Learning Guide for Chapter 7 - Organic Reactions I

I. Introduction to Reactions
II. Principles of Kinetics
III. Principles of Thermodynamics
IV. Nucleophiles and Electrophiles
V. Acids and Bases

I. Introduction to Chemical Reactions

What a chemical reaction is

What always happens during a chemical reaction?

chemical bonds are broken and/or formed, new compounds are created
only electrons are involved, nucleus is unchanged, same atoms present

How to Represent Chemical Reactions

How can a reaction be represented without showing specific compounds?

most general form

$$A + B \longrightarrow C + D$$

reactants products

often used to write organic reactions

$$A \xrightarrow{B} C + D$$

A - organic - starting material

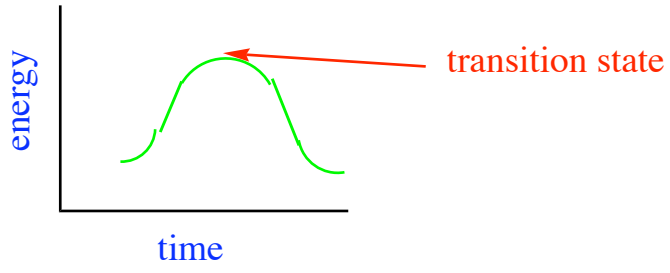
B - inorganic - reagent

Energy Diagrams for Chemical Reactions

What do energy diagrams tell us?

what happens to the energy of all molecules during the reaction

What is on each axis?



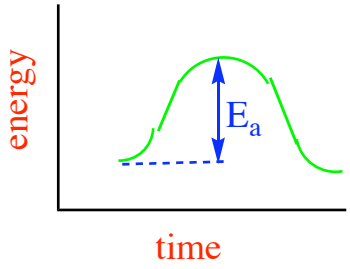
What basic pattern does the energy of all reactions follow?

energy goes up, back down again

Where is the transition state? Why is it higher in energy than either products or reactants?

highest point bonds are partially formed, partially broken

What is the activation energy of a reaction??



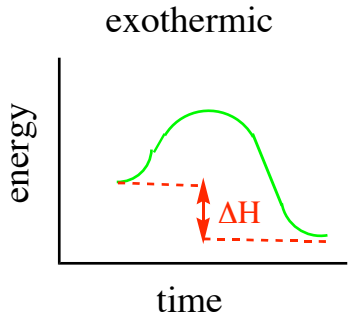
difference in energy between reactants and transition state
amount of energy molecules must have to react

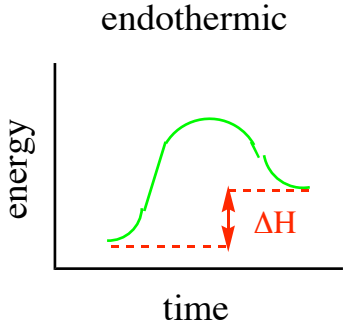
What is the difference between an exothermic and endothermic reaction?

exothermic gives off energy - ends lower than it starts

endothermic uses up energy - ends higher than it starts

Draw the energy diagrams for an exothermic and an endothermic reaction.





What is the difference between the energy at the beginning and at the end?

enthalpy: $\Delta H = H_{products} - H_{reactants}$

When is it positive, and when is it negative?

exothermic - ΔH is negative

endothermic - ΔH is positive

What determines the enthalpy of the reactants and products?

the strength of the chemical bonds

If a reaction has stronger bonds at the beginning than at the end, is it exothermic or endothermic?

endothermic - stronger bonds have to be broken - unfavorable

exothermic - weaker bonds at the beginning - favorable

II. Kinetics of Reactions

What does understanding the kinetics of a reaction tell you? Why do we care?

tells you how fast the reaction will go (measured by molecules formed per second)

we care how long something will take oxidation of fats, formation of an ester

What must happen in order for two molecules to react?

they have to collide (have to be close enough for orbitals to interact)
have to have the correct orientation (the right atoms have to bump into each other)
they have to have enough energy (greater than E_a)

anything that makes more collisions or higher energy will increase the reaction rate
most collisions do not result in a reaction

How will the following factors affect the rate of a reaction, and why?

activation energy (E_a):

higher Ea --> slower reaction
higher barrier for molecules to get over

probability factor (A):

larger A --> faster reaction
more molecules are likely to collide that way

} always the same for a given reaction

concentration of the reactants [ ]:

higher concentrations --> faster reaction
more collisions between molecules

temperature (T):

higher T --> faster reaction
1 - more collisions
2 - more molecules have E > Ea

} we can change these

Which are always the same for a certain reaction?

activation energy, probability factor - can't change without changing the reaction

Which of these are within our control?

concentration, temperature - can change for a given reaction

What does the rate law for a reaction look like?

rate = $k_r[A]^x[B]^y$ k_r --> rate constant $k_r = Ae^{-Ea/RT}$

gives proportion of molecules with enough energy to react

[A], [B] --> concentrations of the reagents

x, y --> order of the reaction

If a reaction has a large rate, what does that tell you? large rate - fast reaction

What do the exponents tell you?

how much effect the concentration of that reactant has on the rate

How do we find out what the exponents are?

by doing experiments, or by knowing the mechanism

What is a mechanism?

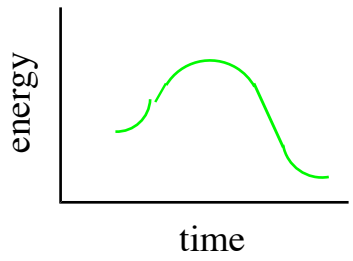
the individual collisions required for a reaction to be completed

What would happen with a one step reaction?

