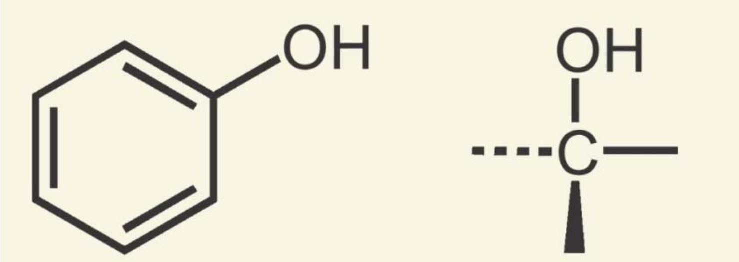
Alcohols, and Phenols

Alcohols and Phenols

- Alcohols contain an OH group connected to a a saturated C (sp^3)
- They are important solvents and synthesis intermediates
- Phenols contain an OH group connected to a carbon in a benzene ring
- Methanol, CH_3OH, called methyl alcohol, is a common solvent, a fuel additive, produced in large quantities
- Ethanol, CH_3CH_2OH, called ethyl alcohol, is a solvent, fuel, beverage
- Phenol, C_6H_5OH ("phenyl alcohol") has diverse uses - it gives its name to the general class of compounds



Phenol

An alcohol

Alcohols, and Phenols

- ➢ Alcohols and phenols may be viewed as organic derivatives of water.

$H{-}O{-}H$	$R{-}O{-}H$	$Ar{-}O{-}H$
Water	Alcohol	Phenol

- ➢ Alcohols and phenols have a common functional group, the hydroxyl group, -OH.

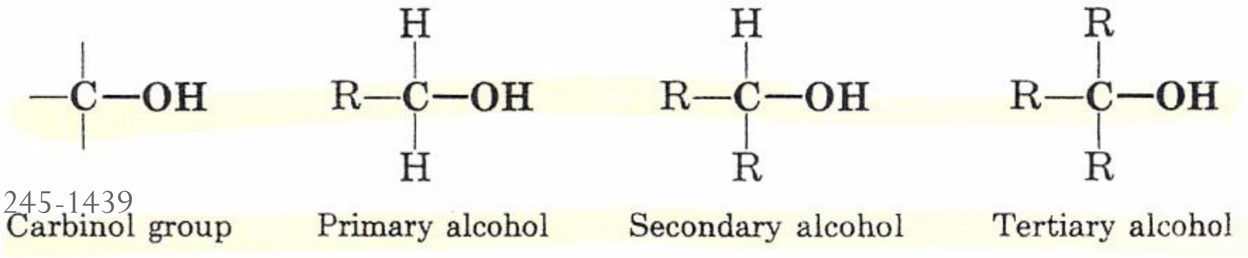
In alcohols the hydroxyl group is attached to an alkyl group, -R.

In phenols the hydroxyl function is attached to an aromatic ring, Ar.

Classification and Nomenclature of Alcohols

Alcohols are subdivided into three classes: depends on the number of alkyl groups bonded to the carbon bearing the —OH, the so-called carbinol carbon

primary (1°), secondary (2), and tertiary (3°).



$$\begin{array}{cccc} \begin{array}{c} | \\ -C-OH \\ | \end{array} & \begin{array}{c} H \\ | \\ R-C-OH \\ | \\ H \end{array} & \begin{array}{c} H \\ | \\ R-C-OH \\ | \\ R \end{array} & \begin{array}{c} R \\ | \\ R-C-OH \\ | \\ R \end{array} \end{array}$$

Carbinol group Primary alcohol Secondary alcohol Tertiary alcohol

The *common names* for the simplest alcohols consist of

- ☐ alkyl group attached to the hydroxyl function followed by the word *alcohol*. Alkyl *alcohol*

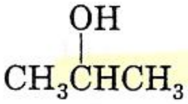
Primary alcohols

CH_3OH
Methyl alcohol

CH_3CH_2OH
Ethyl alcohol

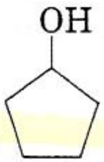
$CH_2{=}CHCH_2OH$
Allyl alcohol

Secondary alcohols



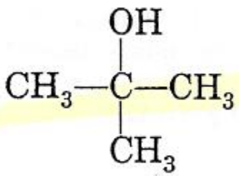
$CH_3CH(OH)CH_3$

Isopropyl alcohol



Cyclopentyl alcohol

Tertiary alcohol



$CH_3{-}C(OH)(CH_3){-}CH_3$

t-Butyl alcohol

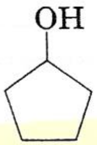
- ☐ In the *IUPAC system*, alcohols are named according to the following rules.

1. Select the longest continuous carbon chain that *contains the* -OH *group*.

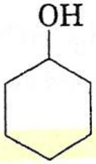
Drop the *–e* ending of the parent alkane and replace it by the suffix *-ol*.

CH_3OH
Methanol
(primary alcohol)

CH_3CH_2OH
Ethanol
(primary alcohol)



Cyclopentanol
(secondary alcohol)



Cyclohexanol
(secondary alcohol)

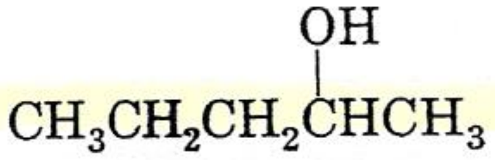
2. When isomers are possible,

the chain is numbered so as to give the functional group (-OH) the *lowest possible number.*

$CH_3CH_2CH_2OH$

1-Propanol

(*not* 3-Propanol)



$CH_3CH_2CH_2\overset{\overset{OH}{|}}{C}HCH_3$

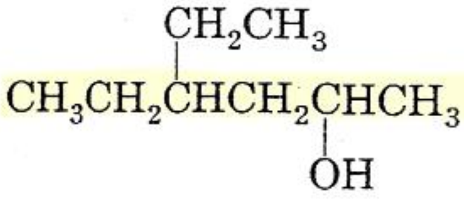
2-Pentanol

(*not* 4-Pentanol)

3. When alkyl side chains or other groups are present,

they are named alphabetically and their positions are indicated by a number.

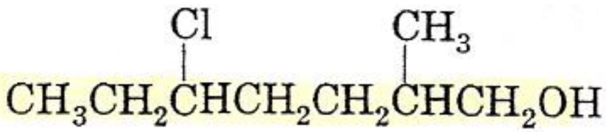
The position of the functional group (-OH) is always given the lowest possible number at the end of the name.



$CH_3CH_2\overset{\overset{CH_2CH_3}{|}}{C}HCH_2\underset{\underset{OH}{|}}{C}HCH_3$

4-Ethyl-2-hexanol

(*not* 3-Ethyl-5-hexanol)

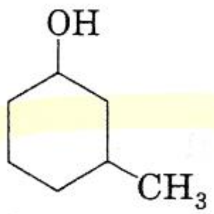


$CH_3CH_2\overset{\overset{Cl}{|}}{C}HCH_2CH_2\overset{\overset{CH_3}{|}}{C}HCH_2OH$

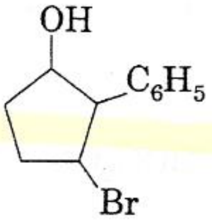
5-Chloro-2-methyl-1-heptanol

(*not* 3-Chloro-6-methyl-7-heptanol)

For cyclic alcohols, numbering always starts from the carbon bearing the -OH group.



3-Methylcyclohexanol
(*not* 1-Methyl-3-cyclohexanol)

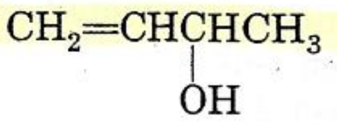


3-Bromo-2-phenylcyclopentanol
(*not* 1-Bromo-2-phenyl-3-cyclopentanol)

4. If a molecule contains both an -OH group and a C=C or C-C triple bond,

The -OH group takes preference before the double or triple bonds in getting the lower number.

The name should include (if possible) both the hydroxyl and the unsaturated groups, even if *this does not make the longest chain the parent hydrocarbon.*

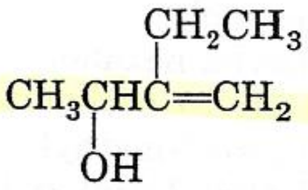


$$CH_2{=}CH\underset{\substack{|\\ OH}}{C}HCH_3$$

3-Buten-2-ol
(*not* 1-Buten-3-ol)

$HC{\equiv}CCH_2CH_2OH$

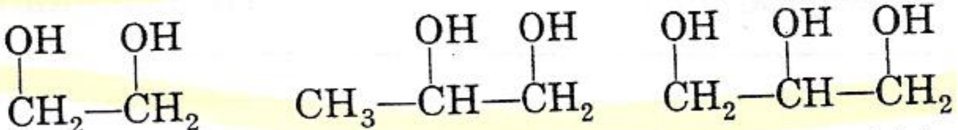
3-Butyn-1-ol
(*not* 1-Butyn-4-ol)



$$CH_3\underset{\substack{|\\ OH}}{C}H\overset{\substack{CH_2CH_3\\ |}}{C}{=}CH_2$$

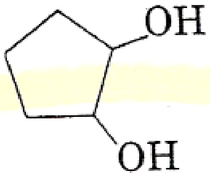
3-Ethyl-3-buten-2-ol
(longest chain including C=C)

