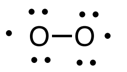
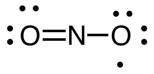
Chapter 10
Free Radicals

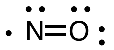
This is an example of a free radical reaction. A radical is a species that has a free unpaired electron. There are several examples of stable radicals, the most common of which is molecular oxygen. Nitrogen dioxide, NO_2, is also a stable radical and the important cell-cell signaling molecule, nitrogen monoxide, NO, is a radical as well.



molecular oxygen

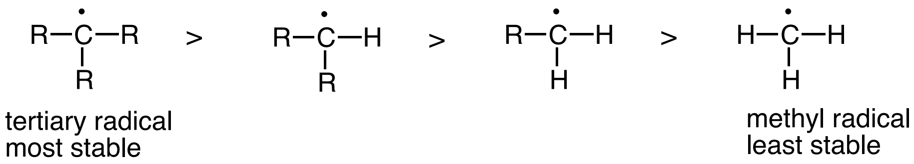


nitrogen dioxide

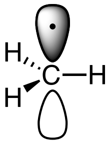


nitrogen monoxide

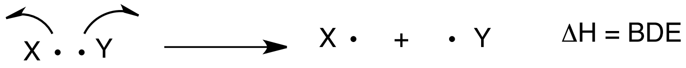
Carbon free radicals are usually much less stable. They are missing one electron and are generally very reactive intermediates that exist only for a short time. Carbon radical stability parallels that of carbocation stability. Since carbon radicals are missing one electron and so are electron deficient species, they are stabilized by electron donating substituents such as alkyl groups. Therefore, tertiary radicals are the most stable and methyl radicals are the least stable. Note also that the carbon radical has no charge.



The methyl radical is planar, trigonal with the hybridization very nearly sp^2. The *t*-butyl radical is slightly pyramidal but still flattened and closer to sp^2 than sp^3 hybridization.



Alkyl groups stabilize the radical just like they stabilize carbocations. Evidence for this stabilization can be seen in terms of the Bond Dissociation Enthalpy (BDE). For homolytic cleavage each atom gets one of the two electrons in the bond between the two atoms. The heat change, ΔH, in this reaction is the bond dissociation energy. Note that by convention in radical reactions, we use a single-headed arrow and that the product(s) of hemolytic cleavage are uncharged species.



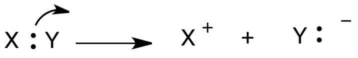
$X\cdot\cdot Y \longrightarrow X\cdot + \cdot Y \qquad \Delta H = \text{BDE}$

In homolytic cleavage, each atom gets one electron.

Note that no charge develops and that the arrows are single headed arrows, showing that only one electron is moving.

Recall that in heterolytic cleavage one atom gets both electrons.

heterolytic cleavage

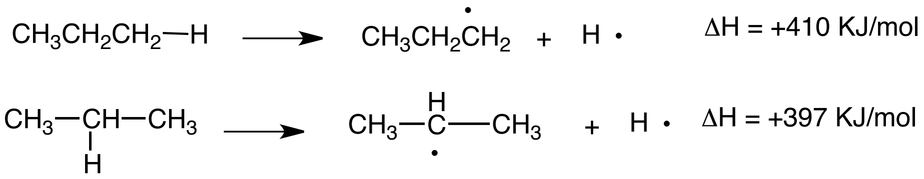


$X:Y \longrightarrow X^+ + Y:^-$

One atom gets both electrons and charges develop in the product(s).

It is generally the case that hemolytic cleavage requires less energy than heterolytic cleavage.

For carbon atoms, the bond dissociation enthalpies are known and can be found in tables. Compare the bond dissociation energy of a primary versus a secondary carbon.

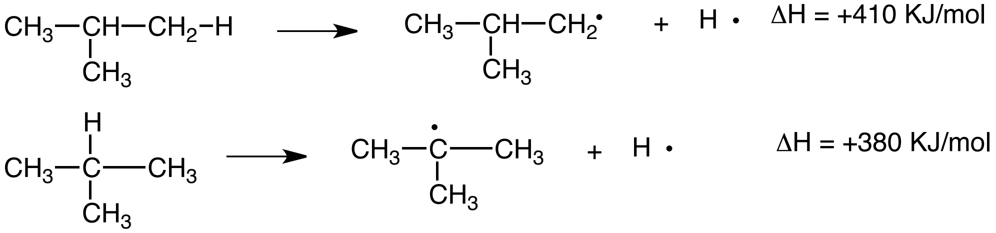


$CH_3CH_2CH_2{-}H \longrightarrow CH_3CH_2\dot{C}H_2 + H\cdot \qquad \Delta H = +410\ \text{KJ/mol}$

$CH_3{-}CH(H){-}CH_3 \longrightarrow CH_3{-}\dot{C}H{-}CH_3 + H\cdot \qquad \Delta H = +397\ \text{KJ/mol}$

We see the cleavage of a secondary carbon is 13 KJ/mol more favorable, implying that the secondary carbon radical is more stable than the primary by 13 KJ/mol.