$A + B \longrightarrow C + D$ A collides with B, they react, C and D bounce away

rate = k_r [A] [B]

1st order in A
1st order in B
2nd order overall



What would happen tot he rate of the reaction if we doubled the concentration of A? of B?

reaction rate would double in either case

What would happen to the rate of the reaction if we doubled the concentration of C or D?

nothing! rate of the reaction is only affected by the concentration of the reactants

What if the reaction is reversible?

reverse reaction will have a separate reaction rate: rate = k_r [C] [D]

What happens if a reaction requires multiple steps?

overall reaction: $A + B + C \longrightarrow E + F + G$

mechanism:

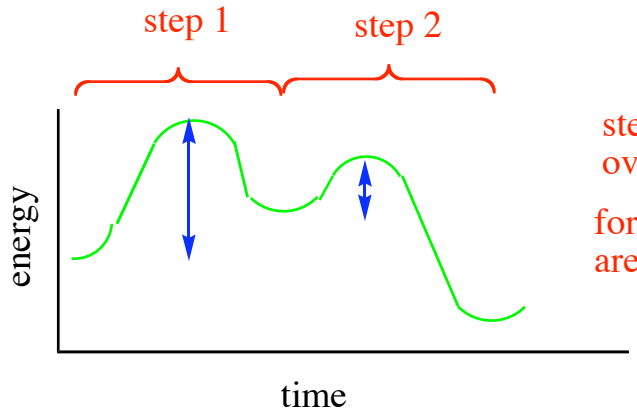
step 1 $A + B \longrightarrow D + E$

step 2 $D + C \longrightarrow F + G$

D is a reactive intermediate - formed but quickly reacts, not there at the end

Which step controls the rate of the reaction?

the one with the highest E_a - called the rate-limiting step



step 1 is endothermic, but the overall reaction is exothermic

formation of reactive intermediates are usually endothermic

step 1 is rate limiting - only its reactants will appear in the rate law

rate = k_r [A] [B] [C]^0 =1

1st order in A
1st order in B
0th order in C
2st order overall

What would happen to the rate of the reaction if we doubled the concentration of each reagent?

A - rate would double
B - rate would double
C - nothing!

D, E, F nothing!

III. Thermodynamics of Reactions

What does studying the thermodynamics of a reaction tell us? Why is this important?

how far the reaction will go - how favorable it is
if a desired reaction is not favorable, we need to know!

How do you show that a reaction is reversible? $A + B \rightleftharpoons C + D$

When a reaction has reached equilibrium, what will be happening?

rate of forward reaction = rate of backward reaction

amount of A, B, C, D present in the reaction is not changing

What is the equilibrium constant?

$$Keq = \frac{\text{products}}{\text{reactants}} = \frac{[C][D]}{[A][B]}$$

If the $K_{eq} = 10^{18}$, what does that tell us? greater than 1

more products than reactants
very favorable, nearly complete

If $K_{eq} = 10^{-25}$, what does that tell us? less than 1

more reactants than products
doesn't go very far

The rate of a reaction and the equilibrium constant are independent. What would happen if:

K_{eq} is large, rate is large

lots of products formed quickly
combustion

K_{eq} is large, rate is small

lots of products formed, but it takes a long time
rusting

K_{eq} is small, rate is large

only small amount of products formed, but formed quickly
weak acid

K_{eq} is small, rate is small

only small amount of products formed, not formed, and it takes a long time
?

Where does the equilibrium constant come from?

difference in free energy of the products and starting materials

$\Delta G = G(\text{products}) - G(\text{reactants})$

If the free energy of the reactants is higher than the free energy of the products, what would you predict about the reaction?

favorable, ΔG -
the universe tends to go from high to low energy

If the free energy of the reactants is lower than the free energy of the products, what would you predict about the reaction?

unfavorable, ΔG +

How are ΔG and K_{eq} related mathematically?

$\Delta G = -RT \ln K_{eq}$ large K_{eq} - positive ln, negative ΔG
small K_{eq} - negative ln, positive ΔG

How is ΔG different from ΔH?

$\Delta G = \Delta H - T\Delta S$ ΔH = enthalpy, energy of bonds being formed and broken

ΔS = entropy, amount of disorder, randomness

ΔH usually much larger than ΔS

When would ΔS be important? when ΔH is around 0

What would cause a significant change in ΔS?

change in the number of molecules - more disorder

How does a reaction get to equilibrium and stay there?

If the K_{eq} =1 and you add 20 moles of A and 20 moles of B together, what will happen in order for equilibrium to be reached?

	A	+ B	--> C	+ D
	20	20	0	0
5 mols react:	15	15	5	5
5 mols react:	10	10	10	10 =)

$$K = \frac{0 \times 0}{20 \times 20} \neq 1$$

$$K = \frac{5 \times 5}{15 \times 15} = \frac{25}{225} = 0.111 \neq 1$$

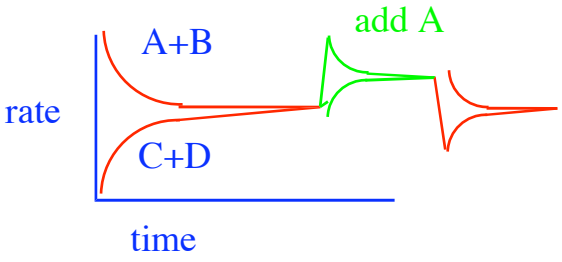
$$K = \frac{10 \times 10}{10 \times 10} = 1 = K_{eq}$$

What happens to the rates of reaction during this process?

at the beginning, the conc of reactants high, products 0
rate of forward reaction starts high, rate of backward reaction starts at 0

as reactants are used up, rate of forward reaction slows
as products are formed, rate of backward reaction picks up

finally they are equal



What would happen if, after the reaction has reached equilibrium, you add 10 more moles of A to the reaction?

A	+	B	-->	C	+	D
20		10		10		10
19		9		11		11
=) 18		8		12		12

$$K = \frac{10 \times 10}{20 \times 10} = \frac{100}{200} = 0.5$$

no longer at equilibrium!
A + B will speed up

Le Chatelier's principle - if you disturb an equilibrium the system will shift to restore it

$$K = \frac{11 \times 11}{19 \times 9} = \frac{121}{171} = 0.71$$ closer!

$$K = \frac{12 \times 12}{18 \times 8} = \frac{144}{144} = 1$$

Yea! Back to equilibrium - both rates the same (but higher than before)

What would happen if C or D were removed?

backward reaction would slow down, allowing more C and D to form
gradually backward reaction would speed up and forward reaction slow down until they are equal again

How could a reagent be removed from a reaction?

precipitate, boil off, add a solid to absorb (water)

What would happen if there was a large excess of A, say 1000 moles?

$$K = \frac{10 \times 10}{1000 \times 10} = \frac{100}{10000} = 0.1$$

A	+	B	-->	C	+	D
10,000		10		0		0
9990.01		0.01		9.99		9.99

9.99 moles of A and B react: $\frac{9.99 \times 9.99}{9990.01 \times 0.01} = 1$ (I rounded a bit - it doesn't come out exactly)

B would be nearly used up to achieve equilibrium

What would happen if the K_{eq} were very large? it would nearly use up both reagents

What would happen if there were two steps in a reaction, and the first had a small K_{eq} and the second had a large K_{eq}?