- **Some alcohols contain more than one hydroxyl group.**
- **The *suffix* -diol is added to the name of the parent hydrocarbon when two hydroxyl groups are present, and the *suffix* -triol is added when there are three -OH groups.**
- **those containing two -OH groups on adjacent carbons are known as 1,2-glycols.**



$$\overset{OH}{CH_2}-\overset{OH}{CH_2} \qquad CH_3-\overset{OH}{CH}-\overset{OH}{CH_2} \qquad \overset{OH}{CH_2}-\overset{OH}{CH}-\overset{OH}{CH_2}$$

IUPAC name: 1,2-Ethanediol; 1,2-Propanediol; 1,2,3-Propanetriol
Common name: Ethylene glycol; Propylene glycol; Glycerol or Glycerin

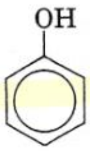


IUPAC name: 1,2-Cyclopentanediol

- **Alcohols that contain more than three hydroxyl groups per molecule are known as polyols.**

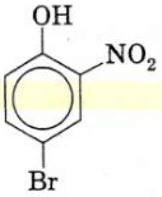
Nomenclature of Phenols

- **Phenols are generally named as derivatives of the simplest member of the family, phenol.**

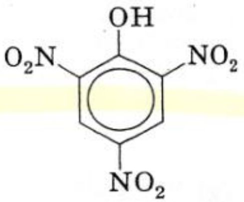


Phenol
(Carbolic acid)

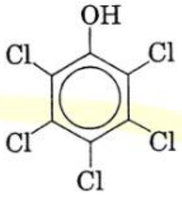
p-Aminophenol



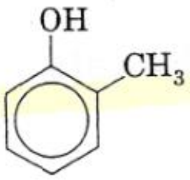
4-Bromo-2-nitrophenol



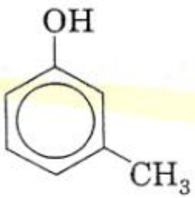
2,4,6-Trinitrophenol
(Picric acid)



Pentachlorophenol



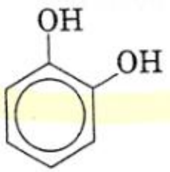
o-Cresol



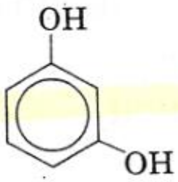
m-Cresol

p-Cresol

- **Several important *__hydroxysubstituted phenols__* also have common names.**

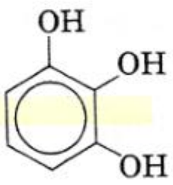


Catechol
(germicide)



Resorcinol
(antiseptic)

Hydroquinone



Pyrogallol
(photographic film developers)

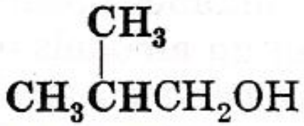
Physical Properties of Alcohols and Phenols

- The simplest alcohol, methanol, is a liquid at room temperature. The lower alcohols are completely miscible with water.
- As the number of carbons in the alcohol increases, the solubility in water decreases.
- Series of normal alcohols,

  The boiling points increase with increase in molecular weights and decreased as the number of branched alkyl group increased.
- A comparison of boiling points among isomeric alcohols;

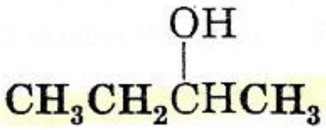
$CH_3CH_2CH_2CH_2OH$

1-Butanol
(mol wt = 74; bp = 118°C)



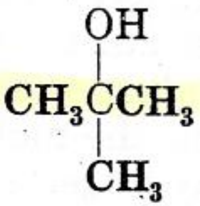
$CH_3\overset{\overset{\displaystyle CH_3}{|}}{C}HCH_2OH$

2-Methyl-1-propanol
(mol wt = 74; bp = 108°C)



$CH_3CH_2\overset{\overset{\displaystyle OH}{|}}{C}HCH_3$

2-Butanol
(mol wt = 74; bp = 99.5°C)



$CH_3\underset{\underset{\displaystyle CH_3}{|}}{\overset{\overset{\displaystyle OH}{|}}{C}}CH_3$

2-Methyl-2-propanol
(mol wt = 74; bp = 83°C)

- The straight-chain isomers have larger molecular surfaces than do their branched-chain isomers.

Therefore, they have higher intermolecular interactions and, as a result, higher boiling points.

- The high values of the boiling points of alcohols compared with alkanes of similar molecular weights.

$CH_3CH_2CH_3$
Propane
(mol wt = 44; bp = −42°C)

CH_3CH_2OH
Ethanol
(mol wt = 46; bp = 78°C)

- The O—H bond and not to the presence of oxygen can be proved by comparing the boiling point of ethanol with Alcohols, Phenols, that of its structural isomer, methyl ether:

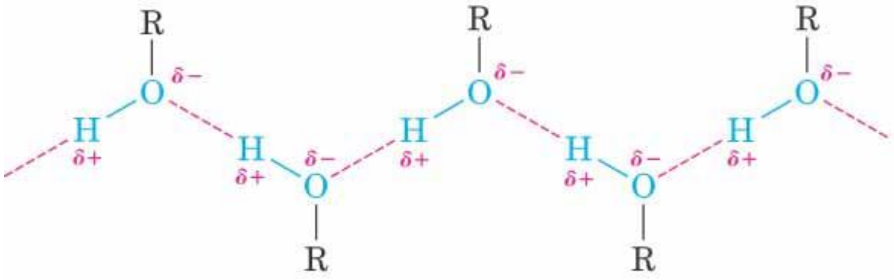
CH_3CH_2OH
Ethanol
(mol wt = 46; bp = 78°C)

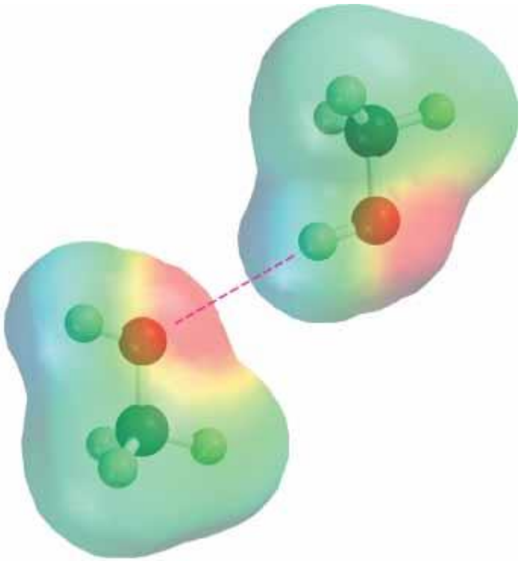
CH_3OCH_3
Methyl ether
(mol wt = 46; bp = −24°C)

- Therefore, the large increase in boiling points of alcohols compared with alkanes (or ethers) also must be due to the O—H group.

Alcohols Form Hydrogen Bonds

- A positively polarized —OH hydrogen atom from one molecule is attracted to a lone pair of electrons on a negatively polarized oxygen atom of another molecule
- This produces a force that holds the two molecules together
- These intermolecular attractions are present in solution but not in the gas phase, thus elevating the boiling point of the solution





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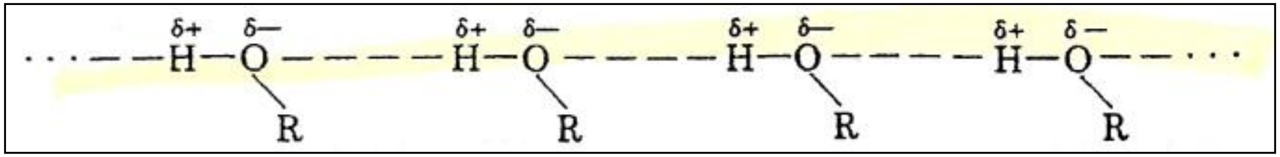
- *Hydrogen Bonding*

The effect of the OH group on the physical properties of alcohols can be explained as follows.

The O—H bond is *highly polar*.

The oxygen, a highly electronegative atom carries a partial negative charge (δ-), and the hydrogen a partial positive charge (δ+).



Hydrogen bonding accounts also for the differences in physical states between lower alcohols and lower alkanes.

Hydrogen bonding also explains the solubility of the lower alcohols in water.

When those alcohols are mixed with water,

They dissolve because of hydrogen bonding between the OH bond of the alcohol and the hydroxyl group of the water.

<u>As the number of carbons in an alcohol increases,</u>

The nonpolar alkyl group becomes more and more important and the polar OH group becomes less important.

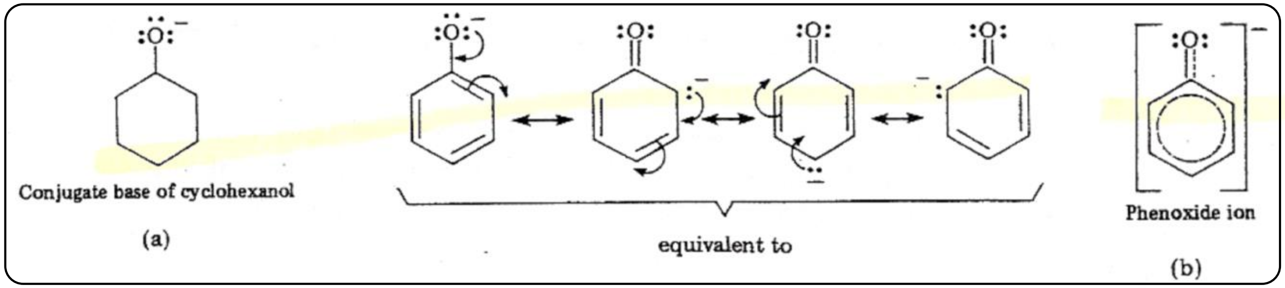
Phenols

Phenol is a colorless, crystalline, low-melting solid, with a high boiling point, that is moderately soluble in water.

