

# Chemistry 210 -- Winter Semester 1997

## Chapter 8

### The Hydroxyl Functional Group — Alcohols

#### Nomenclature

##### Nomenclature System I

Use the name of the hydrocarbon skeleton and add the ending -ol.

Example: The alcohol derived from ethane is ethanol



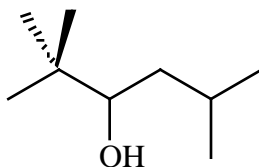
The location of the hydroxyl group is specified by a location number before the name.

Example: 1-propanol and 2-propanol



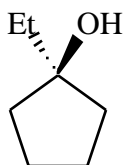
If there are other substituents, then they are added as prefix.

Example: 2,2,5-trimethyl-3-hexanol

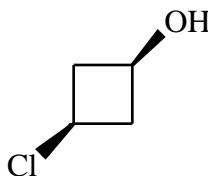


Cyclic alcohols are dealt with in the same way.

Example: 1-Ethylcyclopentanol



Example: *cis*-3-chloro-cyclobutanol



### **Nomenclature System II**

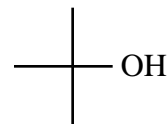
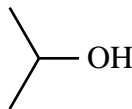
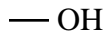
Use the name of the alkyl group and add the ending alcohol.

Example: Methylalcohol aka methanol

Example: Isopropylalcohol aka 2-propanol

Example: Tert-Butylalcohol aka 2-methyl-2-propanol

The examples in bond line notation:



## Structural and Physical Properties

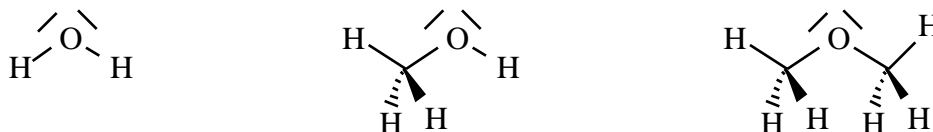
### Hybridization and Conformation

Consider water, methanol and dimethylether

all contain  $sp^3$  hybridized oxygen. (2 sigma bonds and two lone pairs)

for methanol, the methyl conformation is “staggered”.

for dimethylether, both methyl conformations are “staggered”.



### Water Solubility and Chain Length

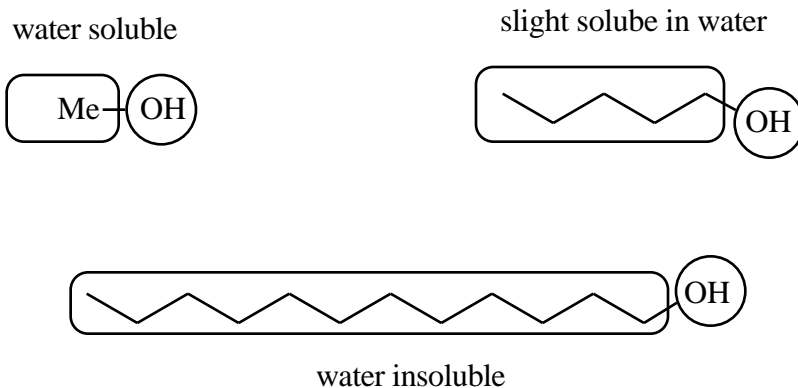
Solubility of methanol in water: In any ratio.

Solubility of pentanol in water: 2.2g in 100 ml.

A matter of the relative size of the **hydrophobic** and the **hydrophilic** parts of the molecule.

hydrophobic nonpolar alkyl groups

hydrophilic polar hydroxyl group



## Hydrogen Bonding of Alcohols

Alcohols and alkylhalides have similar molecular dipole moments.