$A + B \longrightarrow C \quad K_{eq} = 10^{-12}$

$C + D \longrightarrow E \quad K_{eq} = 10^{8}$

as soon as any C is formed, it is used up by the second reaction, which allows more A and B to react - lots of E formed

What if the first was large and the second small? the reaction would only go half way

When $K_{eq} = 1$, why are the rates equal when the reaction is at equilibrium?

$K_{eq} = 1$, so energy of products and reactions equal [draw]
Ea's equal

How can the rates be equal in an exothermic reaction?

$K_{eq} > 1$, so energy of reactants higher than products [draw]
Ea of backward reaction higher than Ea of forward reaction
must have higher concentrations of products to speed up backward reaction

How can the reaction rates be equal in an endothermic reaction?

$K_{eq} < 1$, so energy of reactants lower than products [draw]
Ea of backward reaction lower than Ea of forward reaction
must have higher concentrations of reactants to speed up forward reaction

III. Electrophiles and Nucleophiles

Write the definitions of the following terms:

Bronsted-Lowry acid:

proton donor
gives up a H

Bronsted-Lowry base:

proton acceptor
takes a H

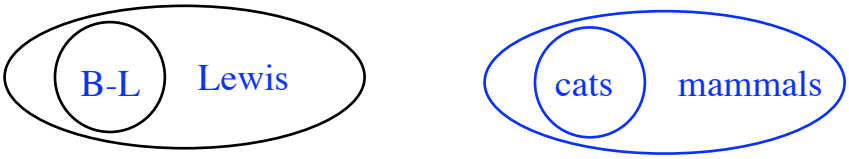
Lewis acid: electrophile

electron pair acceptor
is attacked

Lewis base: nucleophile

electron pair donor
attacker

What is the relationship between these definitions?



Lewis acid/base definition is more general, B-L is more limited
all B-L reactions are Lewis reactions, but not vice versa

There are three basic types of Lewis acid/base reactions. What do each of these words mean in ordinary English? What do they remind you of?

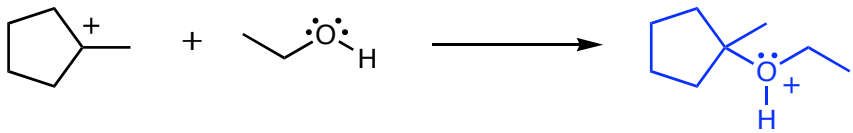
displacement: one thing replaces another

association: two things come together

dissociation: something comes apart

Below are some a Lewis acid/base reactions. Watch how the electron movement causes the reaction to occur. What description fits best?

e- carry O with them

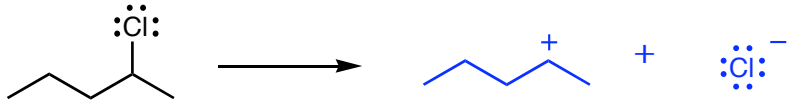


electrophile nucleophile charge on O

association

What happens in an association reaction?

a bond is formed between two atoms (one arrow)



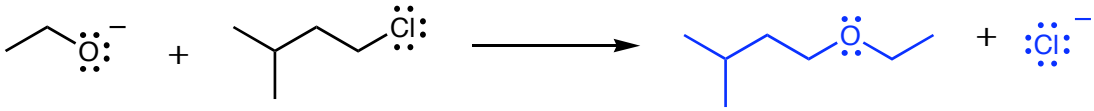
Which description fits?

dissociation

(no Nu or E)

What happens in a dissociation reaction?

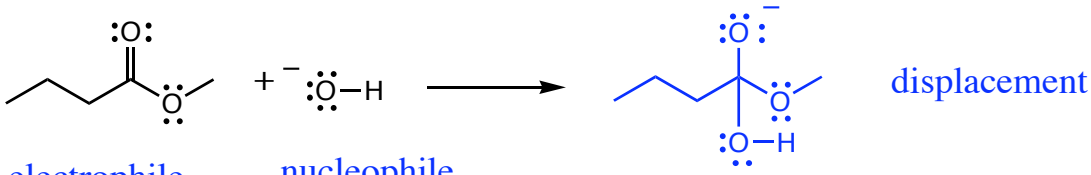
a bond breaks (one arrow)



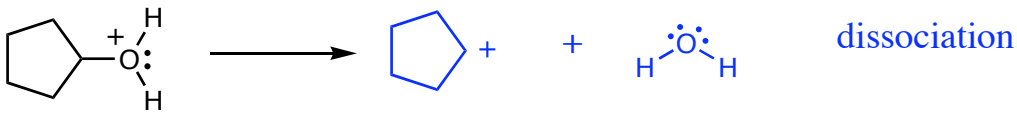
nucleophile electrophile displacement

What happens in a displacement reaction?

an atom loses one bond and gains another (two or more arrows)



electrophile nucleophile displacement



dissociation

(no Nu or E)

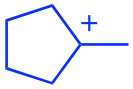
When a bond is broken, which atom gets the electron pair?

the most electronegative atom

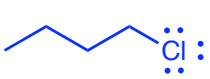
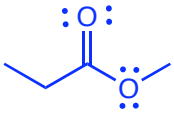
What do all of the nucleophiles in the examples have in common?

lone pair of electrons - used to attack (form a new bond)

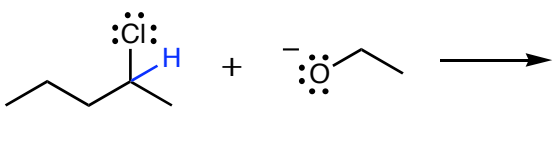
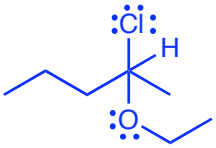
How is the electrophile in an association reaction different from an electrophile in a displacement reaction?

electrophile: association - E needs a bond 

displacement - has a bond that can be pushed off

What would happen if you tried to do an association reaction on the following compound?

Texas carbon!
Not allowed!

