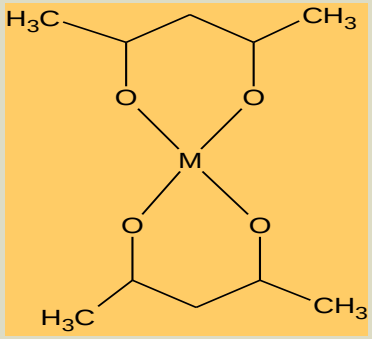
Larger shifts in carbon -13 nmr of carbonyl are induced by titanium tetrachloride compared to those observed in the presence of EU-$(fod)_3$[tris(6,6,6,7,7,8,8,8,-heptafluoro-2,2- dimethyl – 3,5 – octanedionato) erupium]. Ti(IV) is harder than Eu(III).

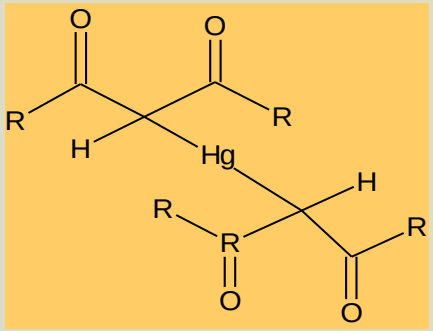
Organometallic species can be considered as M^+R^- acid–base pairs. R^- is a soft base, if $M^{\oplus}$ is soft, organometllic is stable.

stability are: RMgX >> RLi > RNa and RK

Organomercury, thallium and lead derivatives are especially stable.

Most metal ions form 2,4-pentanedione chelates having the following general formula.



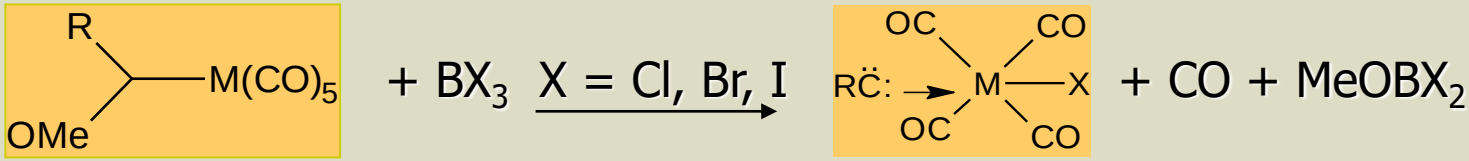


Mercuric ion is σ bonded to the central carbon of the β–diketones. Hg(II) is soft.

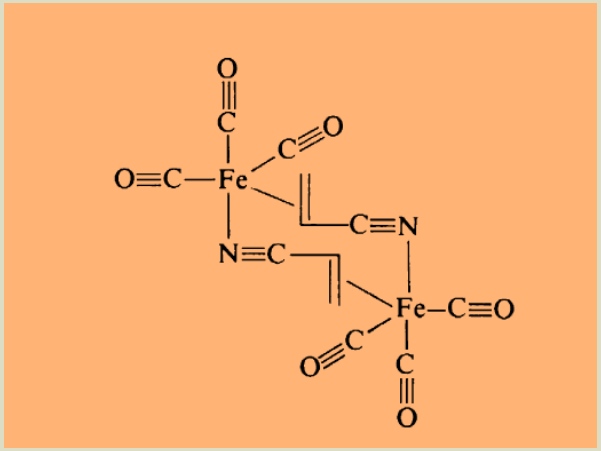
Primary carbocation $MeHgCH_2CH_2^+$ and $Me_3SnCH_2CH_2^+$ are kinetically more than trityl cations. These species can be considered as three-centered bound ethylene metal ions in which a considerable amount of the positive charge is carried by the metal that interact so strongly with the moderately soft carbenium center.

Many organometallic compounds owe their stability to soft–soft interactions. **valent heavy metals are soft** acceptors and usually to soft ligands such as **isonitrile, carbon monoxide, sulfide and phosphine.**

Methoxycarbene pentacarbonyl complexes of Cr, Mo, and W reacted with trihalides, loss of the methoxy group and a carbon monoxide ligand results. The metal becomes coordinate to a halogen and a carbyne.