Most other phenols also are solids, with slight solubility in water and high boiling points.

The most significant physical property that distinguishes alcohols from phenols is the *acidity* of phenols.

Acidities of Phenols and Alcohols Compared



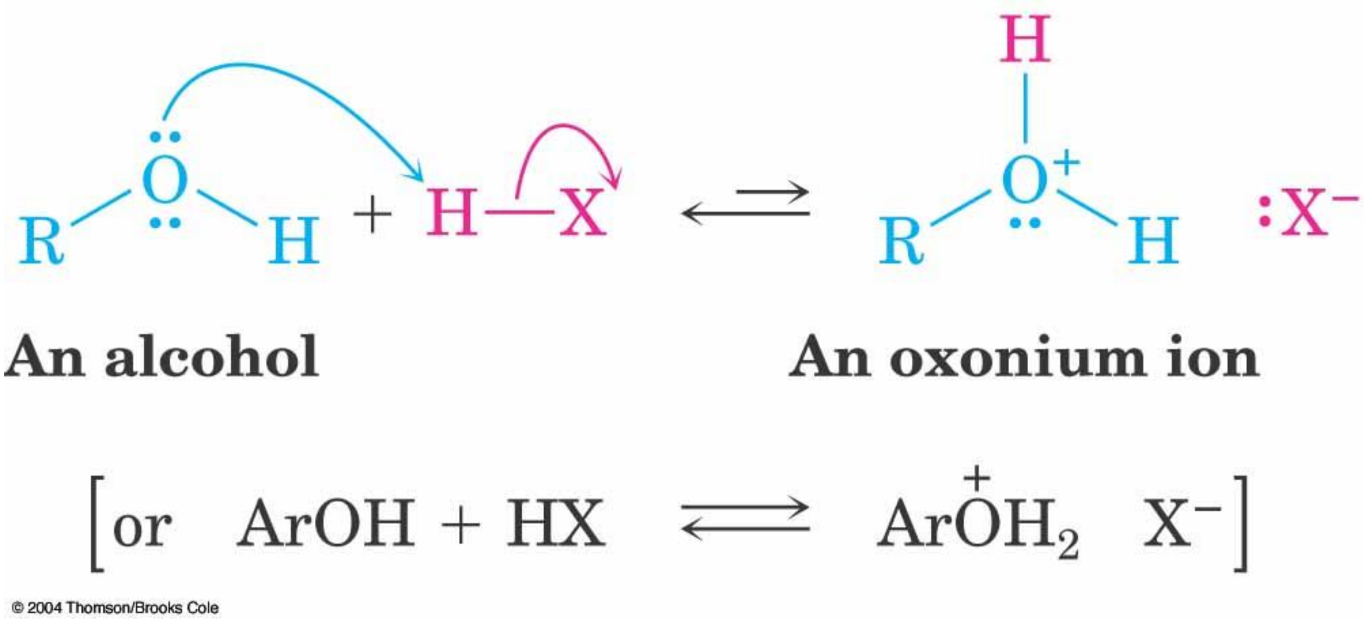
Why is the phenoxide ion more stable?

Because the negative charge on the oxygen is *dispersed* by *resonance* through the benzene ring.

No such delocalization of charge can take Place for the conjugate base of cyclohexanol

Properties of Alcohols and Phenols: Acidity and Basicity

- Weakly basic and weakly acidic
- Alcohols are weak Brønsted bases
- Protonated by strong acids to yield oxonium ions, ROH_2^+



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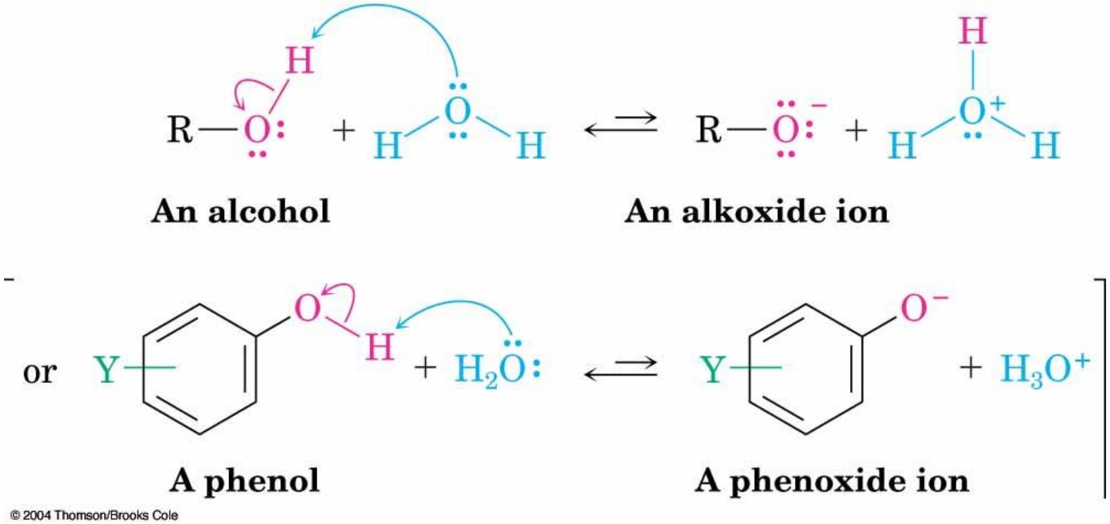
- Can transfer a proton to water to a very small extent
- Produces H_3O^+ and an **alkoxide ion, RO^-**, or a **phenoxide ion, ArO^-**



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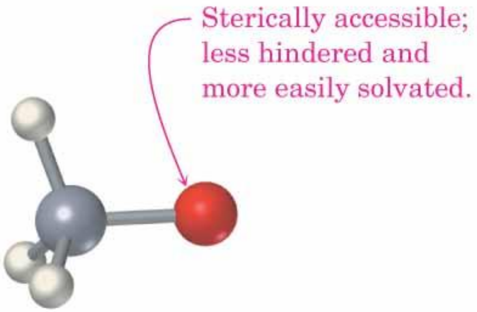
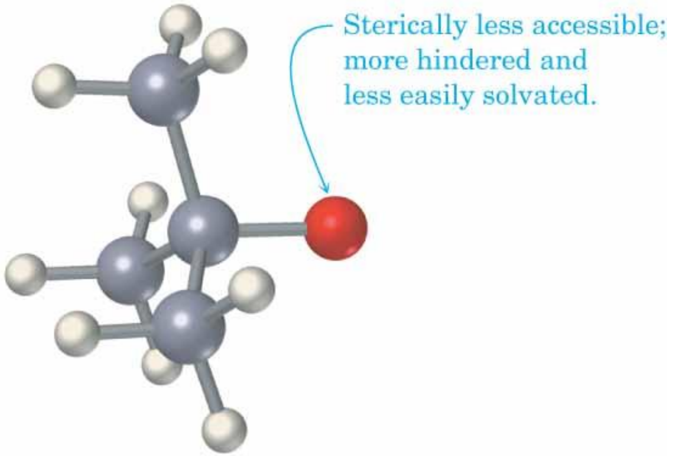
Relative Acidities of Alcohols

- Simple alcohols are about as acidic as water
- Alkyl groups make an alcohol a weaker acid
- The more easily the alkoxide ion is solvated by water the more its formation is energetically favored
- Steric effects are important



Sterically accessible; less hindered and more easily solvated.

Methoxide ion, CH_3O^-
(pK_a = 15.54)



Sterically less accessible; more hindered and less easily solvated.

***tert*-Butoxide ion, $(CH_3)_3CO^-$**
(pK_a = 18.00)

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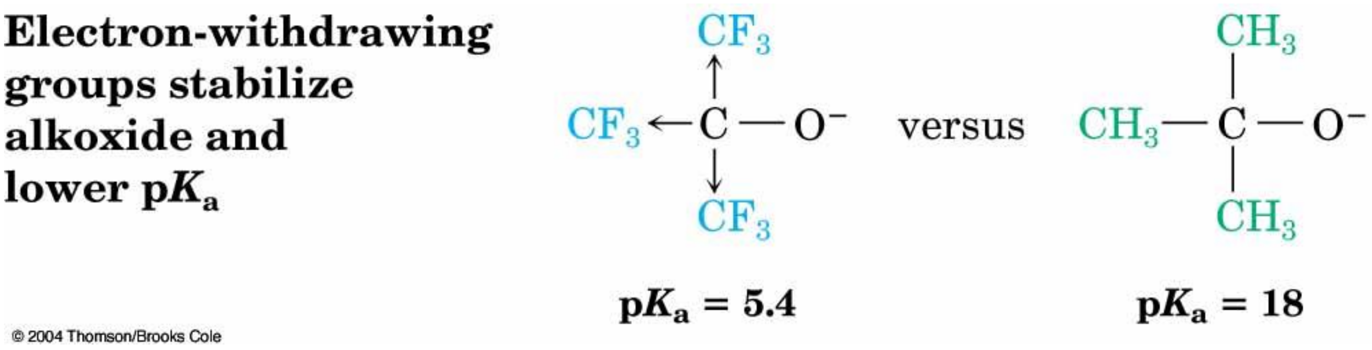
Inductive Effects

- Electron-withdrawing groups make an alcohol a stronger acid by stabilizing the conjugate base (alkoxide)