Yet, the physical properties are very different

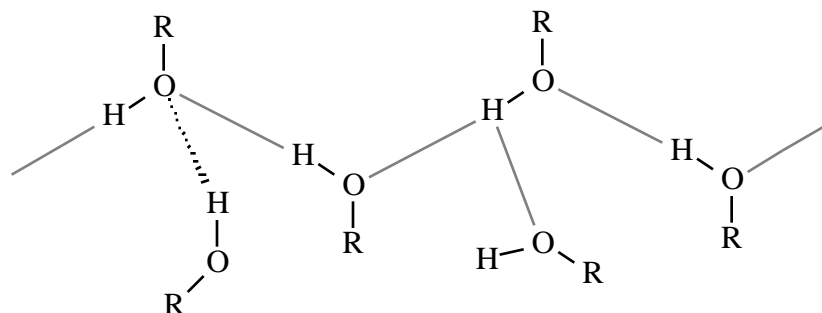
Alcohols have higher boiling points than alkylhalides

Alcohols have better water solubility than alkylhalides

Reason: The O-H bond is very polar and is very suitable for H-bonding.

Example: Boiling points of methane -161 C, chloromethane -24 C, and methanol 65 C.

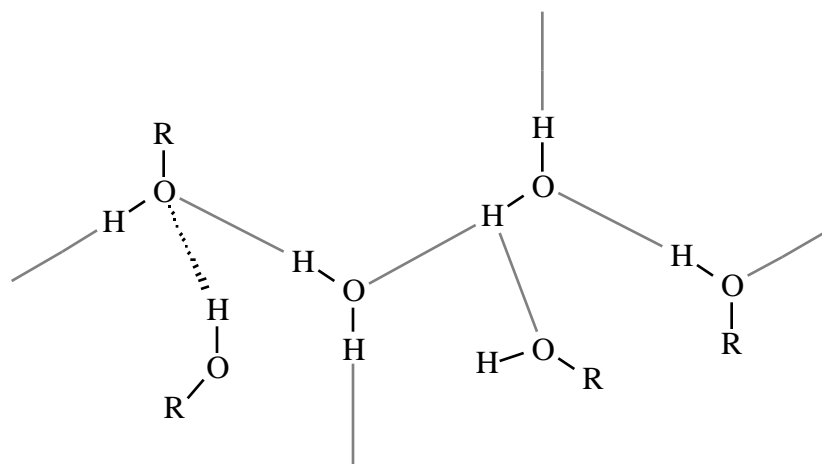
Draw H-bonded methanol "chain".



Each O-atom can have none, one, or two H-bonds. Each hydroxyl-H usually engages in one H-bond but it also may be H-bonded to two O-acceptors (bifurcating H-bond).

Example: Solubility with water is low for chloromethane (<1g/100ml) but infinite for methanol.

Draw H-bonded mixture of water and methanol.



## Acids and Bases

Alcohols are amphoteric, that is, they can act as acids and as bases.

in basic media: alcohols acts as acids and they are deprotonated

in neutral media: alcohols remain neutral

in acidic media: alcohols act as bases and they are protonated

## Acidity of Alcohols

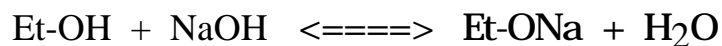
Dissociation yields the alkoxide ion:  $\text{ROH} \rightleftharpoons \text{RO}^- + \text{H}^+$

	pKa values
water	15.7
methanol	15.5 about like water
ethanol	15.9 about like water
Cl-CH <sub>2</sub> -CH <sub>2</sub> -OH	14.3 a bit more acidic, electronegative substituent stabilizes the anion

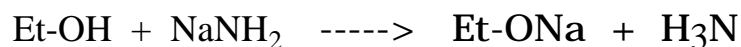
Since the alcohols are weak acids, it takes strong bases to abstract the proton.

Example 1: EtOH and NaOH.

The pKa values of EtOH and H<sub>2</sub>O are about the same, equilibrium.

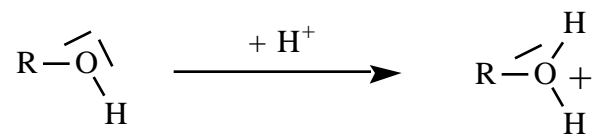


Example 2: Deprotonate with amide. The ammonia formed is much less acidic. Equilibrium very much on the side of the alkoxide.