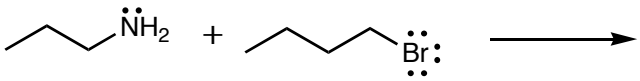
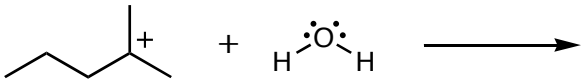
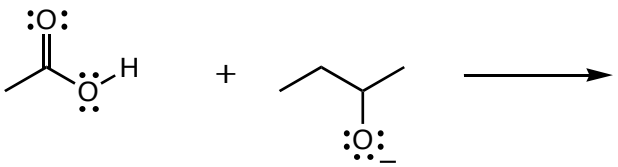
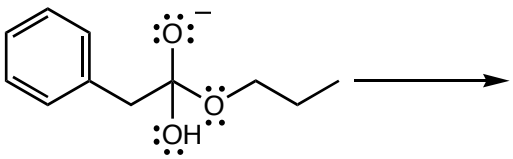
** Every time something attacks, something else much come off!
(unless it is already electron deficient, which means it already did!)

What makes reactions happen?

movement of electrons

What products would result from the following reactions? Identify the nucleophile and electrophile, and classify the reaction as an association, dissociation, or displacement.

add arrows

Look for patterns of what electrons do:

What can lone electron pairs do?

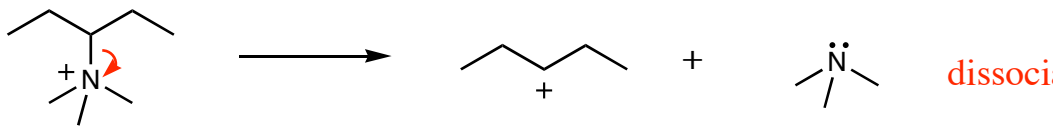
1 - become a bond between the original atom and a new atom (in the same molecule or a different one)

What can electron pairs in bonds do?

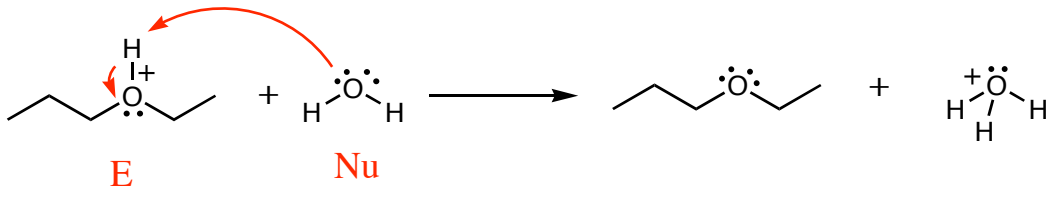
1 - become a lone pair on one of the atoms in the bond
2 - detach from one atom and form a new bond with one original and one new atom

**Electrons can't fly through the air and end up in a totally separate place - no travelling. They must remain attached to at least one of the original atoms (if a lone pair, must remain attached to that atom).

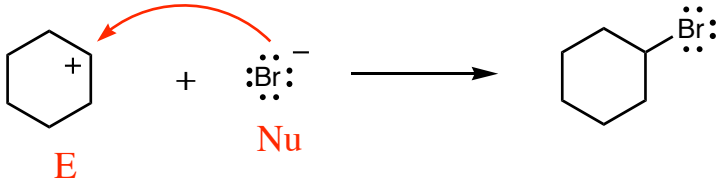
Draw arrows to show how the following took place. Identify the nucleophile and electrophile (if any). Classify them as association, dissociation, or displacement reactions.



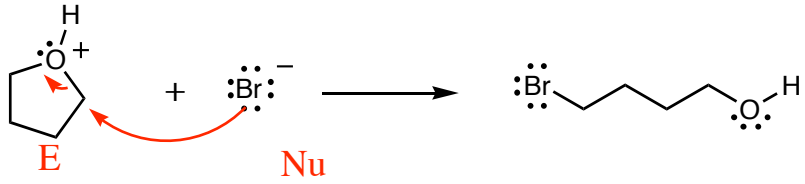
dissociation



displacement



association



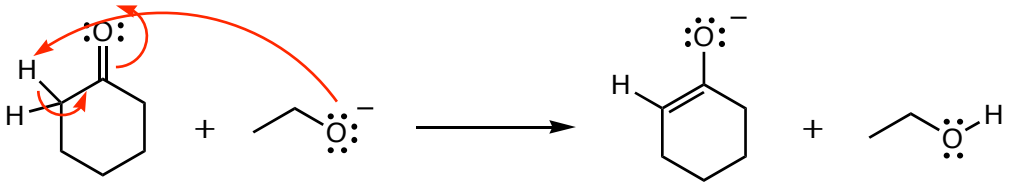
displacement

Some complex displacements involve more than two arrows. When dealing with these kinds of electron movements, it can be helpful to number the carbons, so that you can keep track of where they went. Then look at exactly what happened:

What bonds were broken?
Which were formed?
Which electron pairs appeared?
Which electron pairs disappeared?
What happened to the charge?

When you have established this, you must then figure out how the bonds that were broken and electron pairs that disappeared could move (without flying through the air) to create the bonds that were formed and electron pairs that appeared.

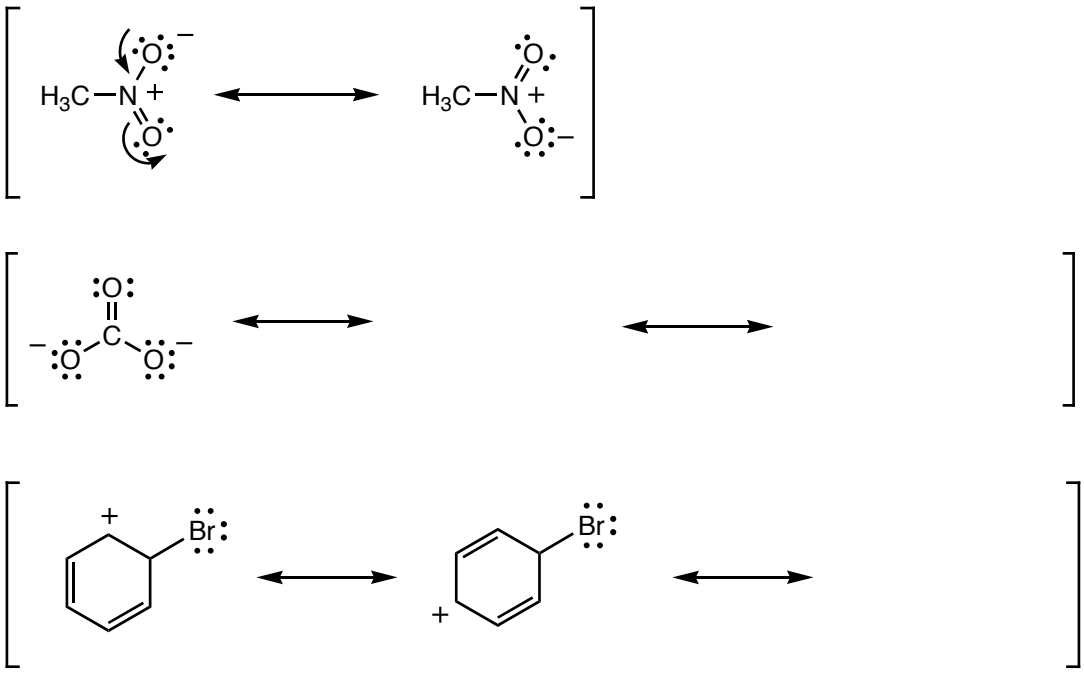
What arrows would be needed to show how the following reaction occurs?