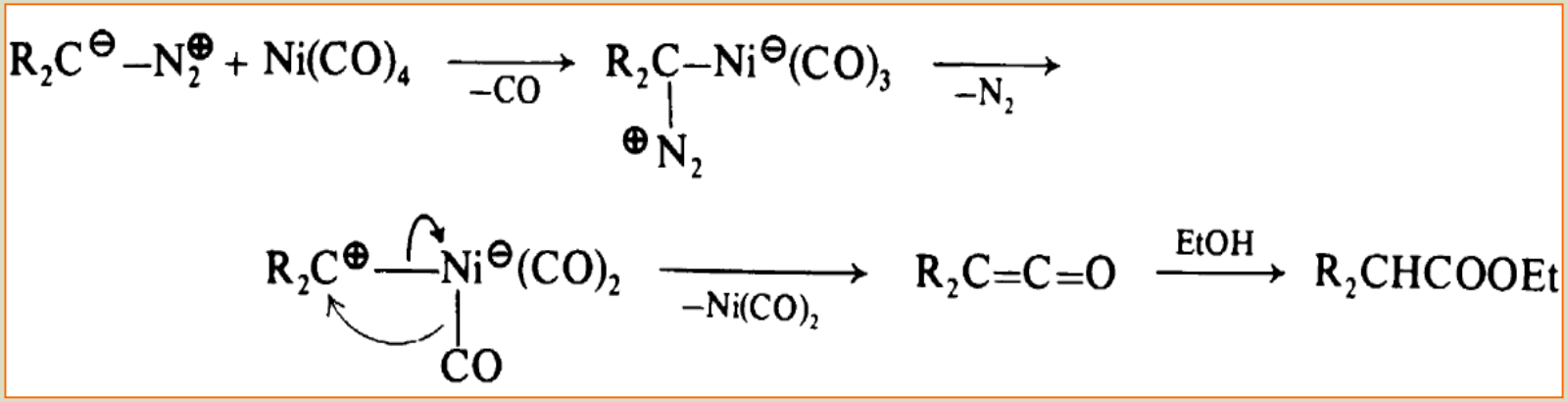


An unusual complex, di-μ-acrylonitrilebis(tricarbonyliron), contains *π* and *n* donors. The nitrogen occupies an axial position which is preferred by harder ligands. However, the most striking feature is the nonlinear CN —► Fe bond. It is possible that because of this orientation the nitrogen donor becomes softer.



Diazo compounds lose nitrogen readily on contact with heavy metals (Ag, Cu, Pd) and their salts. These metallic species provide vacant orbitals to accept an electron–pair from the diazo carbon atom and simultaneous back–donation aids in the expulsion of nitrogen.

In other words, the soft–soft interactions throughout the biphilic process account for the effectiveness of the catalysts.
Treatment of diazo compounds with an excess of nickel carbonyl in ethanol leads to the formation of carboxylic esters.



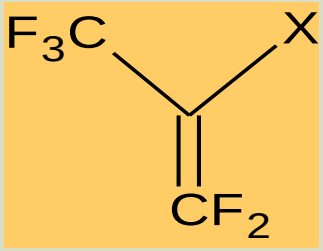
It is likely that the reduction of organic azides with vanadium(II) chloride involves the formation of vanadium coordinated nitrene intermediate. Also treatment of Ru(III) azide complexes with acid produce nitrene coordinate–Ru(III).

Phosphorus and sulfur ylides are more stable than the nitrogen and oxygen analogous. The former species are comprised of carbenes complexed to soft donors, whereas in the latter the carbenes are not stabilized by the adjoining hard bases.

CH_2I^- is more stable than CH_2F -. If regarded as $X^{\ominus} \longrightarrow {}^{\cdot}CH_2$ complex, the hard $F^{\ominus}$ is not expected to interact strongly with the soft carbenic center.

Likewise, the enhanced reactivity of $FC(NO_2)_2^-$ may be considered as a consequence of the destabilization of the hypothetical dinitrocarbene by the hard halide ion.

Iodide ion-initiated decomposition of the mercurials proceeds faster with X = CF_3 than with X = F. The fluorobis (trifluoromethyl)methide ion intermediate is less stable than tris (trifluoromethyl) methide.

$$[(CF_3)_2CX]_2Hg + 2I^- \longrightarrow$$  $$+ 2F^- + HgI_2$$

Stability of Cl_2C: with several ions are as: $I^{\ominus} \sim Br^{\ominus} > Cl^{\ominus} > F^{\ominus} > NO_3^{\ominus}$,$ClO_4^{\ominus}$

However, $F^{\ominus}$ is more reactive than $Cl^{\ominus}$ towards F_2C:.

Si-H bond is thermodynamically unstable, because Si^+ is hard acid and H^- is soft base. The thermal isomerization of these substances are known when the carbon analogs remain unperturbed.

