2023 JC2 H2 CHEMISTRY (9729)
CARBOXYLIC ACIDS AND DERIVATIVES

Name: ____ Civics Group: 22 – ____

Students should be able to:

(a) describe the formation of carboxylic acids from alcohols, aldehydes and nitriles

(b) describe the reactions of carboxylic acids in the formation of

  (i) salts

  (ii) esters on reaction with alcohols, using ethyl ethanoate as an example

  (iii) acyl chlorides, using ethanoyl chloride as an example

(c) explain the acidity of carboxylic acids and of chlorine-substituted ethanoic acids in terms of their structures

(d) describe the hydrolysis of acyl chlorides

(e) describe the reactions of acyl chlorides with alcohols, phenols and primary amines

(f) explain the relative ease of hydrolysis of acyl chlorides, alkyl chlorides and aryl chlorides

(g) describe the formation of esters from acyl chlorides, using phenyl benzoate as an example

(h) describe the acid and base hydrolyses of esters

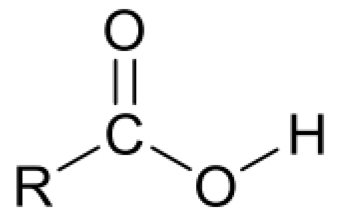
LECTURE CONTENT

REFERENCES

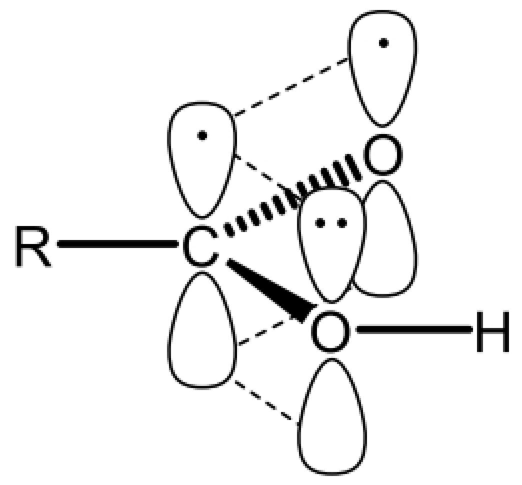
1. A-Level Chemistry (by Ramsden)
2 Organic Chemistry (by David Klein)
3 www.chemguide.co.uk

1 Carboxylic acids

1.1 Structure and Nomenclature

Carboxylic acids may be represented as RCO_2H,  where R is H or alkyl or aryl group.

Name of functional group: **carboxylic acid**



Note:

⇒ C is sp^2 hybridised.

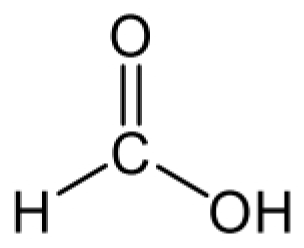
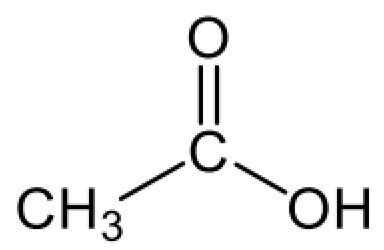
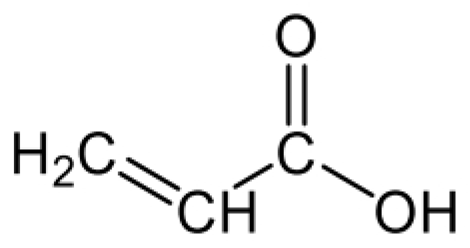
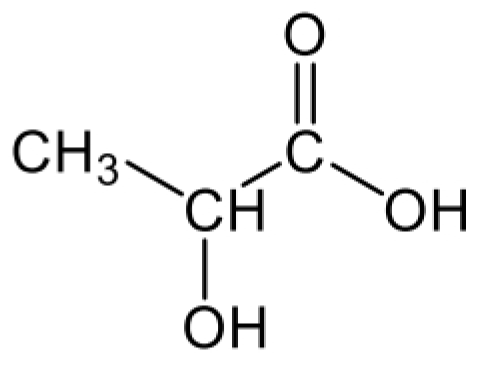
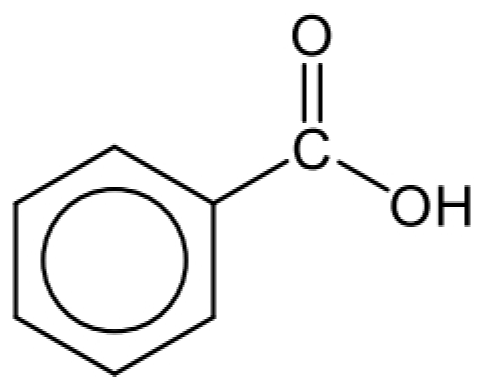
⇒ Molecular geometry is trigonal planar with respect to carboxyl C.