We can use the bond dissociation enthalpies to compare the stabilities of a primary versus a tertiary carbon radical.



$CH_3{-}CH(CH_3){-}CH_2{-}H \longrightarrow CH_3{-}CH(CH_3){-}CH_2\cdot + H\cdot \qquad \Delta H = +410\ \text{KJ/mol}$

$CH_3{-}C(H)(CH_3){-}CH_3 \longrightarrow CH_3{-}\dot{C}(CH_3){-}CH_3 + H\cdot \qquad \Delta H = +380\ \text{KJ/mol}$

We see that the tertiary radical is more stable than the primary radical by 30 KJ/mol and more stable than the secondary radical by 17 KJ/mol.

Halogenation of Alkanes

A hydrogen atom on a simple alkane can be replaced with a halogen atom.

$R{-}H + X_2 \longrightarrow R{-}X + H{-}X \qquad X = Br, Cl$

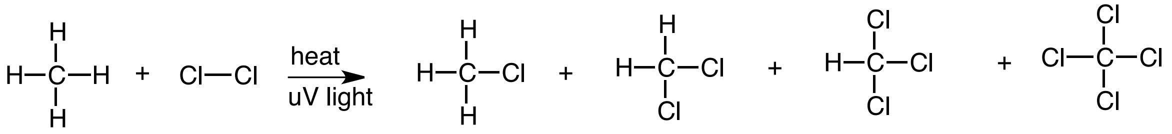
The order of reactivity for the halogens is: $F_2 > Cl_2 > Br_2 > I_2$.

Fluorine is too reactive. It is a strong oxidizing reagent and the reaction is strongly exothermic and difficult to control. Iodine is unreactive. The reaction is endothermic and not useful. Therefore, the only useful halogenations occur with bromine and chlorine.

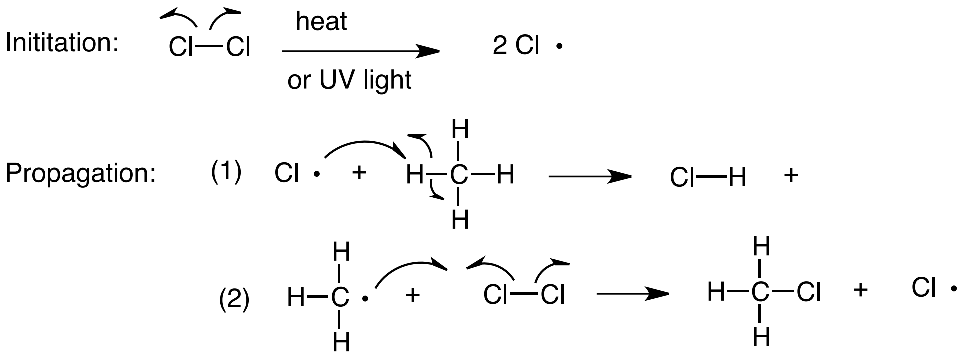
This is not a nucleophilic substitution reaction like the reactions we just studied with alcohols and halogen acids. The C-H bond is not polarized and H:$^-$ is not a leaving group. This is an example of a free radical reaction.

Chlorination of methane:

The reaction can give up to four products due to over reaction. On a large industrial scale the products can be separated by distillation.



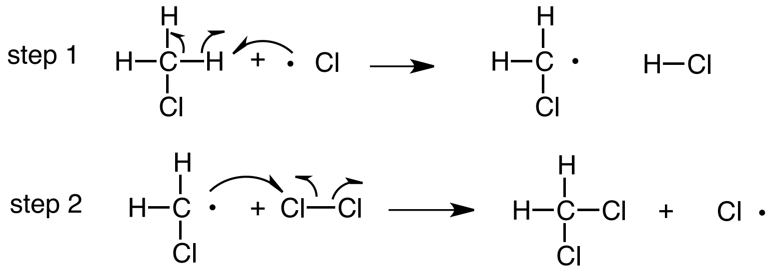
Halogenation of alkanes occurs by means of a radical chain reaction. This is shown below for the chlorination of methane.