displacement

Resonance structures

The electron arrows used in Lewis acid/base reactions can also be used to convert one resonance structure to another.

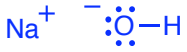


Remember, with resonance structures, the electrons are not actually moving. This is just a convention to represent electrons occupying orbitals that cover more than two atoms.

Strengths of nucleophiles and electrophiles

What makes nucleophiles strong?

1) negative charge vs. neutral atom of the same element

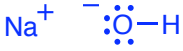
H_2O  NaOH 

neutral — negative

weaker Nu — stronger Nu

why? negative ions become neutral; neutral ions become positive

2) less electronegative atom vs. more electronegative atom in the same period

NaOH  HC≡CNa 

more electronegative — less electronegative

strong Nu — even stronger Nu

why? less EN atoms don't hold onto e- as hard as more EN atoms

3) larger atoms vs. smaller atoms in the same family

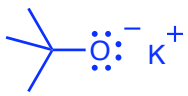
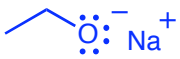
NaOH  NaSH 

smaller atom — larger atom

strong Nu — stronger Nu

why? in larger atoms their valence e- are farther from the nucleus, easier to donate

4) less hindered vs. more hindered atoms of the same element

$(CH_3)_3COK$  CH_3CH_2ONa 

very hindered — not hindered

not a Nu — strong Nu

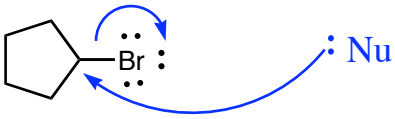
why? atoms which are sterically hindered are poor Nu

What makes electrophiles strong?

1. having an empty orbital

empty orbital

stronger E

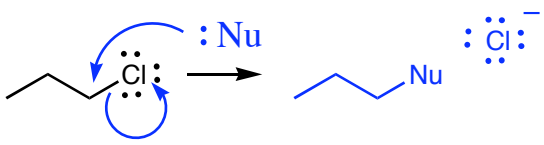


complete octet

weaker E

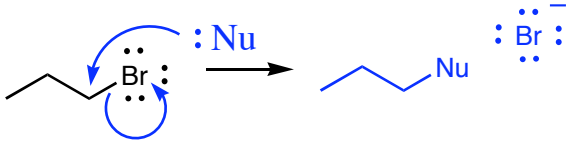
why? atoms with empty orbitals are high in energy otherwise, something has to be pushed off

2. Having a weak bond between the carbon and leaving group



strong C-Cl bond (small atom)

weaker E

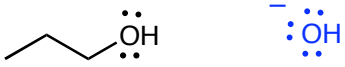


weak C-Br bond (large atom)

stronger E

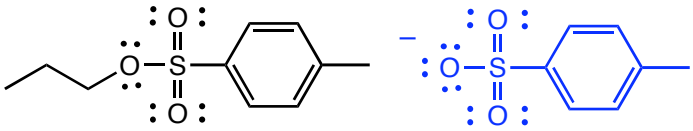
why? the weaker the bond to the leaving group, the easier displacement is

3. Having a leaving group that is low in energy



reactive leaving group

not an electrophile

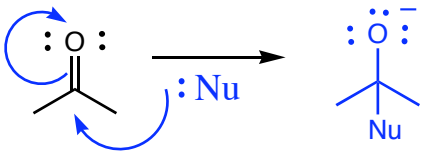


leaving group stabilized by resonance

good electrophile

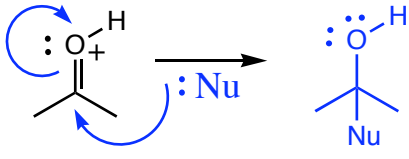
why? if the leaving group is low in energy, then the overall energy of the products is lower, the reaction is more favorable

4. Having a positively charged atom next door



O is neutral

weaker electrophile



O is positive

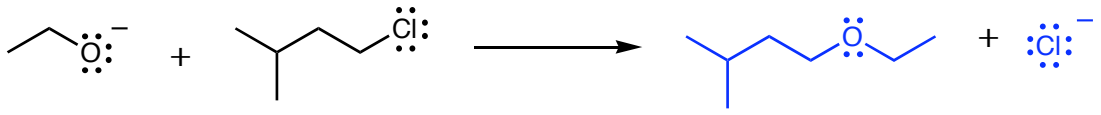
stronger electrophile

why? neutral atom becomes negative, while positive atom becomes neutral

V. Bronsted-Lowry acids and bases

Introduction to acids and bases

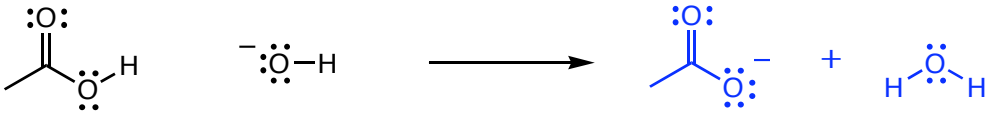
What makes Bronsted-Lowry acids and bases different from Lewis acids and bases?



nucleophile
e- donor

electrophile
e- acceptor

no H involved, only fits one defintion



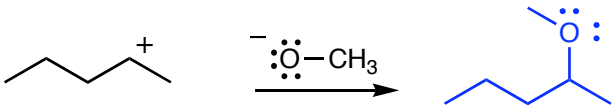
acid
e-acceptor
H donor

base
e- donor
H acceptor

H is always the e- acceptor, fits both definitions

always a displacement

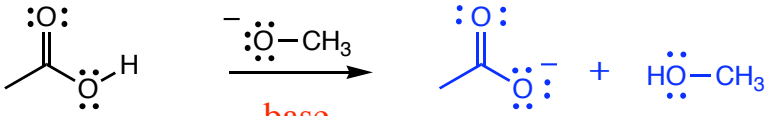
Could the same reactant be a nucleophile or base? If so, how do we know which?