The ***carboxyl*** group is a combination of the ***carbo***nyl and the hydro***xyl*** groups.

IUPAC names are formed by taking the name of the appropriate hydrocarbon, dropping the –*e* and then adding the suffix –*oic acid*.

- The longest chain carrying the carboxyl group is considered the parent structure. **Numbering of the carbon chain starts from the <u>carboxyl carbon</u>** (principal functional group).
- When two carboxyl groups are present, the suffix –*dioic* acid is used and an 'e' is added in front of the suffix.
  e.g. $HO_2C–CO_2H$ ethanedioic acid
  $HO_2CCH_2CO_2H$ propanedioic acid

Examples:

 methanoic acid (formic acid)	 ethanoic acid (acetic acid)	 propenoic acid (acrylic acid)
 2-hydroxypropanoic acid (lactic acid)	 benzenecarboxylic acid (benzoic acid)	$HO_2C—CO_2H$ ethanedioic acid (oxalic acid)

1.2 Physical Properties

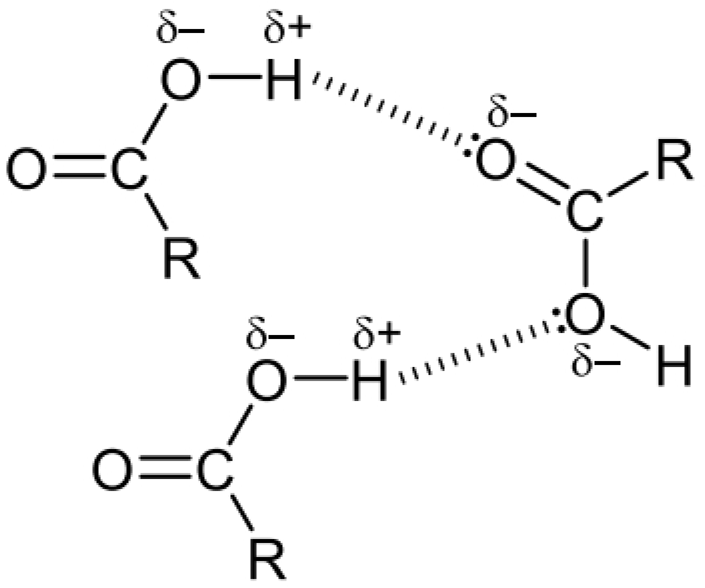
1.2.1 Volatility

Comparison with compounds of other homologous series

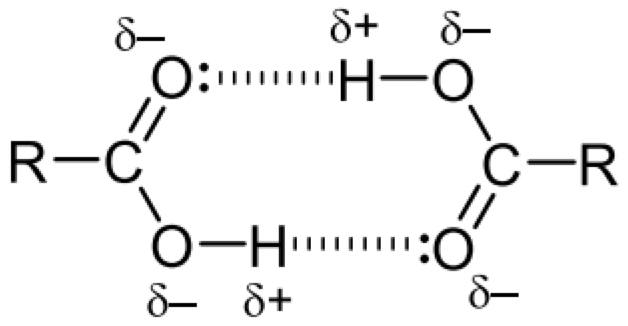
Carboxylic acids have **higher boiling points** than the corresponding alkanes and alcohols of similar M_r.

compound	M_r	boiling points / °C
$CH_3CH_2CH_2CH_3$	58	–0.5
$CH_3CH(OH)CH_3$	60	97
CH_3CO_2H	60	118

Reasons are:



- Carboxylic acids can form hydrogen bonds with each other.
- Carboxylic acids form **stronger** hydrogen bonds than alcohols because the **–OH group is more polarised** due to the presence of the **electron-withdrawing carbonyl group**. Hence, the H atom is more electron-deficient, i.e. greater δ+.
- Carboxylic acid molecules **dimerise** in the vapour state and in non-polar solvents, forming two hydrogen bonds between each pair of molecules.



The two hydrogen bonds are formed between the O atom of the C=O bond on one molecule and the H atom on the O–H bond of another molecule.