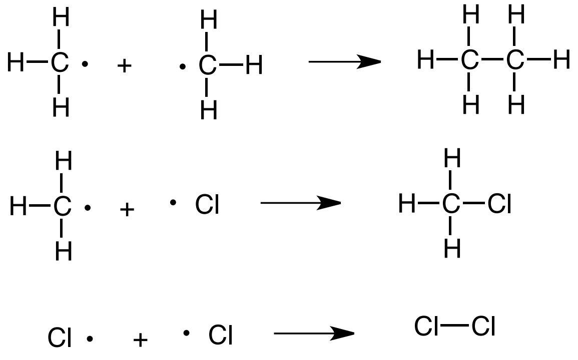
The first step is the initiation step. This is the hemolytic cleavage of the chlorine molecule into two chlorine radicals. This bond cleavage occurs due to heating or to ultra-violet (UV) light. Generally, this step occurs only once.

The next two steps occur over and over again. These are the propagation steps. In each propagation step a new radical is formed which then goes on to react to generate a new radical, which continues the chain reaction.

We can also get dichloromethane, tricholormethane and even tetrachloromethane. This occurs when the initial chloromethane continues to react and is more likely to occur toward the end of the reaction as the concentration of starting methane begins to decrease and the concentration of chloromethane increases.



The chain reaction can be broken by termination steps. Termination steps are those in which two radicals come together to react with each other. This does not generate a new radical and so the chain is broken. Some termination steps for the chlorination of methane are:

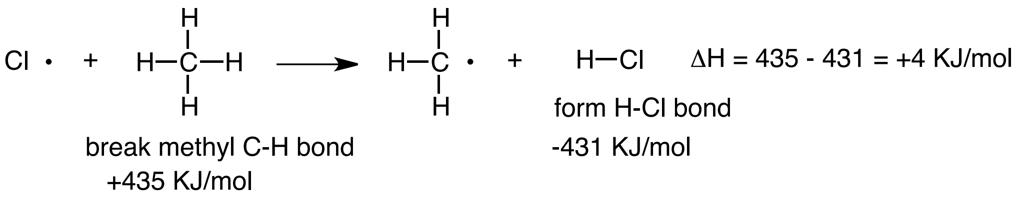


We can use bond dissociation enthalpies to calculate the overall in enthalpy, ΔH, for the reaction. In general, the overall change in enthalpy, ΔH, is equal to the sum of the bond dissociation enthalpies of the bonds broken plus the sum of the bond dissociation enthalpies of the bonds formed. We will use the convention that a bond broken is a positive number, since energy is required to break a bond, and a bond formed is a negative number, since heat is given off when a bond is formed.

$\Delta H = \Sigma BDE_{\text{bonds broken}} + \Sigma BDE_{\text{bonds broken}}$ Where bonds broken = (+)
bonds formed = (-)

Typically, we ignore the initiation step since it happens only once, where as the propagation steps can happen thousands of times.

step 1



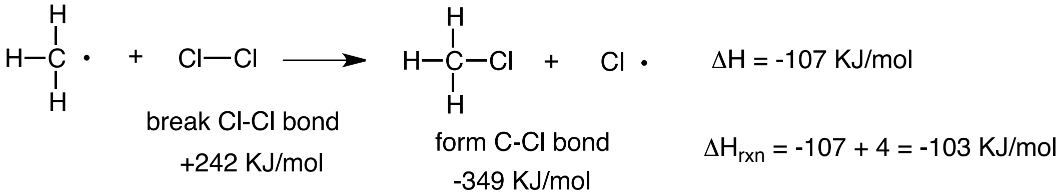
$$\mathrm{Cl}\cdot + \mathrm{H{-}\underset{H}{\overset{H}{C}}{-}H} \longrightarrow \mathrm{H{-}\underset{H}{\overset{H}{C}}}\cdot + \mathrm{H{-}Cl}$$

break methyl C-H bond
+435 KJ/mol

form H-Cl bond
-431 KJ/mol

$\Delta H = 435 - 431 = +4$ KJ/mol

step 2



$$\mathrm{H{-}\underset{H}{\overset{H}{C}}}\cdot + \mathrm{Cl{-}Cl} \longrightarrow \mathrm{H{-}\underset{H}{\overset{H}{C}}{-}Cl} + \mathrm{Cl}\cdot$$

break Cl-Cl bond
+242 KJ/mol

form C-Cl bond
-349 KJ/mol

$\Delta H = -107$ KJ/mol

$\Delta H_{rxn} = -107 + 4 = -103$ KJ/mol

To find the overall enthalpy of reaction, add step 1 and step 2 to get (-107 KJ/mol + 4 KJ/mol) -103 KJ/mol. The reaction is exothermic and therefore favorable.