Electron-withdrawing groups stabilize alkoxide and lower p*K*$_a$

$$CF_3 \leftarrow \overset{\displaystyle CF_3 \atop \uparrow}{\underset{\displaystyle \downarrow \atop CF_3}{C}} - O^- \quad \text{versus} \quad CH_3 - \overset{\displaystyle CH_3 \atop |}{\underset{\displaystyle | \atop CH_3}{C}} - O^-$$

$pK_a = 5.4$ $pK_a = 18$

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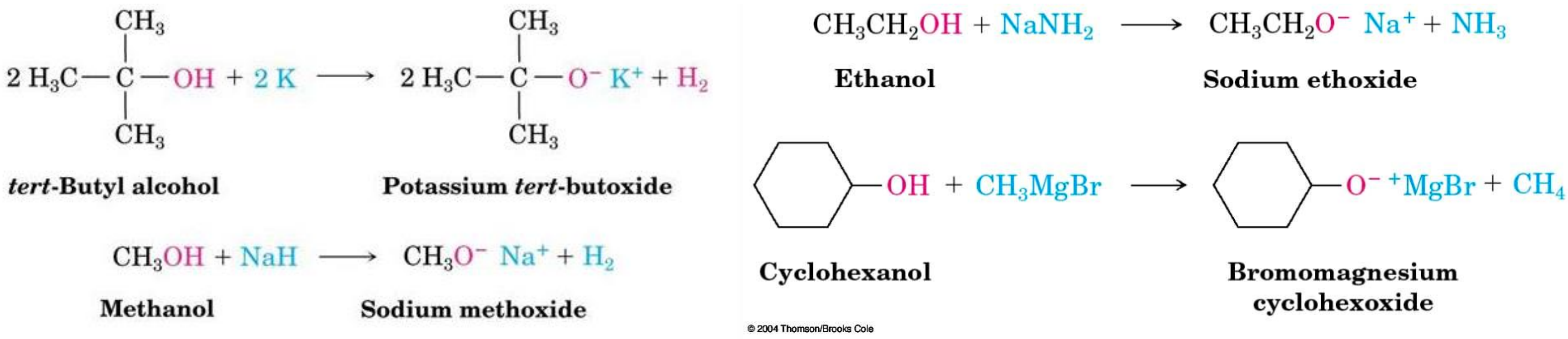
Generating Alkoxides from Alcohols

- Alcohols are weak acids – requires a strong base to form an alkoxide such as NaH, sodium amide $NaNH_2$, and Grignard reagents (RMgX)
- Alkoxides are bases used as reagents in organic chemistry



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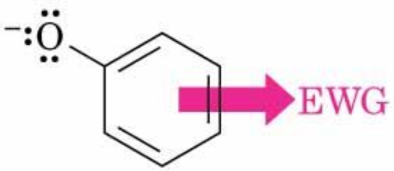
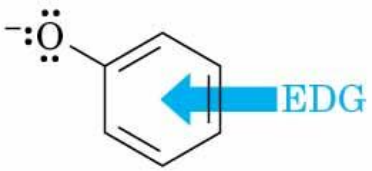
Substituted Phenols

- Can be more or less acidic than phenol itself
- An electron-withdrawing substituent makes a phenol more acidic by delocalizing the negative charge
- Phenols with an electron-donating substituent are less acidic because these substituents concentrate the charge



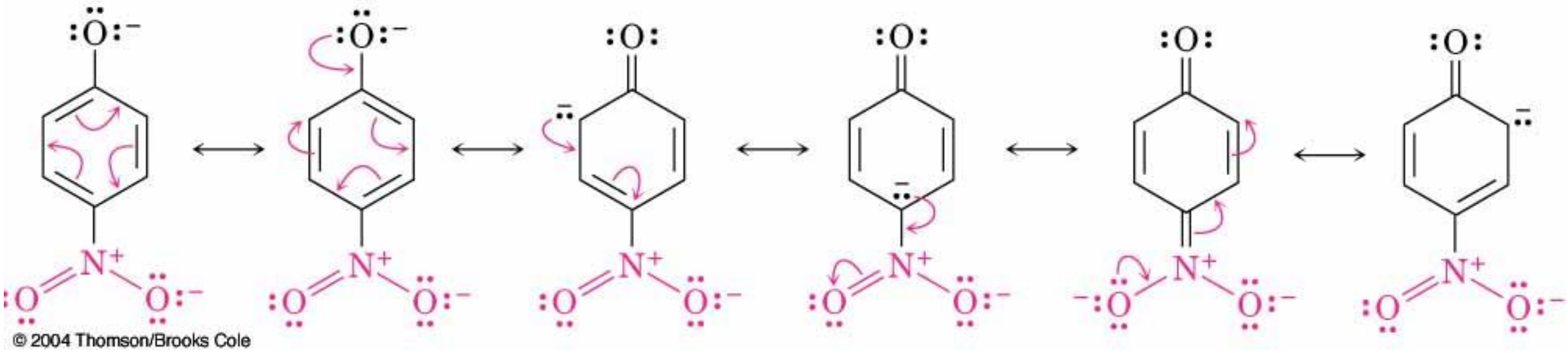
Electron-withdrawing groups (EWG) stabilize phenoxide anion, resulting in increased phenol acidity



Electron-donating groups (EDG) destabilize phenoxide anion, resulting in decreased phenol acidity

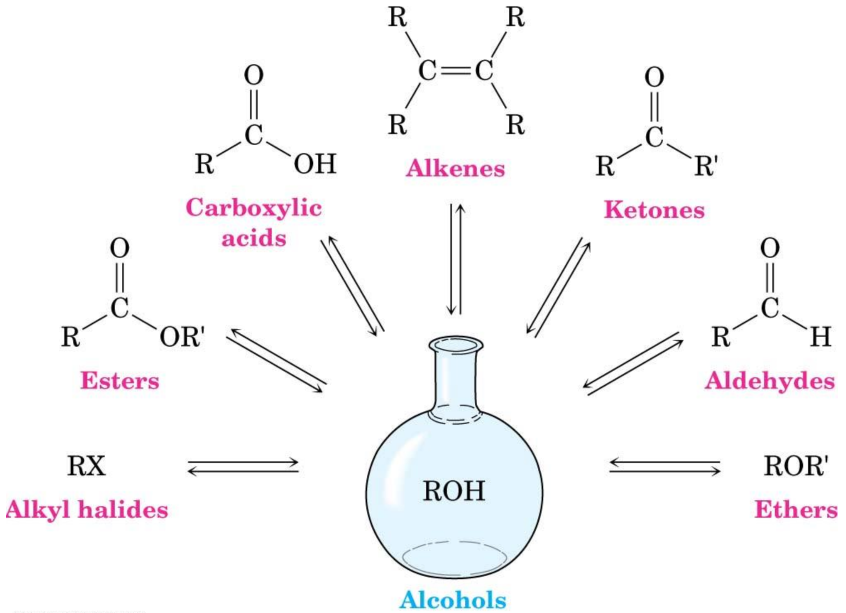
Nitro-Phenols

- Phenols with nitro groups at the ortho and para positions are much stronger acids
- The pKa of 2,4,6-trinitrophenol is 0.6, a very strong acid



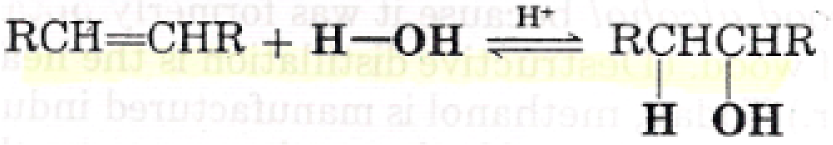
Preparation of Alcohols

- Alcohols are derived from many types of compounds
- The alcohol hydroxyl can be converted to many other functional groups
- This makes alcohols useful in synthesis



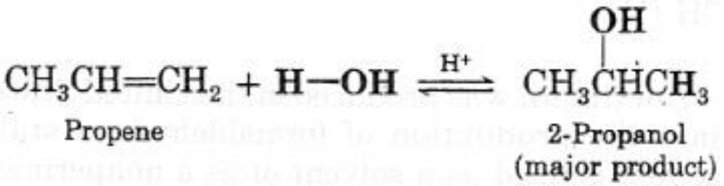
A. Hydration of Alkenes

1. **Addition of water to a double bond in the presence of an *acid catalyst, H^+*.**



$$RCH{=}CHR + H{-}OH \overset{H^+}{\rightleftharpoons} \underset{\substack{| \\ H}}{RCH}\underset{\substack{| \\ OH}}{CHR}$$

2. **The addition follows *Markovnikov's rule*.**



$$CH_3CH{=}CH_2 + H{-}OH \overset{H^+}{\rightleftharpoons} CH_3\overset{\substack{OH \\ |}}{C}HCH_3$$

Propene

2-Propanol
(major product)

3. ***It is not possible to prepare primary alcohols* except Ethanol.**

B. Hydroboration-Oxidation

The addition of diborane, B_2H_6, followed by *oxidation* with alkaline hydrogen peroxide.

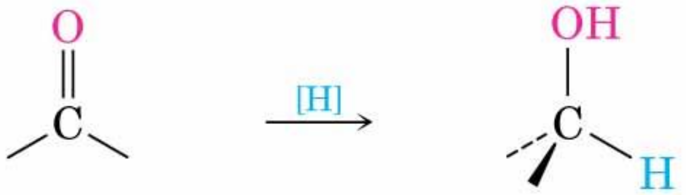
$$CH_3CH{=}CH_2 \xrightarrow[\text{(2) } H_2O_2,\ NaOH]{\text{(1) } B_2H_6} CH_3CH_2CH_2OH$$

Propene 1-Propanol

The net result is the addition of H_2O across C=C in an *anti-Markovnikov* manner.