E

Nu

if it attacks a H, its a base
if it attacks a C, its a Nu



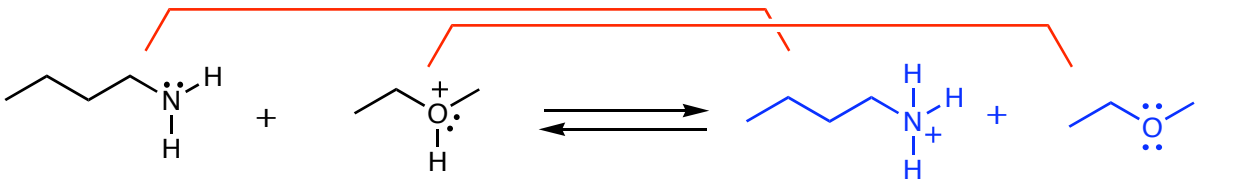
acid

base

Are acid/base reactions usually reversible? yes

How are the products related to the reactants? base becomes the conjugate acid

acid becomes the conjugate base



base

acid

conjugate acid

conjugate base

you can think of an acid as a base with its H still attached acid = H-base

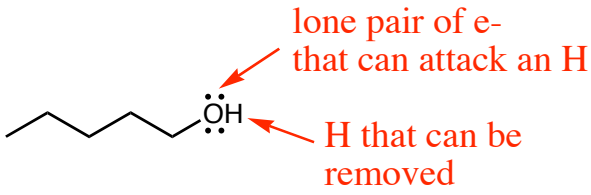
H-base$_1$ + :base$_2$ ⇌ :base$_1$ + H-base$_2$

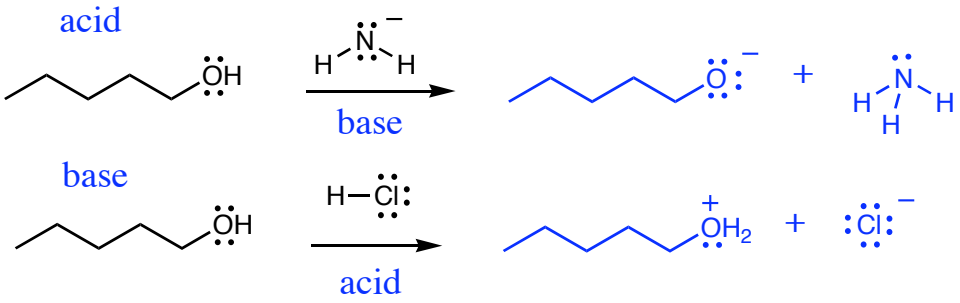
Some compounds are amphoteric - what does this mean?

can act as an acid or a base

What must they have in order to do this?

acid - H that can be removed
base - lone pair of e- than can attack a H

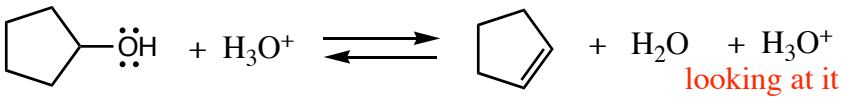




How is a reaction related to its mechanism?

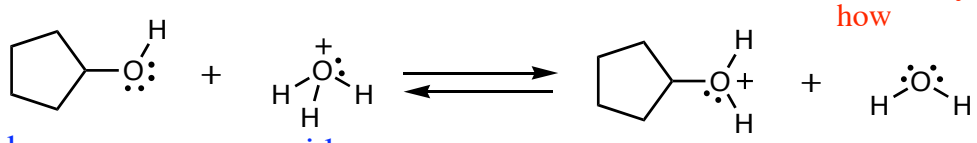
a reaction tells what compounds you start and end with

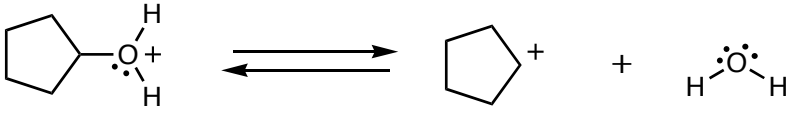
the mechanism gives you the actual steps that occur

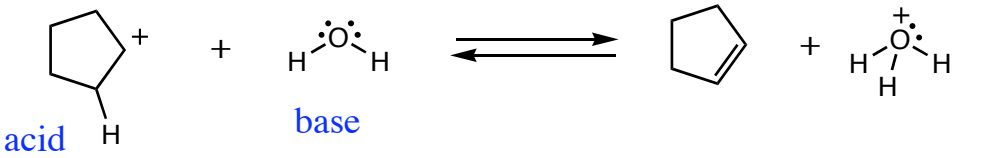
overall reaction: 

looking at it, there's no way to know why this happened, or how

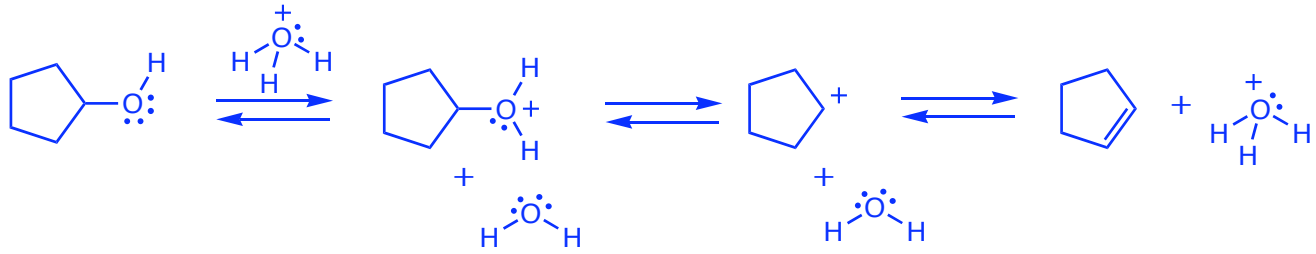
mechanism:

step 1: 

step 2: 

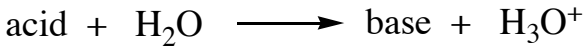
step 3: 

easier way to write the steps:



Using pKa's to determine acid and base strength

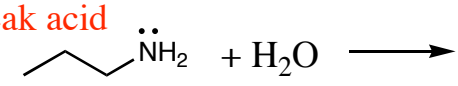
What is the equilibrium constant for the reaction of an acid with water?