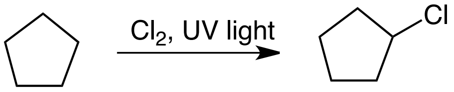
If the same calculation is done for fluorination, we find that ΔH is -426 KJ/mol. This is a very large amount of energy that is released for each step. As more molecules react, more energy is released, the reaction mixture heats up and reacts even faster. It quickly becomes uncontrollable. Free radical fluorinations are dangerously explosive.

If we do the same calculation for bromination, we find that the ΔH = -30 KJ/mol, considerably less than that for chlorination and much less than that for fluorination. As we will see, free radical bromination reactions are much more selective than free radical chlorinations.

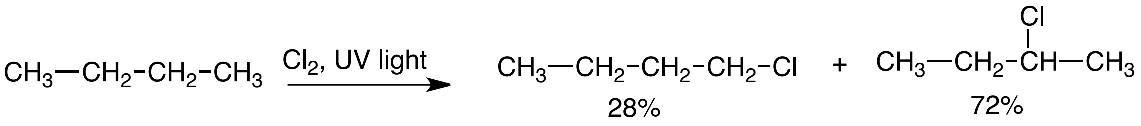
For iodination, ΔH = +54 KJ/mol. In the case of iodination, the reaction is unfavorable and free radical iodination reactions are not feasible.

Halogenation of Higher Alkanes

If the molecule is symmetrical, we get only one monochloro- product.



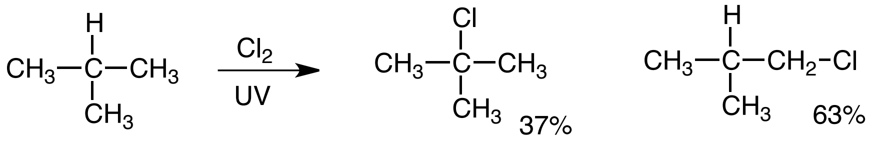
But if the molecule is not symmetrical, a mixture of products can form. We see that the major product is the one that results from the formation of the secondary radical.



$$\mathrm{CH_3{-}CH_2{-}CH_2{-}CH_3} \xrightarrow{\mathrm{Cl_2,\ UV\ light}} \underset{28\%}{\mathrm{CH_3{-}CH_2{-}CH_2{-}CH_2{-}Cl}} + \underset{72\%}{\mathrm{CH_3{-}CH_2{-}\overset{Cl}{CH}{-}CH_3}}$$

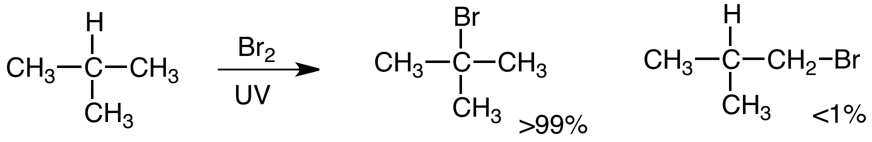
Since there are six primary hydrogens and only four secondary hydrogens, we would expect a mixture of 60% (6 of 10) 1-chlorobutane and 40% (4 of 10) of the 2-chlorobutane. But we see 72% of 2-chlorobutane. This tells us that the secondary radical is formed faster than the primary radical by a factor of 72/28 x 6/4 = 3.9/1.

Bromination is even more selective. Tertiary hydrogens are abstracted selectively. For example, compare the product rations of free radical chlorination and free radical bromination of 2-methylpropane.