However, in polar solvents such as water, the molecules exist as monomers or dissociate to some extent into H^+ and RCO_2^-:

$$RCO_2H + H_2O \rightleftharpoons RCO_2^- + H_3O^+$$

Self Check 1A

Explain, with the aid of a suitable diagram, why the relative molecular mass of ethanoic acid in benzene is approximately 120, but in water it is 60.

Modified from J88/I/2(a)

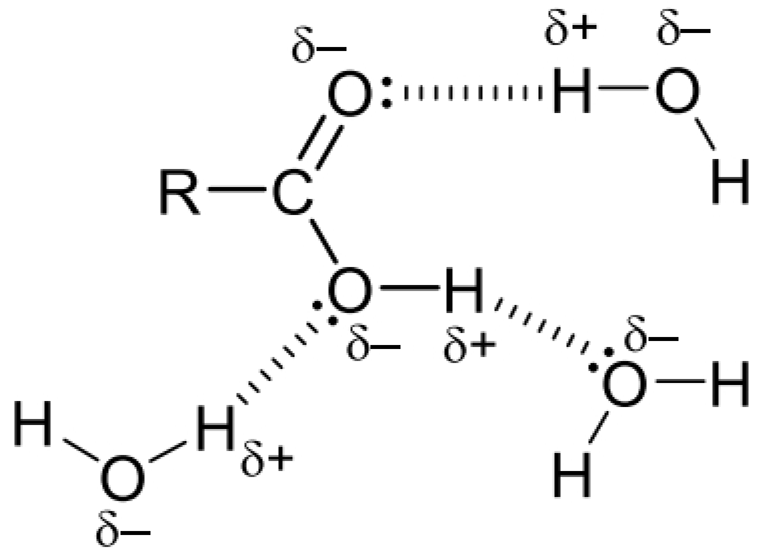
Comparison within the homologous series

Boiling points **increase with** increasing relative molecular mass because this leads to an **increase in the number of electrons** the molecules have and thus lead to **stronger instantaneous dipole-induced dipole interactions between the molecules**.

1.2.2 Solubility

The lower aliphatic acids are completely miscible with water because of:

- the ability of the $–CO_2H$ group to form **hydrogen bonds** with water molecules.



- However, as the hydrocarbon chain lengthens, the **permanent dipole-induced dipole (pd-pd) interactions** between the larger non-polar alkyl group and water molecules **do not release sufficient energy** to overcome the strong **hydrogen bonds** between the water molecules. In addition, the larger alkyl group also **hinders the formation of hydrogen bonds between the carboxylic acid functional group and water molecules**.

E.g. Benzoic acid dissolves readily in hot water but forms white needle crystals when cooled as it is only slightly soluble in cold water.

At the end of sections 1.1 and 1.2, you should know that:

1. The carbon atom in a COOH group is sp^2 hybridised and is trigonal planar.
2. The COOH group forms hydrogen bonds with water, making carboxylic acids soluble in water.
3. When the carbon chain lengthens, the energy released from the pd-pd interactions is insufficient to overcome the strong hydrogen bonds between water molecules. The larger alkyl group also hinders the formation of H-bonds between the COOH group and water molecules. Hence solubility decreases.
4. Carboxylic acids dimerise in the vapour state and in non-polar solvents.

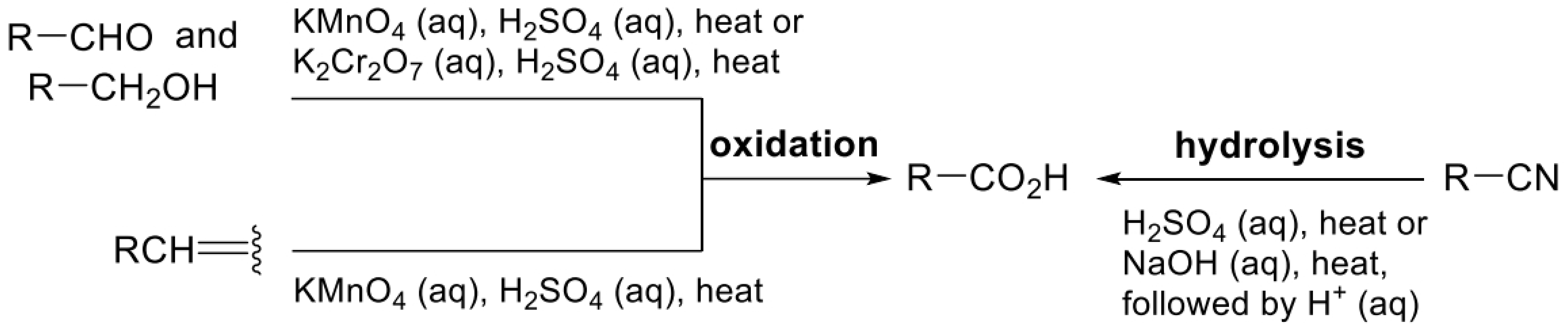
1.3 Preparation

LO (a) describe the formation of carboxylic acids from alcohols, aldehydes and nitriles.