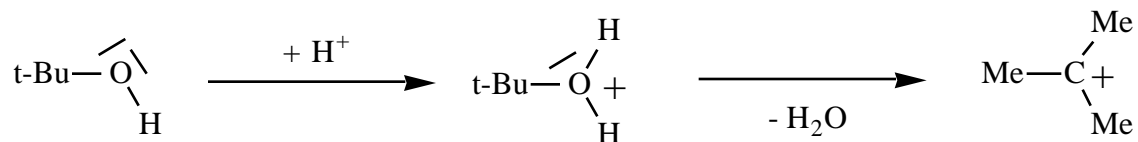


## Basicity of Alcohols

The hydroxyl-oxygen contains lone pairs and these can be protonated by strong acids. The basicity of alcohols is very low and the concentrations of the protonated alcohols will be very small. The protonated alcohols are called **alkyloxonium ions**.



However, this reaction will turn out to be very important later on. We will use the protonation of alcohols frequently to convert the poor leaving group “OH” into the super leaving group “H<sub>2</sub>O”. The protonated alcohol is all set to lose water and form a carbenium ion. In other words, the acid facilitates the nucleophilic substitution.



## Syntheses of Alcohols in Large Industrial Scale

### Methanol from “Synthesis Gas”: Hydrogenation of CO

Synthesis gas is a mixture of CO and H<sub>2</sub> generated by heating coal in the presence of water.

The CO triple bond is hard to break!!

Catalyst required, oxide of Cu, Zn, Cr. The oxides will be reduced by the hydrogen gas.

High T (250), high pressure (50-100 atm)



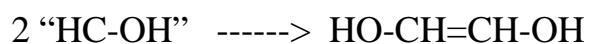
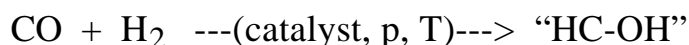
### Glycol from “Synthesis Gas”: Incomplete hydrogenation of CO

Catalyst required, oxide of Rh, Ru. High T (250), high pressure (50-100 atm)

First step: Make HCOH, a carbene.

Second step: Carbene dimerizes.

Third step: Add another hydrogen molecule to form 1,2-ethanediol (glycol).



### Ethanol from “Cracking Process”: Hydration of Ethene

Cracking is the process of breaking down large alkanes into small alkenes. The ethene produced can be hydrated to form ethanol.

Catalyst: H<sub>3</sub>PO<sub>4</sub>

High temperature: 300 C

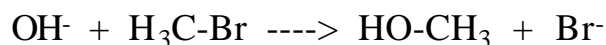


## Syntheses of Alcohols in the Laboratory

### Syntheses of Alcohols by Nucleophilic Substitution

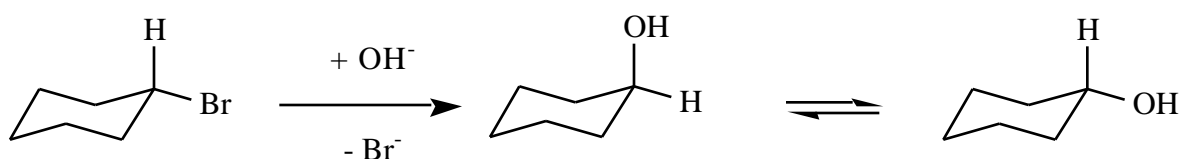
Avoid unimolecular substitution as they tend to give eliminations and rearranged products.

Example 1: Bromomethane (bimolecular)



Example 2: Chlorocyclohexane (bimolecular)

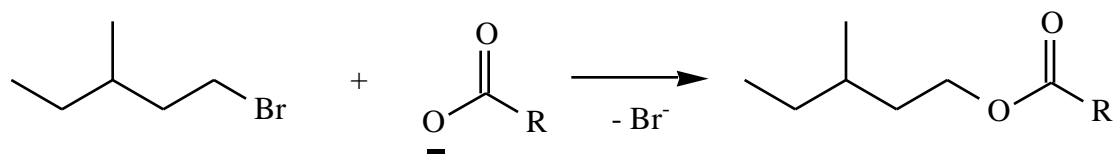
Note that axial cyclohexanol is the primary product which then undergoes ring-flipping to the thermodynamically more stable equatorial cyclohexanol.