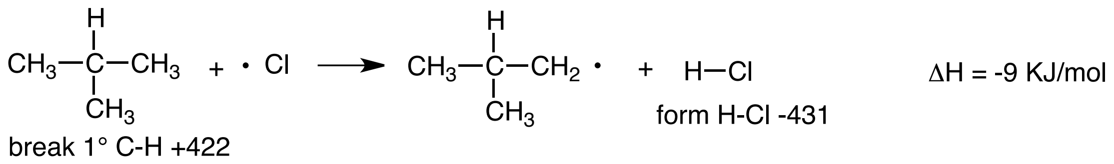


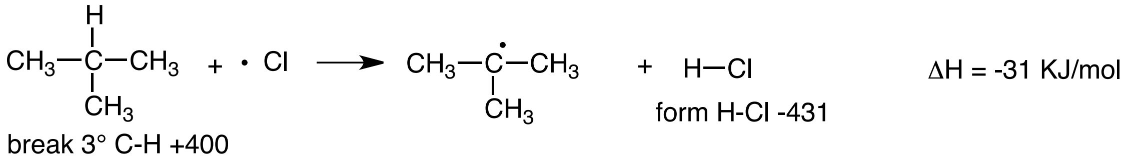
Here we see that there are nine primary hydrogens and only one tertiary hydrogen, so if primary hydrogens and tertiary hydrogens reacted at the same rate we would expect a product ratio of 10% 2-chloro-2-methyl propane and 90% 1-chloro-2-methylpropane. So clearly, the tertiary position reacts faster by a ratio of 37/63 x 9/1 = 5.2.

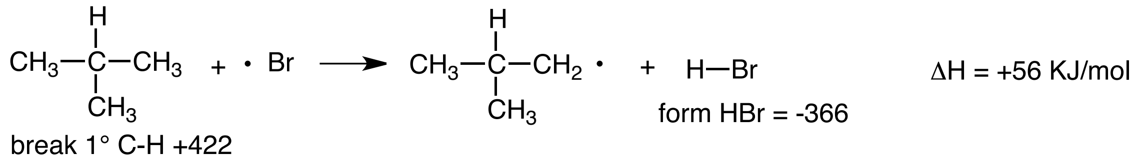
For bromination the results are very striking: bromination is much more selective for removal of the tertiary hydrogen than chlorination. Doing the same calculation that we did before, we see that in the bromination reaction, the tertiary hydrogen reacts 99/1 x 9/1 = 891 times faster.



The reason for this is that the first step in the chlorination reaction is quite exothermic (early transition state) for both primary and tertiary products while the first step in the bromination reaction is endothermic (late transition state) for both products.





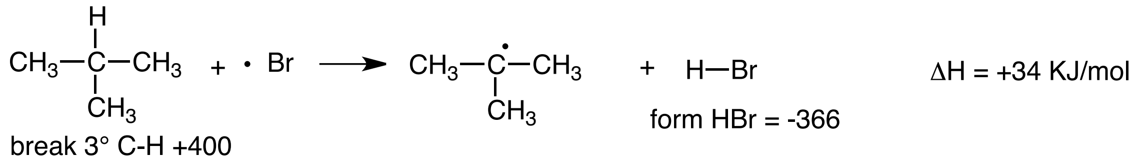


$$CH_3-\overset{H}{\underset{CH_3}{C}}-CH_3 \ + \ \cdot Br \longrightarrow CH_3-\overset{H}{\underset{CH_3}{C}}-CH_2\cdot \ + \ H-Br$$

break 1° C-H +422

form HBr = -366

ΔH = +56 KJ/mol



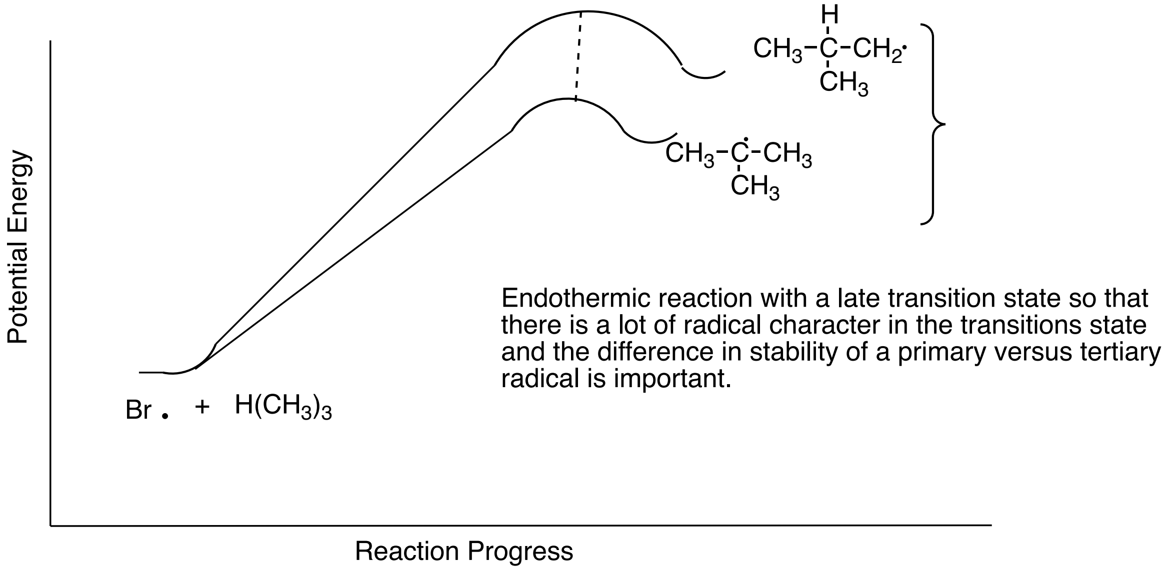
$$CH_3-\overset{H}{\underset{CH_3}{C}}-CH_3 \ + \ \cdot Br \longrightarrow CH_3-\overset{\bullet}{\underset{CH_3}{C}}-CH_3 \ + \ H-Br$$