Alcohols from Reduction of Carbonyl Compounds

- Reduction of a carbonyl compound in general gives an alcohol
- Note that organic reduction reactions add the equivalent of H_2 to a molecule



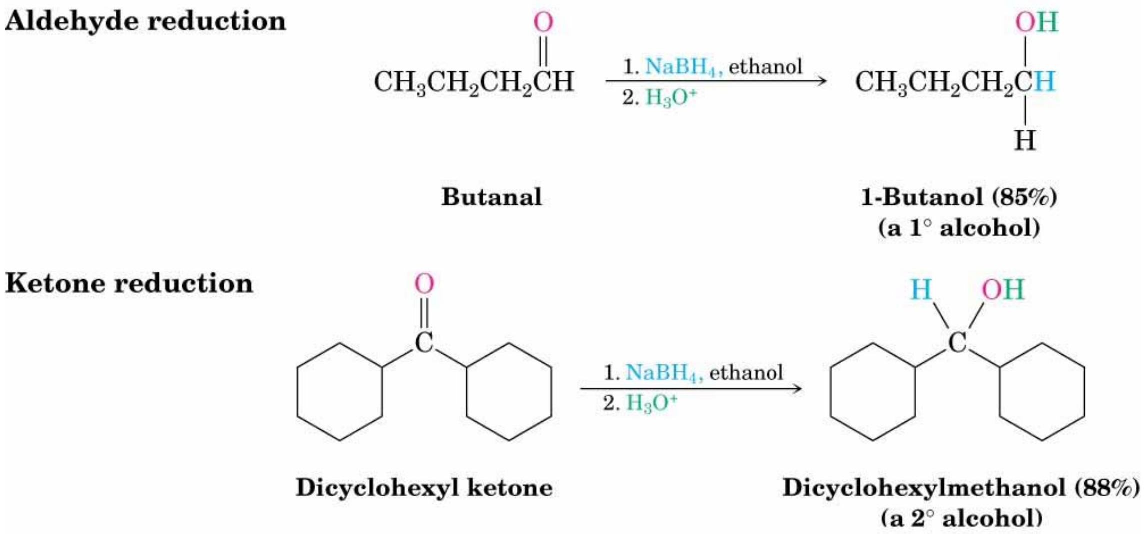
where [H] is a generalized reducing agent

A carbonyl compound

An alcohol

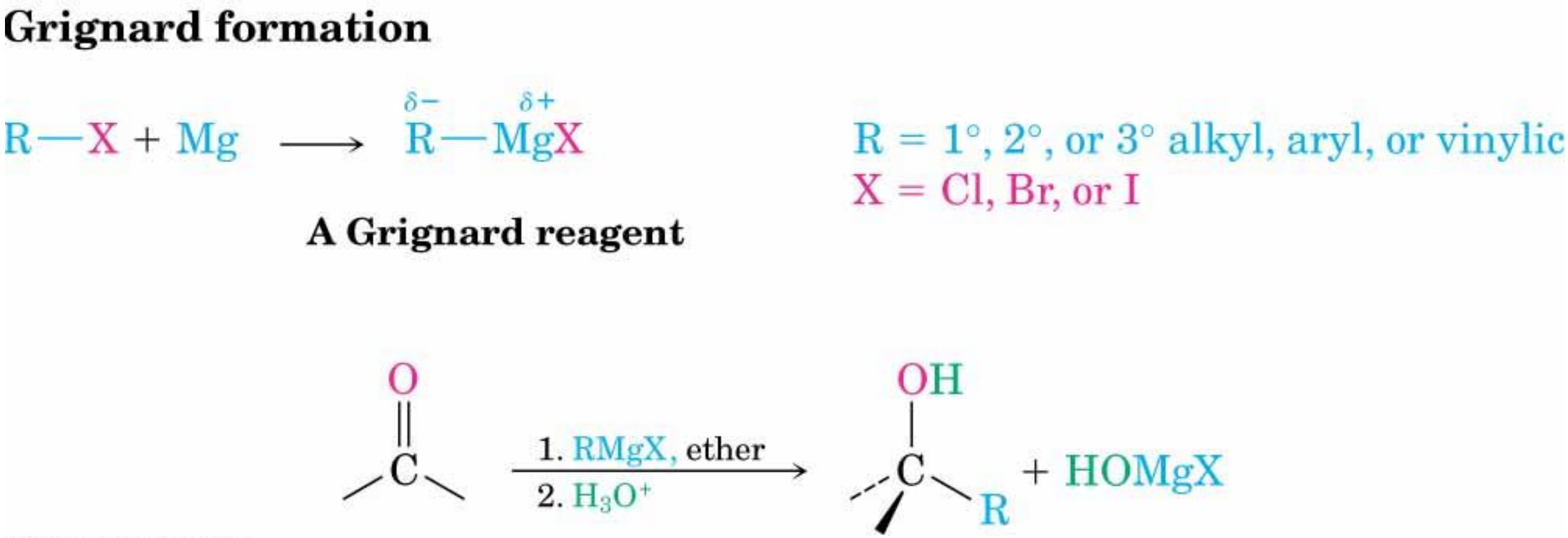
Reduction Reagent: Sodium Borohydride

- $NaBH_4$ is not sensitive to moisture and it does not reduce other common functional groups
- Lithium aluminum hydride ($LiAlH_4$) is more powerful, less specific, and very reactive with water
- Both add the equivalent of "H^-"



Alcohols from Reaction of Carbonyl Compounds with Grignard Reagents

- Alkyl, aryl, and vinylic halides react with magnesium in ether or tetrahydrofuran to generate Grignard reagents, RMgX
- Grignard reagents react with carbonyl compounds to yield alcohols



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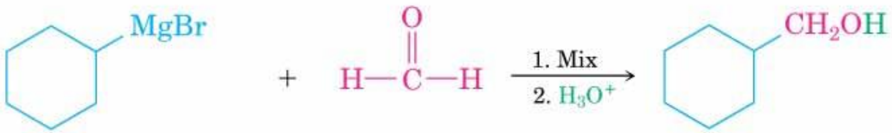
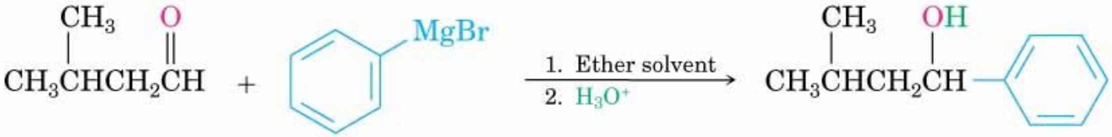
Examples of Reactions of Grignard Reagents with Carbonyl Compounds

Formaldehyde reaction



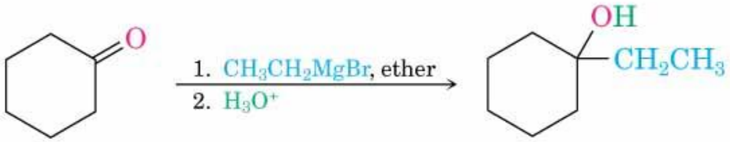
Cyclohexylmagnesium bromide   **Formaldehyde**   **Cyclohexylmethanol (65%)**
(a 1° alcohol)

Aldehyde reaction



3-Methylbutanal   **Phenylmagnesium bromide**   **3-Methyl-1-phenyl-1-butanol (73%)**
(a 2° alcohol)

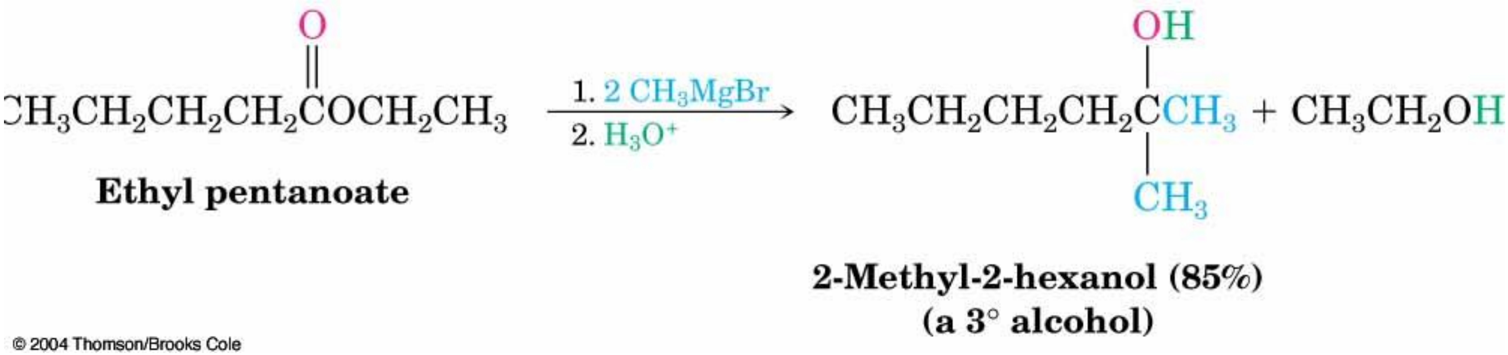
Ketone reaction



Cyclohexanone   **1-Ethylcyclohexanol (89%)**
(a 3° alcohol)