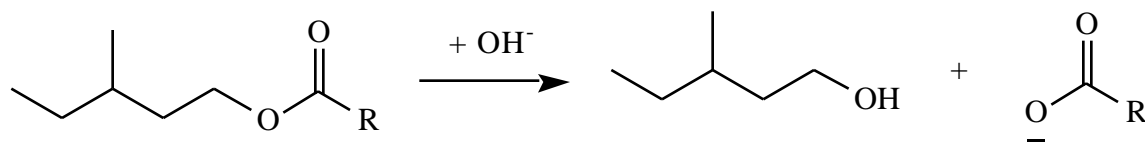
### Syntheses of Alcohols from Esters

The idea is to do a nucleophilic substitution with a **nucleophile that is much less basic** so as to reduce the chance for elimination reactions. The product is converted into the desired alcohol.

Step 1: Bimolecular nucleophilic substitution with sodium acetate to form an **organic ester** (an ester formed between an alcohol and a carboxylic acid).



Step 2: Hydrolysis of the ester yields desired alcohol and acetic acid. (This step looks like a nucleophilic substitution but it is not. You will learn the mechanisms of ester hydrolysis later.)





## Syntheses of Alcohols Using Organometallic Reagents

### Organometallic Compounds: Carbanionic Carbon!

Organometallic compounds contain a bond between a carbon and a metal.

Due to electronegativities  $EN(C) > EN(\text{metal})$ , the carbon is **anionic** and the metal is **cationic**.

Having compounds with “negatively charged carbons”, “anionic carbon atoms”, “carbanionic centers” makes it possible to react these compounds with **electrophiles**.

### Synthesis of Organometallic Compounds

Reaction of elemental metal with alkylhalide in ether.

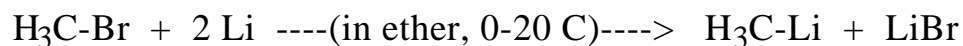
The alkyl**halides** are bromides, chlorides, and iodides.

The **alkyl**halide can be any hydrocarbon (saturated, unsaturated, aromatic).

The **metals** are usually Li, Na, and Mg.

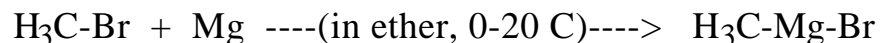
The **ether solvents** are diethylether or tetrahydrofuran (THF). THF is a 5-ring with one O-atom and four methylene groups.

Example 1: Lithiation of methylbromide



Example 2: Grignard Synthesis

A “Grignard Reagent” is an organometallic reagent that contains Mg as the metal. Named after the French chemist Mr. Grignard. The magnesium metal inserts to form the alkylmagnesium halide.



### Function of the ether solvent

Reason 1: The ether creates an atmosphere of ether above the reaction mixtures and that keeps water vapor away from the Grignard reagent.

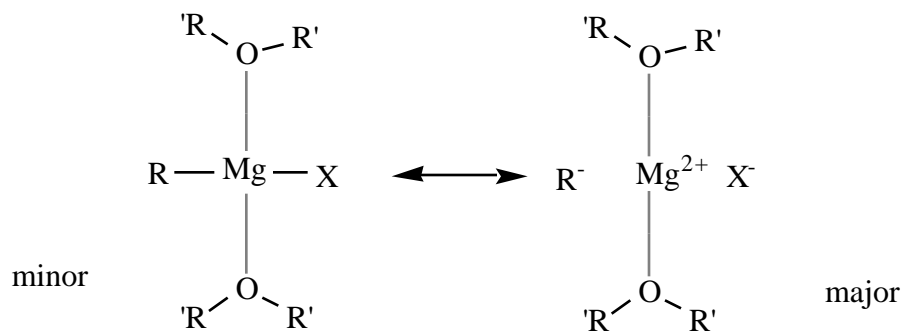
Water reacts with  $\text{RMgBr}$  to form  $\text{R-H}$  and  $\text{HOMgBr}$ .

In general, organometallic reagents will react with anything that contains **protic hydrogen!** The anionic carbon always will pick up the cationic hydrogen and form a C-H bond. This is why we need to work in aprotic solvents and keep all protic materials away.

Reason 2: The ether stabilizes the Grignard reagent. Two ether molecules coordinate to the Mg.