break 3° C-H +400

form HBr = -366

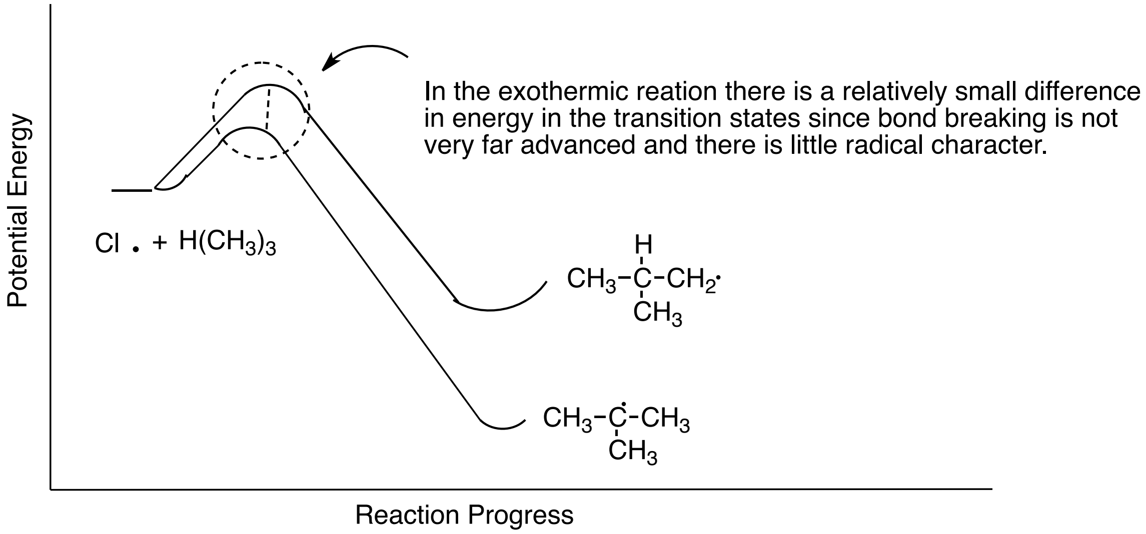
ΔH = +34 KJ/mol

Hammond's postulate tells us that we have a late transition state in an endothermic reaction so that there is a large difference in energy between the transition states leading to the primary radical and the tertiary radical.



Endothermic reaction with a late transition state so that there is a lot of radical character in the transitions state and the difference in stability of a primary versus tertiary radical is important.

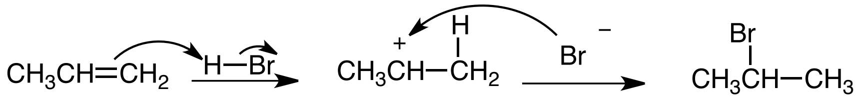
The chlorination reaction is exothermic. Therefore there is an early transition state with little radical character and the difference in energy between the transition states is small.



In the exothermic reation there is a relatively small difference in energy in the transition states since bond breaking is not very far advanced and there is little radical character.

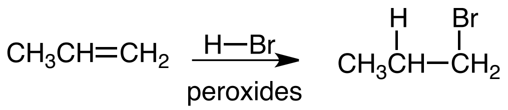
Radical Addition to Alkenes

As we learned, hydrogen bromide adds to an unsymmetrical alkene in such a fashion that the hydrogen (the electrophile) adds to the less substituted carbon so as to form the more substituted (and more stable) carbocation intermediate and then the bromine subsequently adds to the carbocation.