Reactions of Esters and Grignard Reagents

- Yields tertiary alcohols in which *two* of the substituents carbon come from the Grignard reagent
- Grignard reagents do not add to carboxylic acids – they undergo an acid-base reaction, generating the hydrocarbon of the Grignard reagent



$$CH_3CH_2CH_2CH_2\overset{\overset{O}{\|}}{C}OCH_2CH_3 \xrightarrow[2.\ H_3O^+]{1.\ 2\ CH_3MgBr} CH_3CH_2CH_2CH_2\underset{\underset{CH_3}{|}}{\overset{\overset{OH}{|}}{C}}CH_3 + CH_3CH_2OH$$

Ethyl pentanoate

2-Methyl-2-hexanol (85%)
(a 3° alcohol)

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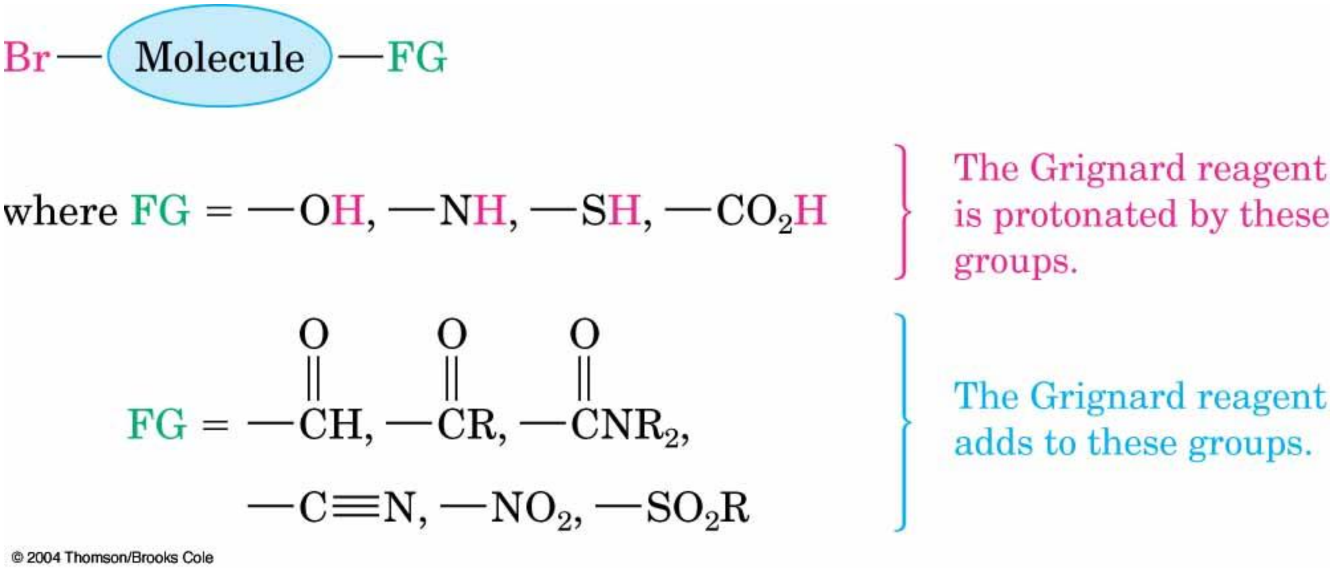
Grignard Reagents and Other Functional Groups in the Same Molecule

- Can't be prepared if there are reactive functional groups in the same molecule, including proton donors



Br—Molecule—FG

where FG = $-\text{OH}$, $-\text{NH}$, $-\text{SH}$, $-\text{CO}_2\text{H}$

The Grignard reagent is protonated by these groups.

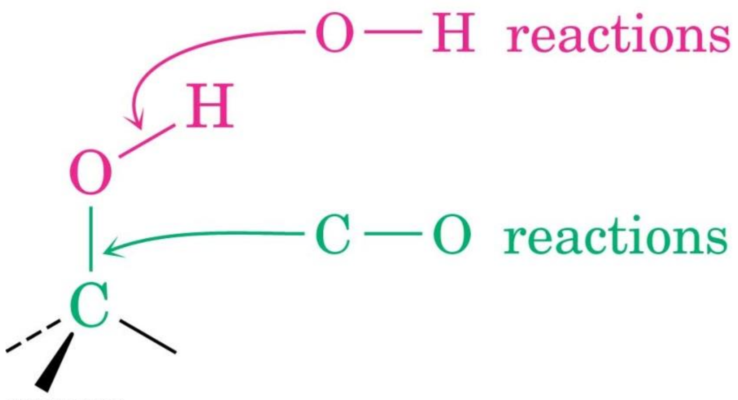
FG = $-\overset{\text{O}}{\overset{\|}{\text{C}}}\text{H}$, $-\overset{\text{O}}{\overset{\|}{\text{C}}}\text{R}$, $-\overset{\text{O}}{\overset{\|}{\text{C}}}\text{NR}_2$,

$-\text{C}\equiv\text{N}$, $-\text{NO}_2$, $-\text{SO}_2\text{R}$

The Grignard reagent adds to these groups.

Some Reactions of Alcohols

- Two general classes of reaction
  - At the carbon of the C–O bond
  - At the proton of the O–H bond



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- **Since alcohols are weaker acids than water**

it is not possible to form the salt of an alcohol in aqueous alkaline solutions.

$$\boxed{R{-}OH + Na^+\,OH^- \longrightarrow \text{No reaction}}$$

- **It is possible to form the salt by the action of active metals such as Na or K.**

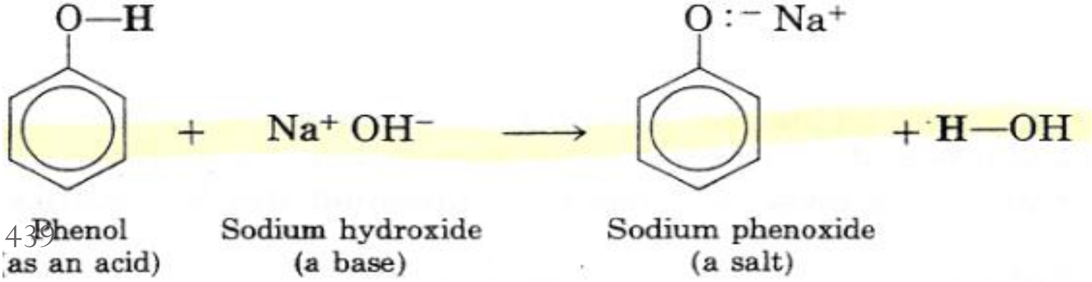
$$2\,CH_3O{-}\mathbf{H} + 2\,Na \longrightarrow 2\,CH_3O{:}^-\,Na^+ + \mathbf{H_2}\uparrow$$

Methanol Sodium methoxide

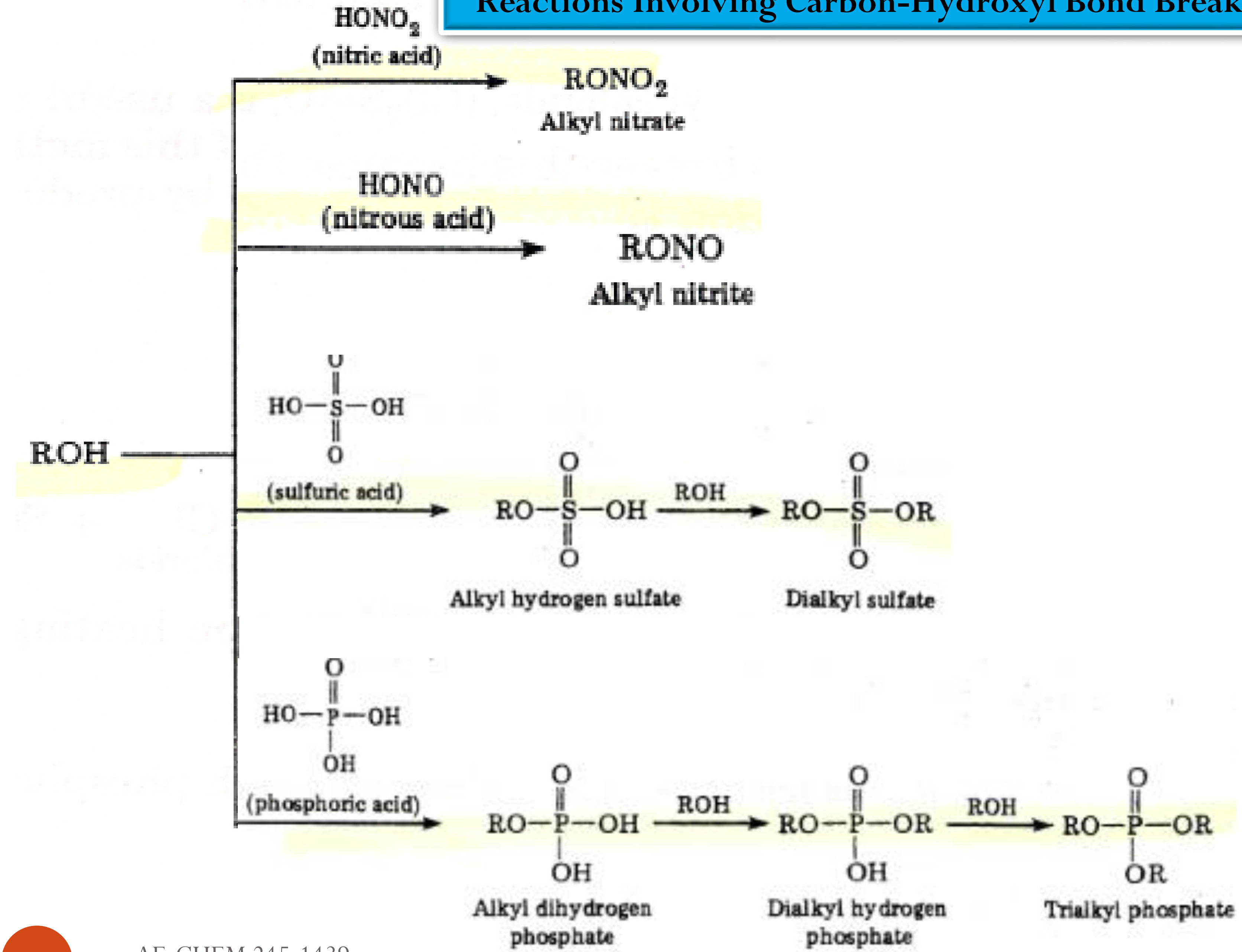
- **The action of metallic sodium on an alcohol is similar to the reaction of metallic sodium with water.**
- **Alkoxides are strong bases, even stronger than hydroxides.**