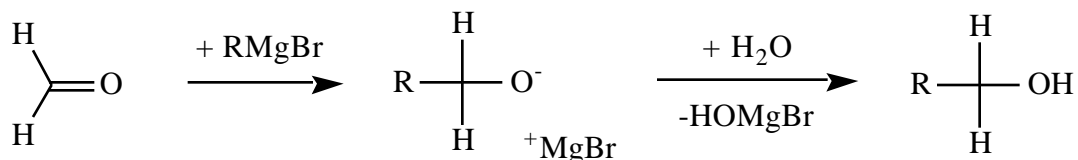
## Structure of Organometallic Reagents

Think of them as **ionic compounds** in which the metal is the cation and the hydrocarbon fragment is an anion.



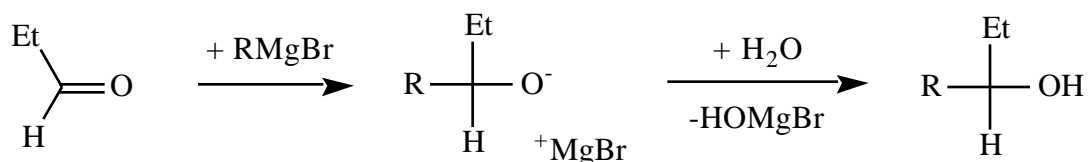
### Organometallic Compounds in Synthesis of Primary Alcohol

React an organometallic compound with **formaldehyde**. The carbanion will add to the positively polarized carbonyl-C atom and form an alkoxide ion. The alkoxide ion is protonated by water during workup.



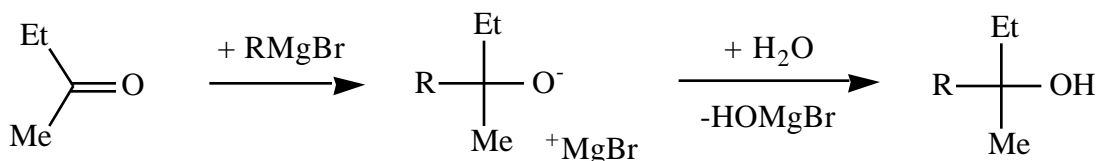
### Organometallic Compounds in Synthesis of Secondary Alcohol

React an organometallic compound with an **aldehyde** (here propanal). The carbanion will add to the carbonyl-C and form an alkoxide ion. The alkoxide ion is protonated by water during workup.



### Organometallic Compounds in Synthesis of Tertiary Alcohol

React an organometallic compound with an **ketone** (here pentanone-2). The carbanion will add to the carbonyl-C and form an alkoxide ion. The alkoxide ion is protonated by water during workup.