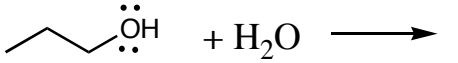
$$K_a = \frac{[base][H_3O^+]}{[acid]}$$

How does K_a show how strong an acid is?

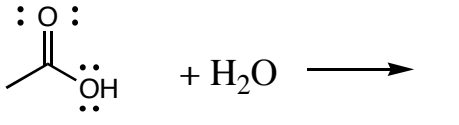
very weak acid



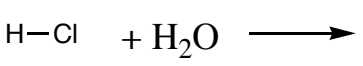
$K_a = 10^{-36}$ favors reactants



$K_a = 10^{-16}$ favors reactants



$K_a = 10^{-5}$ favors reactants

strong acid 

$K_a = 10^{7}$ favors products

How does strong of a base is water?

water is not a very good base, its reaction with most acids is not favorable

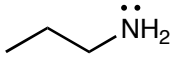
"strong acids" - dissociate completely in water; have a favorable reaction with water

"weak acids" - dissociate partly in water; have an unfavorable reaction with water

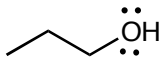
we can still use the numbers to between them!

How does pKa relate to the Ka of an acid?

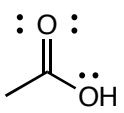
$pK_a = -\log K_a$



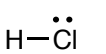
$K_a = 10^{-36}$ pKa = 36 very weak acid



$K_a = 10^{-16}$ pKa = 16



$K_a = 10^{-5}$ pKa = 5



$K_a = 10^{7}$ pKa = -7 strong acid

Get a pKa chart in class or on the course website.

Where are the strongest acids? at the top

Where are the weakest acids? at the bottom

Which compound is the stronger acid in each pair?

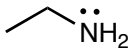
HCl pKa = -7

H_3O^+ pKa = -1.7

H—C≡C—H $pK_a = 26$

H_2SO_4 pKa = -10

HF $pK_a = 3.2$



$pK_a = 36$

stronger acid = lower number! (or more negative)

How can you determine the strength of a base?

look at the pKa of its conjugate acid

the stronger an acid is, the weaker its conjugate base

the weaker and acid is, the stronger its conjugate base

How strong of a base is HSO_4^-?

conjugate acid: H_2SO_4 pKa = -10 very strong acid
so HSO_4^- is a very weak base

How strong of a base is NH_2^-?

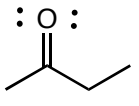
conjugate acid: NH_3 pKa = 36 very weak acid

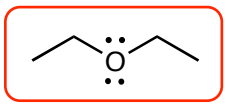
so NH_2^- is a very strong base

Where are the strongest bases on the pKa chart? Where are the weakest bases?

at the bottom at the top

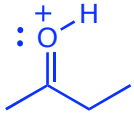
Which compound is the stronger base in each pair?

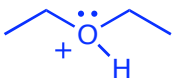




stronger base

conj acids





pKa = -7.3

stronger acid

pKa = -3.6

NaH = $Na^+ H^-$ NaOH

stronger base

H_2 H_2O

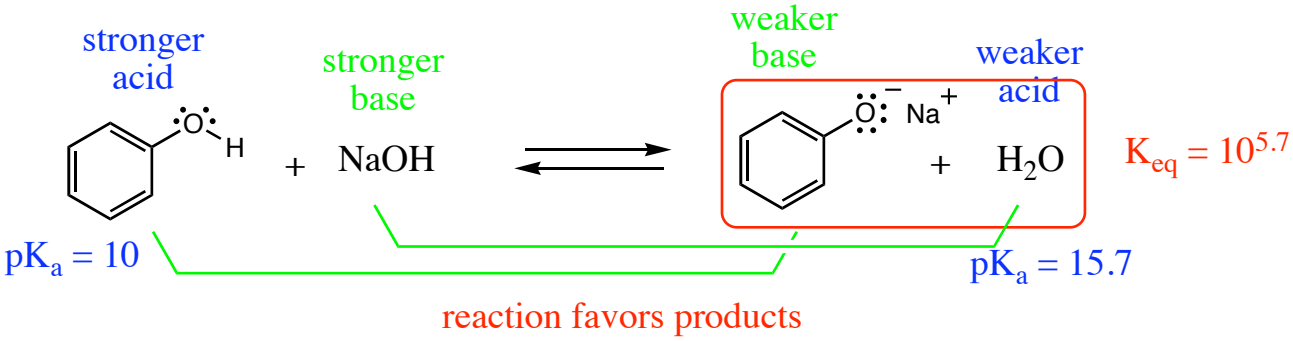
pKa = 35 pKa = 15.7

stronger acid

Using pKa's to predict whether an acid/base reaction will be favorable

How can you use pKa's to get the equilibrium constant for an acid/base reaction?

1. Locate the acid on each side
2. Use their pKa's and determine which acid is stronger.
3. Subtract the pKa of the product acid from the pKa of the reactant acid, and take 10 to that power.

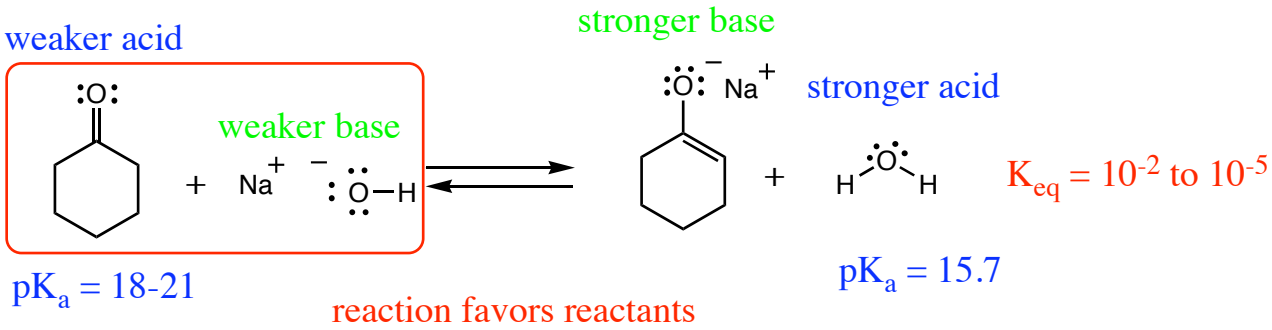


Will the stronger acid be in the reactants or products? reactants

Will the stronger base be in the reactants or products? reactants

reaction always goes away from the stronger acid and base!