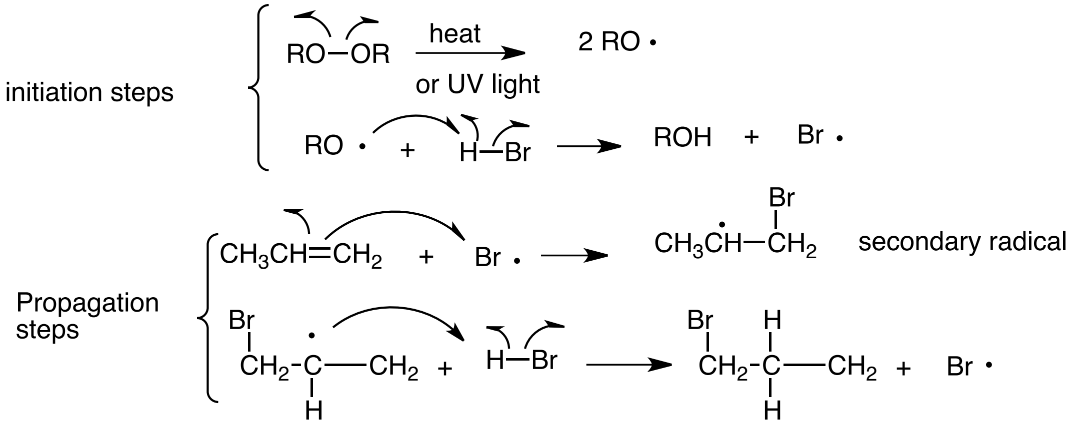
$$CH_3CH{=}CH_2 \xrightarrow{H-Br} CH_3\overset{+}{C}H-\overset{H}{C}H_2 \xrightarrow{Br^-} CH_3\overset{Br}{C}H-CH_3$$

But if we do the same reaction in the presence of peroxides, we see the opposite regiochemistry. The bromine becomes attached to the less substituted carbon and the hydrogen becomes attached to the more substituted carbon.



$$CH_3CH{=}CH_2 \xrightarrow[\text{peroxides}]{H-Br} CH_3\overset{H}{C}H-\overset{Br}{C}H_2$$

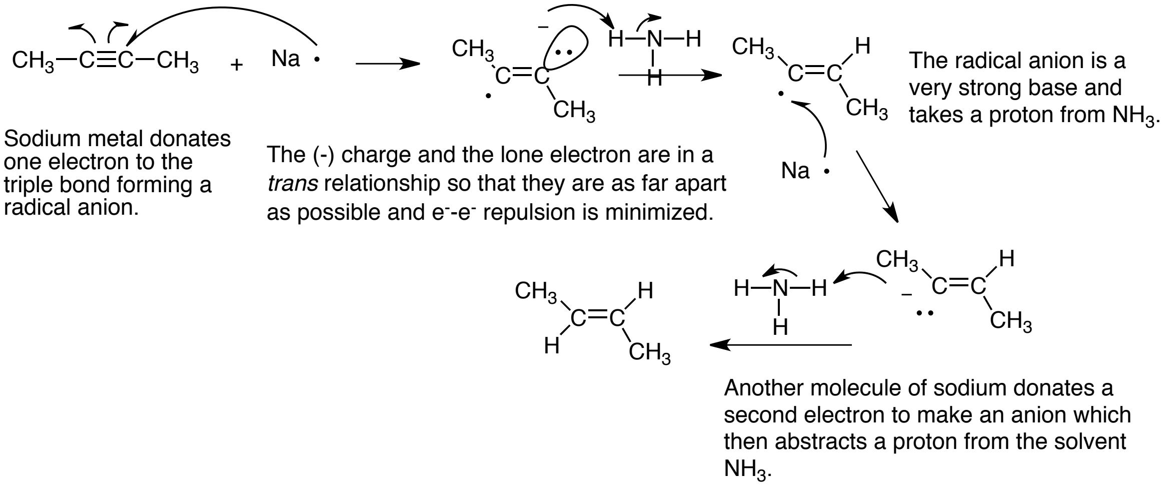
Clearly there is a different mechanism involved. It is a free radical chain reaction. The radical chain reaction is initiated by a hydroxyl radical. The peroxide bond is very weak and is easily cleaved homolytically to give two hydroxyl radicals, one of which then abstracts a hydrogen atom from H-Br to give a bromine radical. This then adds to the alkene in such a fashion as to form the more stable radical, which is the one that is on a carbon that is more substituted with electron donating alkyl groups. In the final step the carbon radical abstracts a hydrogen atom from H-Br to start the chain reaction over again.



This reaction is favorable thermodynamically only for H-Br, not any of the other hydrogen halides.