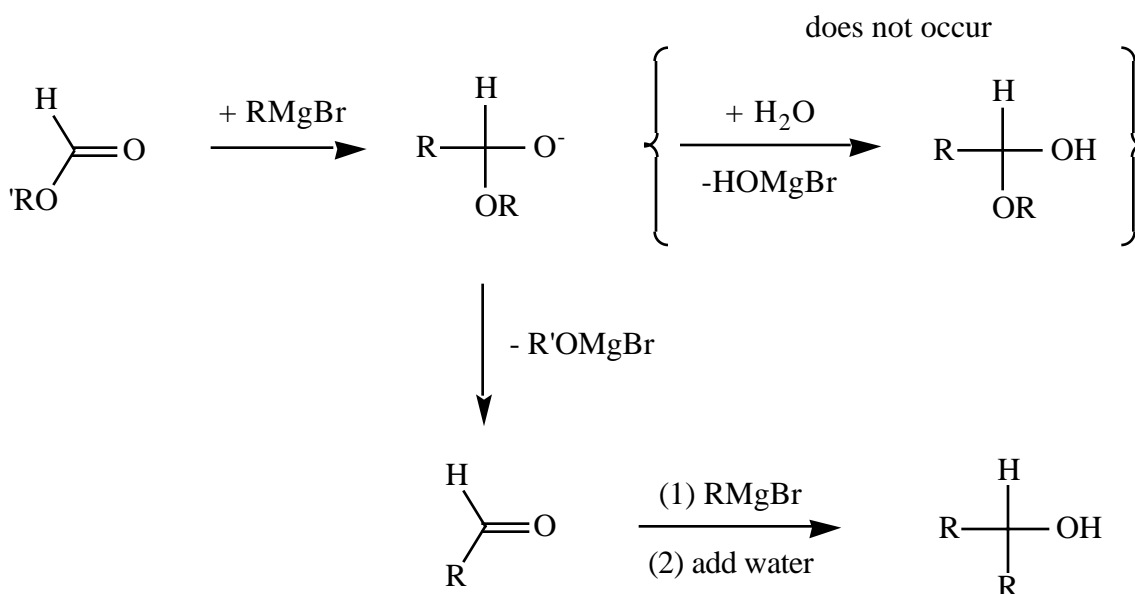


## Synthesis of Alcohols with Two Like R-Groups

React an organometallic compound with an **ester**. The first carbanion will add to the carbonyl-C atom and **replace the OR group** of the ester. Now we have an aldehyde or a ketone. The second carbanion will attack the carbonyl compounds and form an alkoxide. The alkoxide ion is protonated by water during workup.

Use ester of formic acid: Make secondary alcohol with two R groups from OMR.

Use ester of other acid: Make tertiary alcohol with two R groups from OMR.



## Oxidations of Alcohols

Oxidation == Addition of O-atoms (or other electronegative atoms) or removal of H-atoms.

Alcohol oxidation outcome depends on the type of alcohol:

**primary alcohols**

**aldehydes**

**carboxylic acids**

**secondary alcohols**

**ketones**

**tertiary alcohols**

Usually, the oxidation of the aldehyde to the carboxylic acid is faster than is the oxidation of the primary alcohol to the aldehyde. Aldehydes usually cannot be made from primary alcohols.

## Oxidation with Chromium(VI)

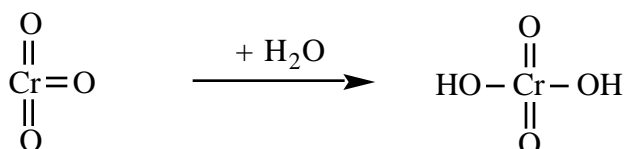
Reagent:  $\text{CrO}_3$ ,  $\text{K}_2\text{Cr}_2\text{O}_7 = \text{K}_2\text{O} + 2 \text{CrO}_3$ ,  $\text{Na}_2\text{Cr}_2\text{O}_7 = \text{Na}_2\text{O} + 2 \text{CrO}_3$

These reagents all are yellow or yellow-orange and they are being reduced to green Cr(III).

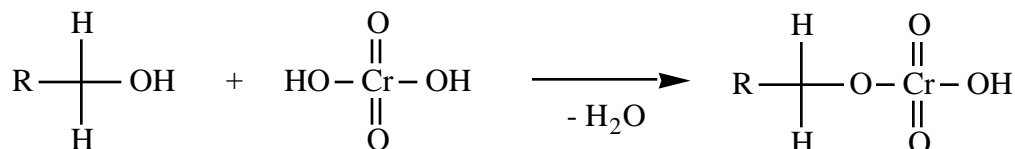
Solvent: Aqueous acid such as dilute  $\text{H}_2\text{SO}_4$

## Mechanism for Oxidation with $\text{CrO}_3$

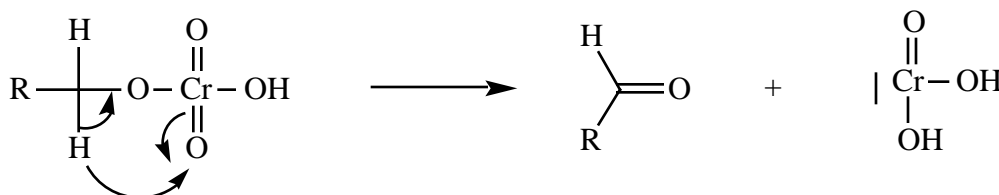
Step 1: Form the chromic acid by addition of water to  $\text{CrO}_3$



Step 2: Alcohol and chromic acid form an **inorganic ester** via **condensation** (loss of water).



Step 3: Transfer of one H-atom from the alcohol head-C to a chromate oxygen. This is the oxidation step! Cr(VI) is now Cr(IV).