$$ArCH_2SiHMe_2 \xrightarrow{\Delta} ArSiMe_3$$

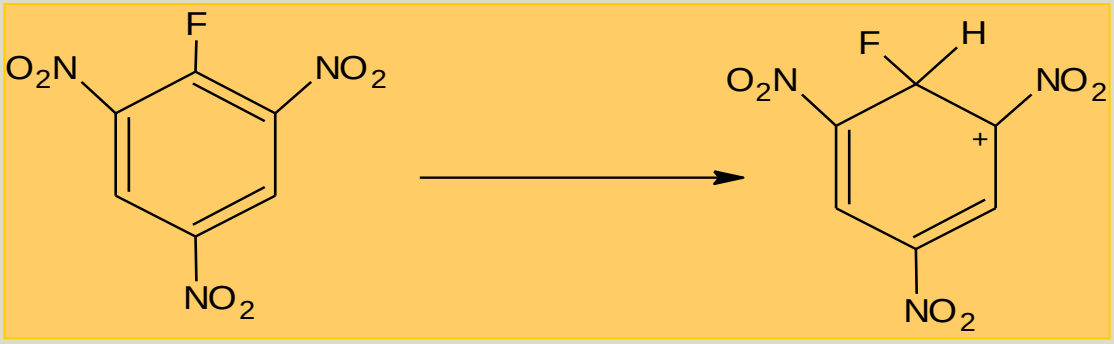
SYMBIOSIS

The term of " symbiosis" is applied to describe the phenomenon of **maximum** flocking of either hard or soft ligand in the same complexes.

Jørgensen noted that **metal ion** prefer **bonding to ligands** of **the same kind** whether they are hard or soft. Hard – soft mixed ligature results in unstable species.

Higher affinity of $:CF_2$ for $F^{\ominus}$ than $Cl^{\ominus}$ is based on symbiosis.

gem–Difluoro Meisenheimer complex from picryl fluoride has been detected by nmr, whereas evidence for the formation of the corresponding *gem* – H, F complex is ambiguous.



C-F bond along as: CH_3F(1.39 A), CH_2F_2(1.36 A), CHF_3(1.33 A), CF_4(1.32 A).

The shorter and stronger C-F bond is a consequence also predicted by symbiosis.

BF_3 readily accepts another $F^{\ominus}$ to form $BF_4^{\ominus}$ and BH_3 gains a hydride ion to give $BH_4^{\ominus}$ which are assisted by symbiosis.

Disproportionation of difluoromethane and formaldehyde and the halogen exchange between iodotrifluoromethane and fluoromethane are assisted by symbiosis.

$$2CH_2F_2 \longrightarrow CH_4 + CF_4$$

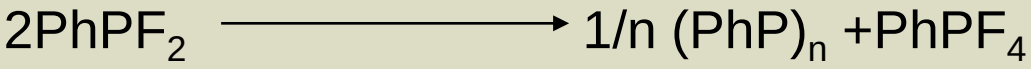
$$2CH_2O \longrightarrow CH_4 + CO_2$$

$$CF_3I + CH_3F \longrightarrow CF_4 + CH_3I$$

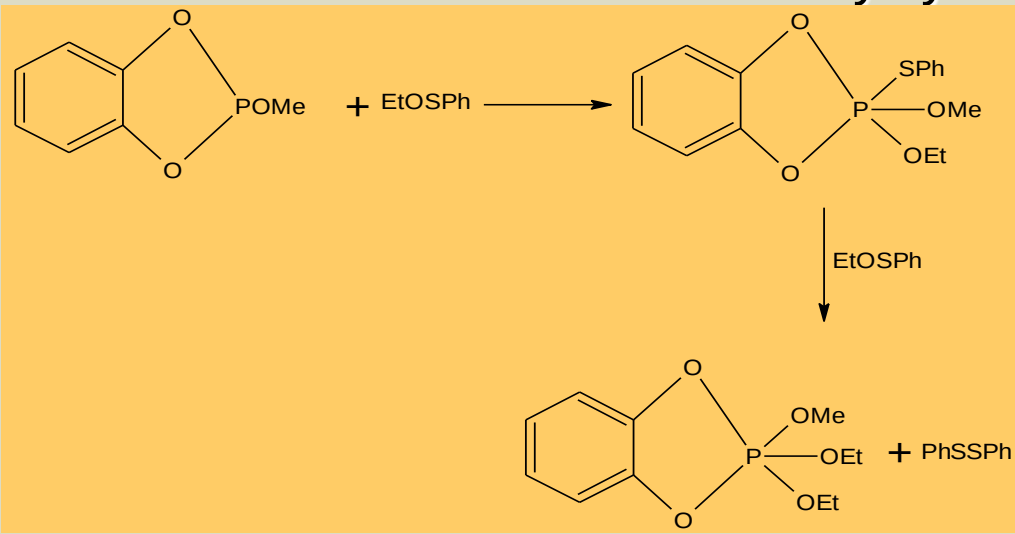
For hydrocarbon molecules, symbiosis implies that those containing a maximum number of either C-H bonds (CH_4) or C-C bonds (e.g., CMe_4) are the most stable.

This simple rule offers an explanation for extra stability of highly branched hydrocarbons.