Carboxylic acids may be prepared in a number of ways, namely

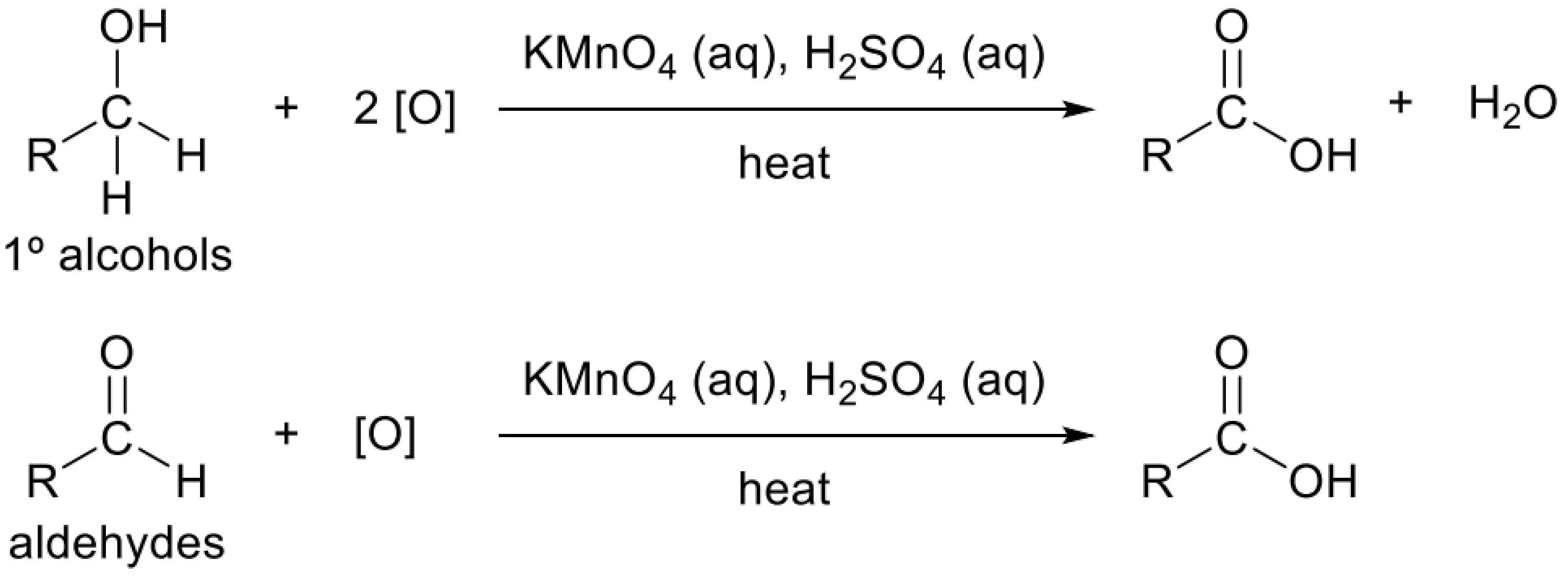
(a) oxidation

(b) hydrolysis



1.3.1 Oxidation of primary alcohols and aldehydes

Heat the primary alcohol or aldehyde with a solution of potassium dichromate(VI) or potassium manganate(VII), acidified with sulfuric acid. Primary alcohols are oxidised to carboxylic acids.