### **Oxidation with PCC: Aldehydes from Alcohols**

PCC = Pyridinium chlorochromate = combination of pyridine (azabenzene), HCl, and CrO<sub>3</sub>.

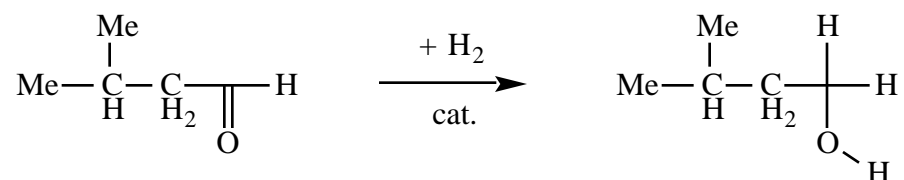
Used **in dichloromethane solution**. This is the key, in the absence of water the overoxidation of aldehyde to carboxylic acid does not occur.

Example: Propanol to propanal.

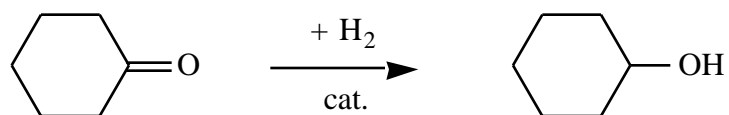
## Reductions of Aldehydes and Ketones with Hydrogen

The hydrogen gas always requires “activation” with metal catalyst. The metal catalyst dissociates the  $H_2$  molecule into atomic hydrogen atoms. This process greatly reduces the activation barrier since the cleavage H-H bond requires 105 kcal/mol.

Example 1: 3-methylbutanal reduced to 3-methyl-1-butanol using  $H_2/Pd-C$



Example 2: Cyclohexanone reduced to cyclohexanol using  $H_2/Pd-C$



## Reductions of Aldehydes and Ketones with Hydride Reagents

Hydrides are compounds that contain **anionic H**.

**Typical hydrides** include

LiH lithium hydride ionic

NaH sodium hydride ionic

KH potassium hydride ionic

AlH<sub>3</sub> aluminium hydride polar covalent

BH<sub>3</sub> borane polar covalent (exists as dimers)

**Complex hydrides** can be seen as mixtures between the simple hydrides and they are prepared just like that (by mixing LiH and AlH<sub>3</sub> for example).

LiAlH<sub>4</sub> is the most famous one! LAH for short. Contains Li<sup>+</sup> and AlH<sub>4</sub><sup>-</sup> ions.

NaBH<sub>4</sub> is another famous one! Contains Na<sup>+</sup> and BH<sub>4</sub><sup>-</sup> ions.

The BH<sub>4</sub><sup>-</sup> and AlH<sub>4</sub><sup>-</sup> ions are tetrahedral and isoelectronic with methane.

### Hydride reagents are used in ether solvents

Obviously the solvent has to be aprotic! Protic solvents react with the hydride reagents vehemently by generation of molecular hydrogen gas.





## Reductions with Hydrides

In general, in “hydride reductions” one

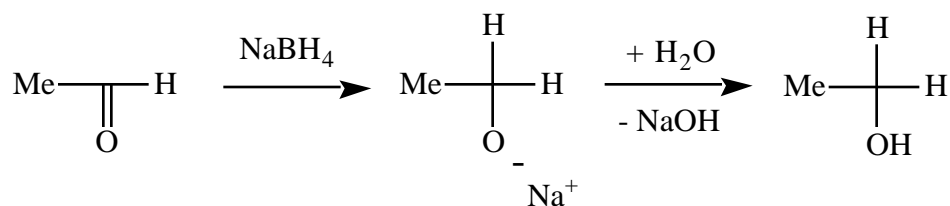
adds one H as an anion (the hydride from the hydride reagent) to form alkoxide

adds another H as a cations (the proton comes from water in the work-up).

Overall the reduction is the addition of two H.

### Example 1: Acetaldehyde and NaBH<sub>4</sub>

(For brevity, pretend that the “NaH” reacts and ignore the “BH<sub>3</sub>”).



### Example 2: Acetone and LiAlH<sub>4</sub>

(For brevity, pretend that the “LiH” reacts and ignore the “AlH<sub>3</sub>”).