Alkoxides are used extensively in the synthesis of ethers

- **It is possible to obtain phenoxide salts from aqueous solutions of alkali.**



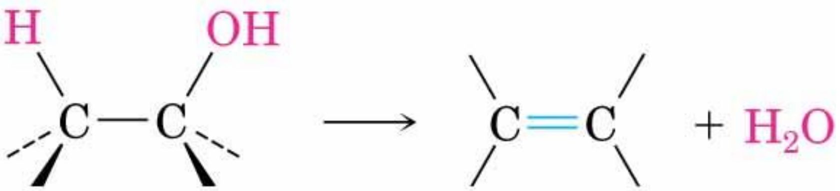
Reactions Involving Carbon-Hydroxyl Bond Breaking



Dehydration of Alcohols to Yield Alkenes

- The general reaction: forming an alkene from an alcohol through loss of O-H and H (hence dehydration) of the neighboring C–H to give π bond
- Specific reagents are needed

A dehydration reaction



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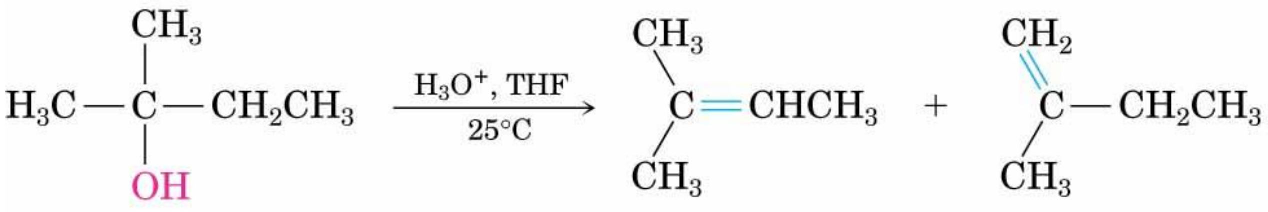
Acid- Catalyzed Dehydration

- Tertiary alcohols are readily dehydrated with acid
- Secondary alcohols require severe conditions (75% H_2SO_4, 100°C) - sensitive molecules don't survive
- Primary alcohols require very harsh conditions – impractical
- Reactivity is the result of the nature of the carbocation intermediate



2-Methyl-2-butanol

2-Methyl-2-butene (trisubstituted)

Major product

2-Methyl-1-butene (disubstituted)

Minor product

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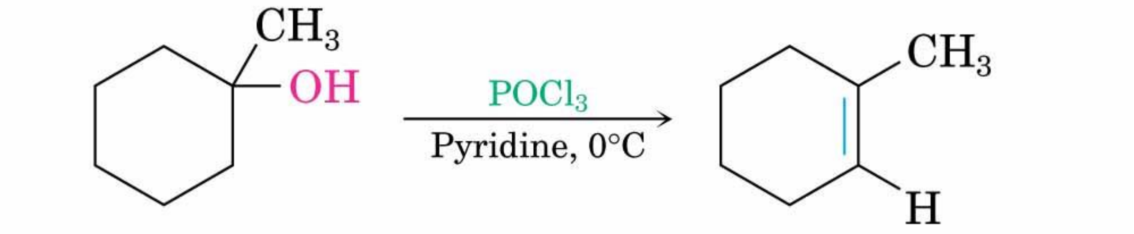
Dehydration with $POCl_3$

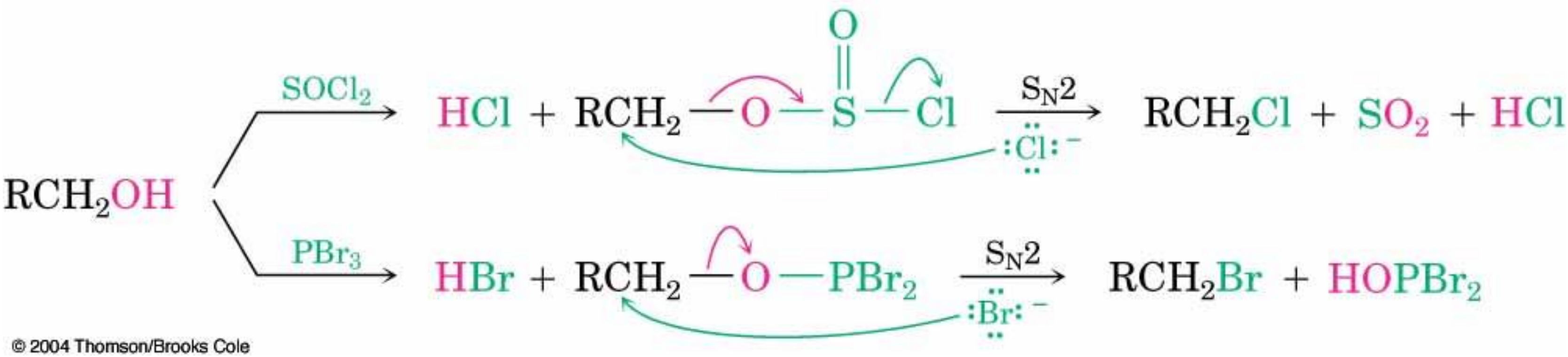
- Phosphorus oxychloride in the amine solvent pyridine can lead to dehydration of secondary and tertiary alcohols at low temperatures
- An E2 via an intermediate ester of $POCl_2$ (see Figure 17.6)



1-Methylcyclohexanol **1-Methylcyclohexene (96%)**

Conversion of Alcohols into Alkyl Halides

- 3° alcohols are converted by HCl or HBr at low temperature
- 1° and alcohols are resistant to acid – use $SOCl_2$ or PBr_3 by an S_N2 mechanism



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The hydroxyl group of alcohols can be replaced by halide to form alkyl halides.

$$\underset{\text{Alcohol}}{R{-}OH} \longrightarrow \underset{\text{Alkyl halide}}{R{-}X} \qquad (X = Cl,\ Br,\ \text{or}\ I)$$

The replacement of OH by halogen is applicable only to chlorides, bromides, and iodides.

Alkyl fluorides, R—F, are not prepared from alcohols.

Reaction with hydrogen halides: Lucas test.

Treatment of alcohols with aqueous concentrated hydrogen halides H-X, or with anhydrous H-X, give alkyl halides.

$$R{-}OH + H{-}X \rightleftharpoons R{-}X + H_2O \qquad (HX{=}HCl,\ HBr,\ \text{or}\ HI)$$

The reaction of halogen acids with various alcohols proceeds at different rates.

Tertiary alcohols react rapidly with hydrogen halides.

Secondary alcohols react somewhat slower.

Primary alcohols, even more slowly.

Lucas test for distinguishing among the three classes of alcohols.

The Lucas test is carried out as follows.

An alcohol is mixed, at room temperature, with concentrated HC1 and $ZnCl_2$ (catalyst).

The alkyl chloride, as it is formed, is insoluble in the medium and causes the solution to become cloudy before it separates as a distinct layer.

Tertiary alcohols react almost immediately.

$$\underset{\text{A 3° alcohol}}{R_3COH} + HCl \xrightarrow[25°C]{ZnCl_2} \underset{\text{(immediate cloudiness)}}{R_3CCl} + H_2O$$

Secondary alcohols, the cloudiness appears after about five minutes.

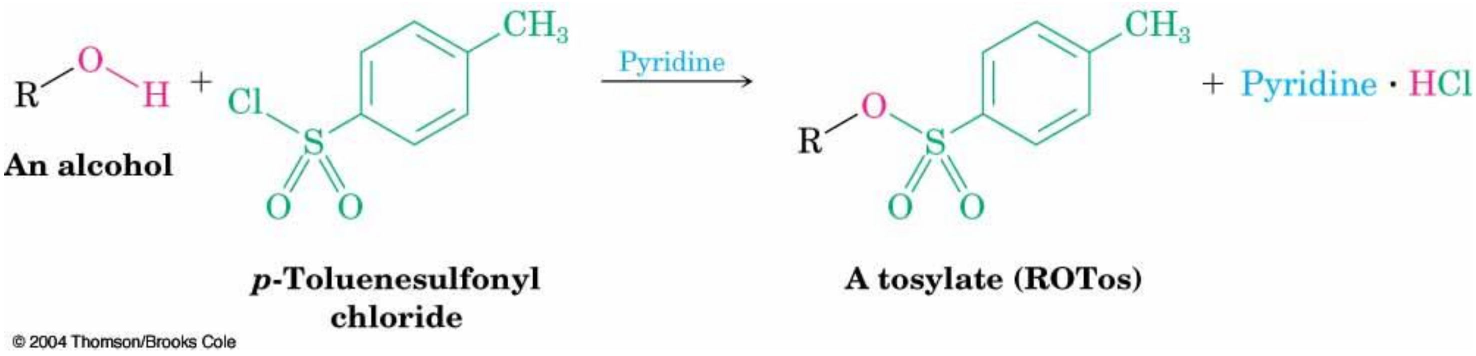
$$\underset{\text{A 2° alcohol}}{R_2CHOH} + HCl \xrightarrow[25°C]{ZnCl_2} \underset{\text{(cloudiness in 5 min)}}{R_2CHCl} + H_2O$$