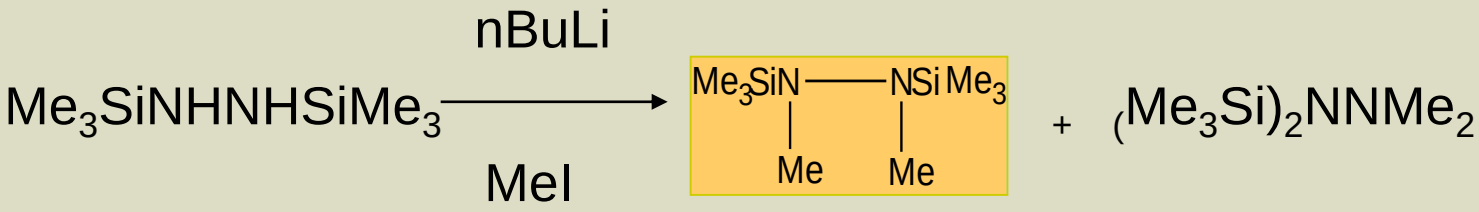
Spontaneous disproportionation of phenyldifluorophosphine occurs at room temperature.



Decomposition of methyl o-phenylenephosphite-O-ethyl phenylsulfenate adduct *in situ* must be dictated by symbiosis.



The methylation of N,N‘–bis(trimethylsilyl) hydrazine occurs with partial rearrangement, which may be interpreted by the symbiotic effect.



Hemiacetals are less stable than acetals and, in fact, they have the tendency to disproportionate to give the parent carbonyl compounds and the acetals. Hemithioacetals are even less stable than hemiacetals and dithioacetals.

The idea of symbiosis has been extended to S_N2 reactions by pearson and songstad. Analysis of rate data from the following reactions in methanol yielded a pattern consistent with symbiotic stabilization of the five-coordinated transition state.

Later, it was demonstrated that the symbiotic effect is even larger in aprotic solvents such as acetonitrile.

Gas phase S_N2 reactions and transition state in aromatic substitution also display this effect.

$$Nu^{\ominus} + MeOTs \longrightarrow NuMe + TsO^{\ominus}$$
$$Nu^{\ominus} + MeI \longrightarrow NuMe + I^{\ominus}$$

Symbiosis effect is not always the dominating, halogen exchange between CI_3F and CF_3I in gaseous phase is 50 kcal endothermic due to large steric strain of tetraiodomethane which has a very positive heat of formation.

A note of caution has been issued by Ahrland who states that the coordination of very soft ligands to a [soft] metal ion acceptor will decrease its soft character, or even turn it into a [hard] acceptor.

In the realm of organic chemistry this factor can be neglected.

INTRINSIC STRENGTH

Pearson states that acid-base complex reactions depends on four parameters: the intrinsic strength S and the softness σ of both acid and base.

Extremely soft Lewis base $H^{\ominus}$ combines with very hard acid H^{+} exothermically to give the stable hydrogen molecule that is not accordance with HSAB principles. This can be attributed to the inherent strength of acid-base complex.

Although we usually concentrate on the influence of softness in discussions, the equally important strength factor should also be considered. Fortunately it seems that strength and softness work together in most cases.

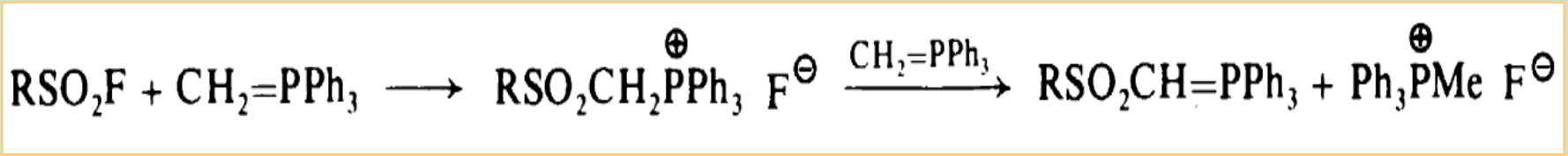
Flagrant examples which violate the HSAB principle are known. Most of these can be attributed to the inherent strength of the acid-base complex which overrides the match in softness.

That the extremely soft Lewis base H^- combines with the very hard acid H^+ exothermically to give the stable hydrogen molecule is a case in point.

In the successive oxidation of methane, exothermicity increases with each step until the last. Pearson and songstad suggested that the acid $HOCO^+$ is very strong, hence it would rather unite with the soft $H^\ominus$ which is stronger than the hard $OH^\ominus$.
Consequently, formic acid is usually stable against further oxidation while conversion to carbonic acid is favored on the basis of HSAB.

CH_4 CH_3OH $CH_2(OH)_2$ HCOOH H_2CO_3

Wittig reagents attack the harder sulfonyl center instead of F in sulfonyl fluorides. The strong polarized S-F bonds forces the soft ylidic carbanion to interact with the harder acceptor.



Sulfonyl chlorides react with the wittig reagant in accordance with the HSAB principle.