Metal-Ammonia Reduction of Alkynes

To make *trans*-alkenes, we use a dissolving metal reduction with either sodium or lithium in liquid ammonia. Ammonia is a gas at room temperature but has a boiling point of -38°C. It is a convenient solvent at low temperatures since it also provides a source of protons in the strongly basic reaction conditions. The actual reducing agent is an electron donated by the lithium or sodium metal to the liquid ammonia solution.



Sodium metal donates one electron to the triple bond forming a radical anion.

The (-) charge and the lone electron are in a *trans* relationship so that they are as far apart as possible and e$^-$-e$^-$ repulsion is minimized.

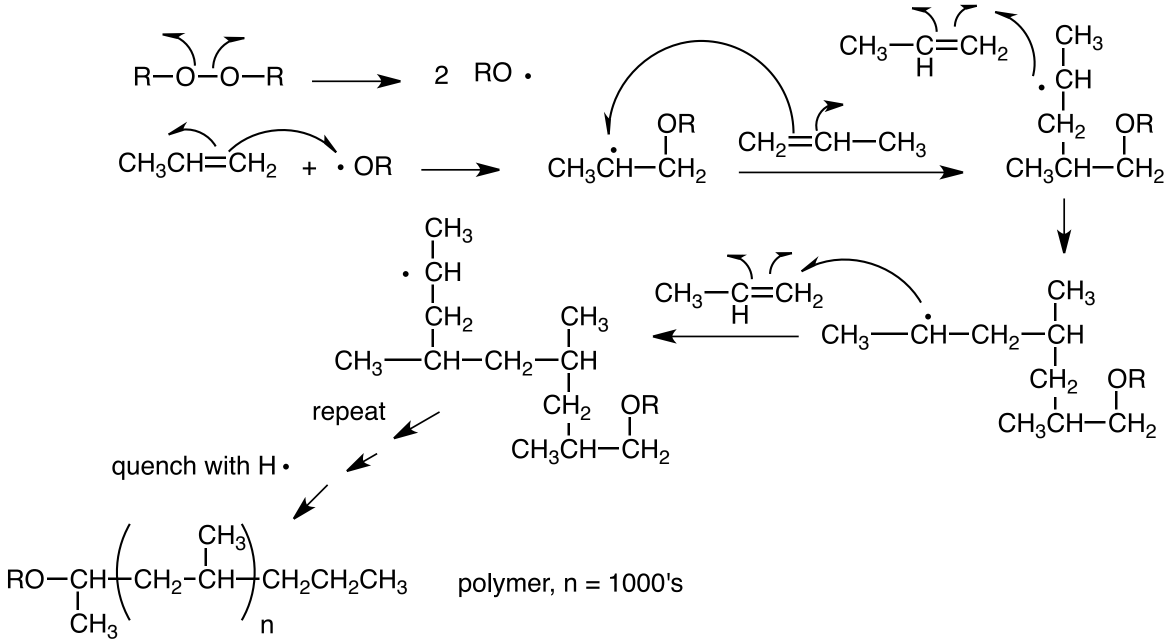
The radical anion is a very strong base and takes a proton from NH_3.

Another molecule of sodium donates a second electron to make an anion which then abstracts a proton from the solvent NH_3.

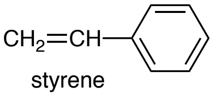
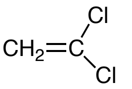
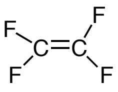
Free Radical Polymerization of Alkenes

We can also see free radical polymerization in the presence of a radical initiator such as a peroxide. In the example below we polymerize propene to make polypropylene.

Polypropylene fibers are used in carpets and automobile tires, consumer items such as luggage and appliances and packaging materials. The properties will vary depending on the length of the polymer chain. The length of the chain can be controlled by varying the reaction time. The reaction is stopped by adding a hydrogen atom ($H^{\cdot}$) source as a termination step in the free radical chain mechanism. The radical initiator can be removed from the polymer at the end of the reacti



There are many polymers that can be made from ethylene derivatives.

Monomer	polymer	application
$CH_2{=}CH_2$ ethylene	polyethylene	polyethyl films are used as packing material such as "plastic" bags and also as "plastic" bottles.
 styrene	polystyrene	polystyrene packaging material, coffee cups, insulated containers, etc.
$CH_2{=}CH-Cl$ vinyl chloride	polyvinyl chloride (PVC)	PVC is used in place of leather in many applications, used in tubing and pipes in place of copper
 1,1-dichloride ethene (vinylidene chloride)		"Saran" wrap, used in packaging
 tetraflouroethene	$-\!\left(CF_2-CF_2\right)_n\!-$ Teflon	Non-stick surfaces for cooking utensils, fittings, etc.