Primary alcohols do not react under these conditions.

$$\underset{\text{A 1° alcohol}}{RCH_2OH} + HCl \xrightarrow[25°C]{ZnCl_2} \underset{\text{(solution remains clear)}}{\text{No visible reaction}}$$

Conversion of Alcohols into Tosylates

- Reaction with *p*-toluenesulfonyl chloride (tosyl chloride, *p*-TosCl) in pyridine yields alkyl tosylates, ROTos
- Formation of the tosylate does not involve the C–O bond so configuration at a chirality center is maintained
- Alkyl tosylates react like alkyl halides



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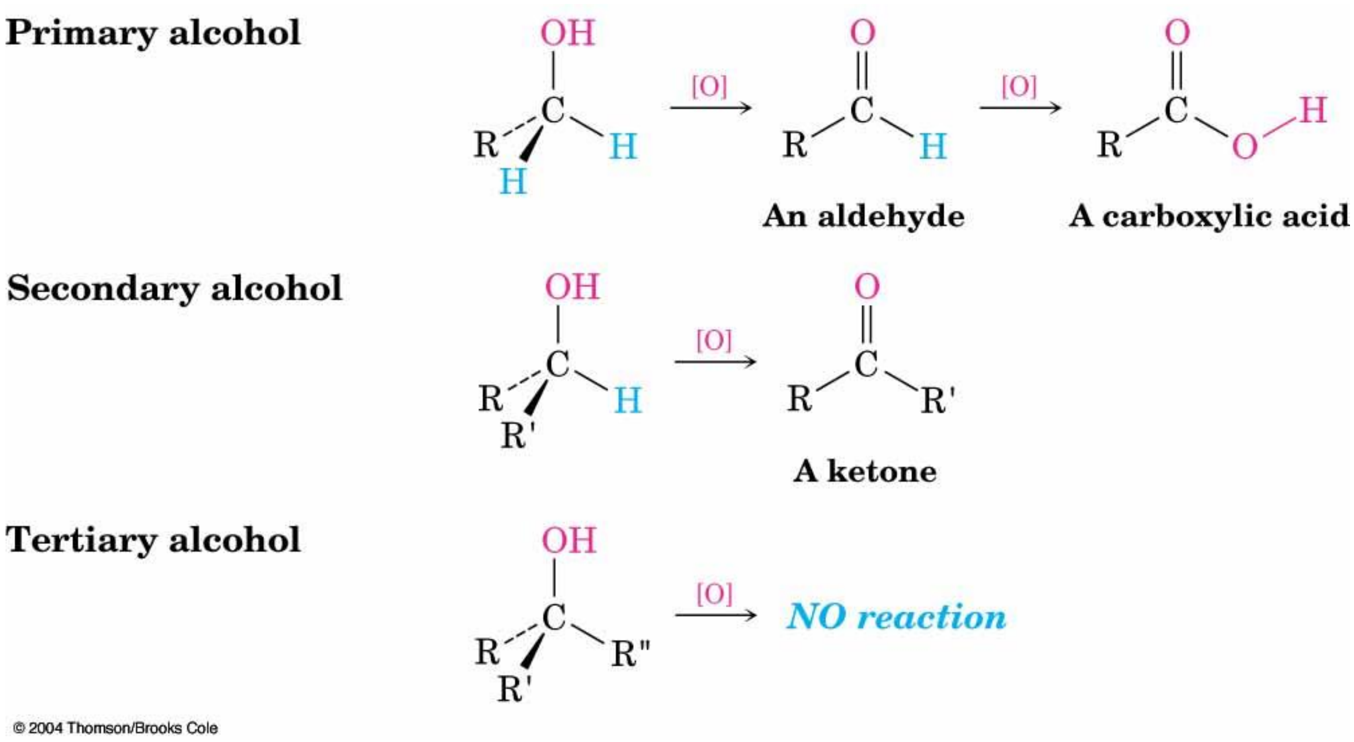
Oxidation of Alcohols

- Can be accomplished by inorganic reagents, such as $KMnO_4$, CrO_3, and $Na_2Cr_2O_7$ or by more selective, expensive reagents



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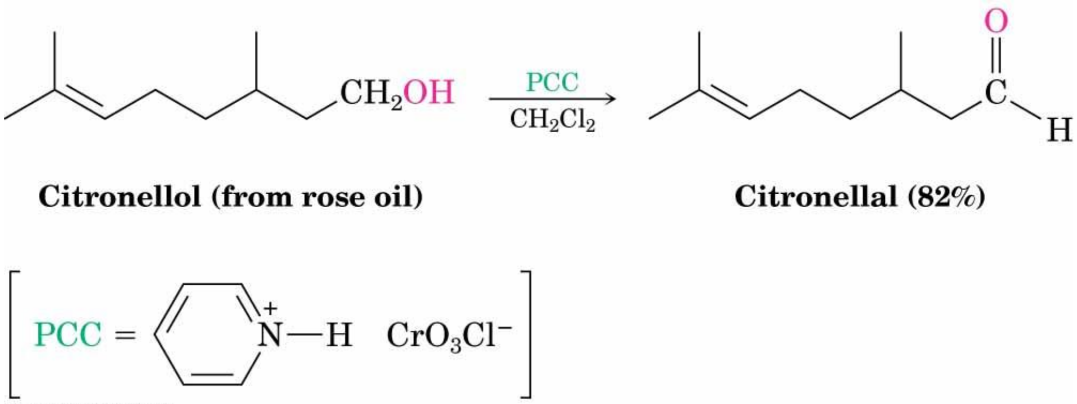
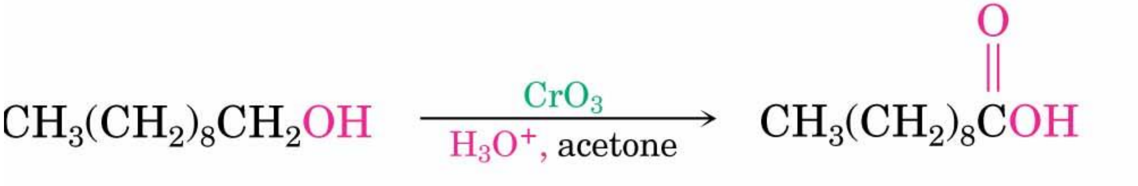
Oxidation of Primary Alcohols

- To aldehyde: pyridinium chlorochromate (PCC, $C_5H_6NCrO_3Cl$) in dichloromethane
- Other reagents produce carboxylic acids



Citronellol (from rose oil)

Citronellal (82%)



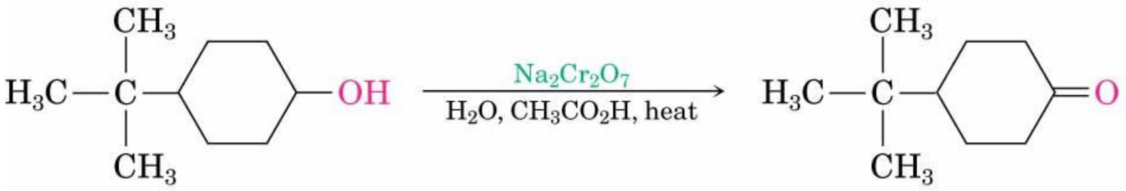
$$CH_3(CH_2)_8CH_2OH \xrightarrow[H_3O^+,\ \text{acetone}]{CrO_3} CH_3(CH_2)_8\overset{\overset{\displaystyle O}{\|}}{C}OH$$

1-Decanol

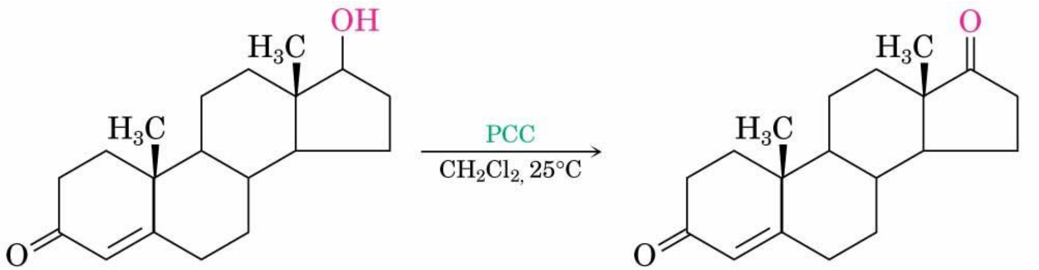
Decanoic acid (93%)

Oxidation of Secondary Alcohols

- Effective with inexpensive reagents such as $Na_2Cr_2O_7$ in acetic acid
- PCC is used for sensitive alcohols at lower temperatures



4-*tert*-Butylcyclohexanol → **4-*tert*-Butylcyclohexanone (91%)**



Testosterone
(steroid; male sex hormone)

4-Androstene-3,17-dione (82%)

Summary -Alcohols

- Synthesis
  - Reduction of aldehydes and ketones
  - Addition of Grignard reagents to aldehydes and ketones
- Protection of OH as TMS) ether
- Reactions
  - Conversion to alkyl halides
  - Dehydration
  - Oxidation