Is NaOH a strong enough base to take the H from phenol? yes



Is NaOH a strong enough base to take the H from a ketone? no

If you need a base to take the H from an amide, where should you look on the chart?

bases w/ conj acids weaker than amides - below it!

If you need an acid to protonate a carboxylate, where should you look on the chart?

acids stronger than carboxylic acids - above it

Which of the following will be favorable? acid above the base acid below the base

Predicting relative acid and base strength

What causes some acids to be stronger than others?

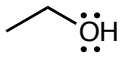
1. Electronegativity of the element the H is attached to:

CH_4	NH_3	H_2O	HF
pK_a = ~60	pK_a = 36	pK_a = 15.7	pK_a = 3.2

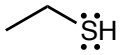
more electronegative atom = stronger acid

why? more EN atom more stable with a negative charge

2. Size of the atoms the H is attached to:



pK_a = 16

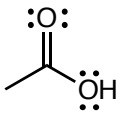


pK_a = 10.5

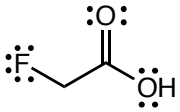
larger atom = stronger acid

why? H is farther from the nucleus, bond is weaker

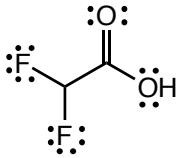
3. The presence of electronegative groups nearby:



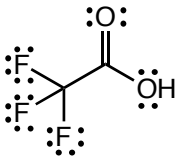
pK_a = 4.76



pK_a = 2.66



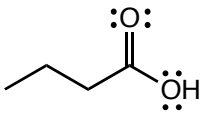
pK_a = 1.24



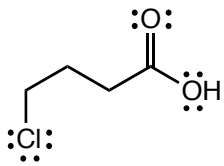
pK_a = 0.23

EN atoms nearby = stronger acid

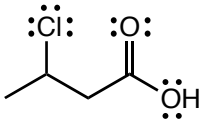
why? EN atoms pull e- density away, stabilize negative charge of conj base



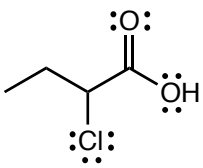
pK_a = 4.82



pK_a = 4.52



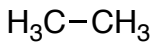
pK_a = 4.06



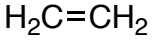
pK_a = 2.84

the closer the EN atom, the more effect it has

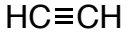
4. Hybridization of the atom the H is attached to:



$pK_a = 50$ sp^3 (1/4 s)



$pK_a = 44$ sp^2 (1/3 s)



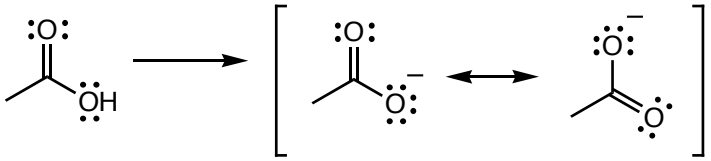
$pK_a = 26$ sp (1/2 s)

more "s" character = stronger acid

why? more "s" character, closer to the positively charged nucleus

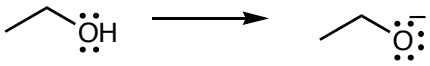
5. Resonance of the conjugate base:

$pK_a = 5$



resonance

$pK_a = 17$

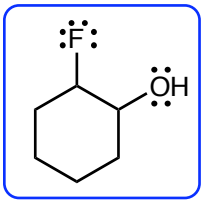


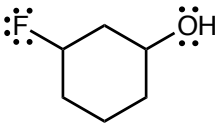
no resonance

resonance stabilized negatively charged conjugate base = stronger acid

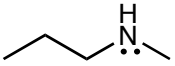
why? lower energy of products gives more favorable reaction

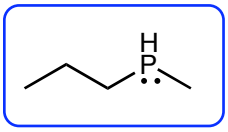
Circle the more acidic compound and explain your reasoning.



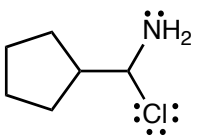


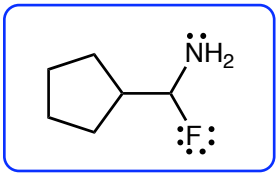
EN atom stabilizes conj base



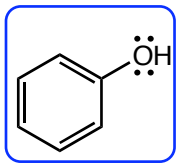
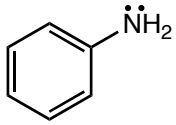


P larger than N
P-H bond is longer
charge on P is more spread out

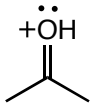
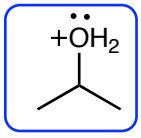




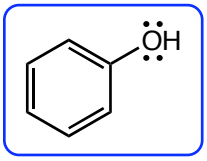
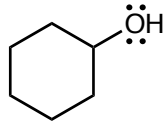
EN group stabilizes conj base
F is more electroneg than Cl

O is more electroneg
O-H bond is weaker
O is more stable w/ neg charge

hybridization - sp^2 is more acidic than sp^3

resonance stabilizes conj base

How can you use these rules to predict the stability of bases?

take the reverse: more EN atom = weaker base

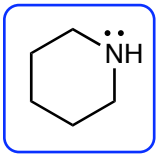
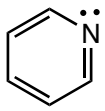
larger atom = weaker base

EN atoms nearby = weaker base

more "s" character = weaker base

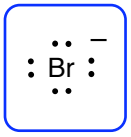
resonance stabilization = weaker base

Circle the more basic compound and explain your reasoning.

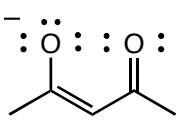
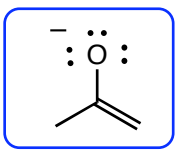
sp^2 is less basic than sp^3

pKa of conj acid 10.6 5.2

-9 -8

larger atom is a weaker base

9-13 18-25

resonance makes a base weaker