Reagents and conditions: $KMnO_4$ (aq), H_2SO_4 (aq), heat **OR**

$K_2Cr_2O_7$ (aq), H_2SO_4 (aq), heat

Observation: purple $KMnO_4$ turns colourless **OR** orange $K_2Cr_2O_7$ turns green

1.3.2 Oxidative cleavage of alkenes

Add alkene to a solution of potassium manganate(VII) acidified with sulfuric acid and heat.

$$\text{RHC}{=}\text{CHR}' \;+\; 4\,[\text{O}] \xrightarrow[\text{heat}]{\text{KMnO}_4\text{ (aq), H}_2\text{SO}_4\text{ (aq)}} \text{RCO}_2\text{H} \;+\; \text{R}'\text{CO}_2\text{H}$$

Reagents and conditions: $KMnO_4$ (aq), H_2SO_4 (aq), heat

(**NOT** $K_2Cr_2O_7$ (aq), H_2SO_4 (aq), heat) **(WHY?)**

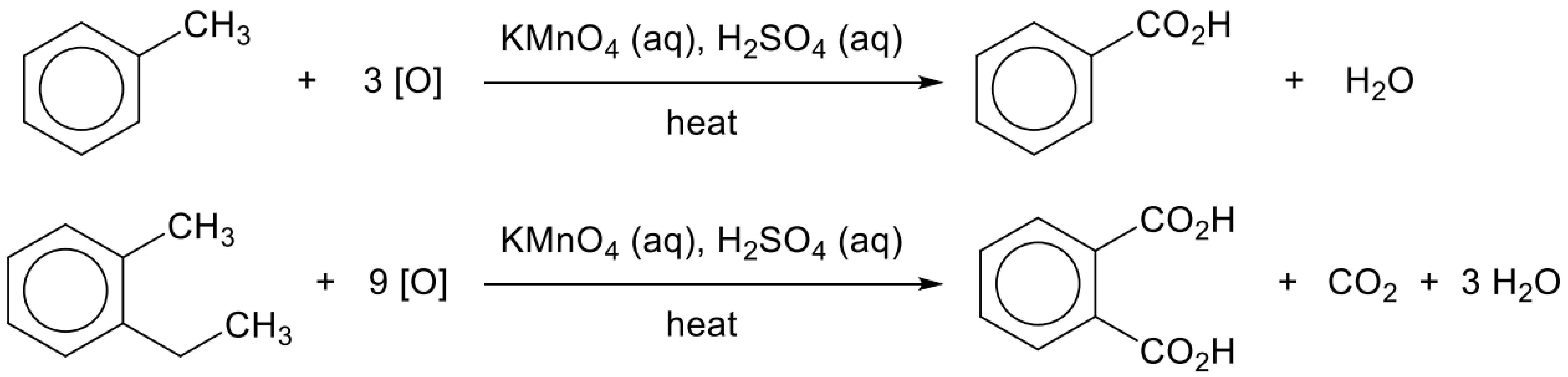
Observation: purple $KMnO_4$ decolourises

Example:

$$\text{CH}_3\text{CH}{=}\text{CHCH}_3 \;+\; 4\,[\text{O}] \xrightarrow[\text{heat}]{\text{KMnO}_4\text{ (aq), H}_2\text{SO}_4\text{ (aq)}} 2\,\text{CH}_3\text{CO}_2\text{H}$$

1.3.3 Side-chain oxidation of an alkylbenzene to form benzoic acid

Add alkylbenzene to a solution of potassium manganate(VII) acidified with dilute sulfuric acid and heat.



Reagents and conditions: $KMnO_4$ (aq), H_2SO_4 (aq), heat

(**NOT** $K_2Cr_2O_7$ (aq), H_2SO_4 (aq), heat)

Observation: purple $KMnO_4$ decolourised

1.3.4 Hydrolysis of nitriles

Acidic hydrolysis

Nitriles can be hydrolysed to carboxylic acids by heating it with a strong acid.

(Is this reaction considered an oxidation reaction since the C in the CN gained two O atoms when forming the RCO_2H? Why or why not?)

$$R-C\equiv N + 2H_2O + H^+ \xrightarrow[\text{heat}]{HCl\text{ (aq) }\textbf{OR}\ H_2SO_4\text{ (aq)}} RCO_2H + NH_4^+$$

Reagents and conditions: HCl (aq) or H_2SO_4 (aq), heat

Alkaline hydrolysis

Nitriles are hydrolysed to carboxylic acids by heating with aqueous alkali followed by acidification (to convert the carboxylate formed to carboxylic acid).

$$\begin{tikzcd} R-C\equiv N + H_2O + OH^- \arrow[r, "NaOH\text{ (aq)}", "\text{heat}"'] & RCO_2^- + NH_3 \arrow[d, "H^+\text{ (aq), r.t.}"] \\ & RCO_2H + NH_4^+ \end{tikzcd}$$

Reagents and conditions: NaOH (aq), heat, followed by HCl (aq) or H_2SO_4 (aq)

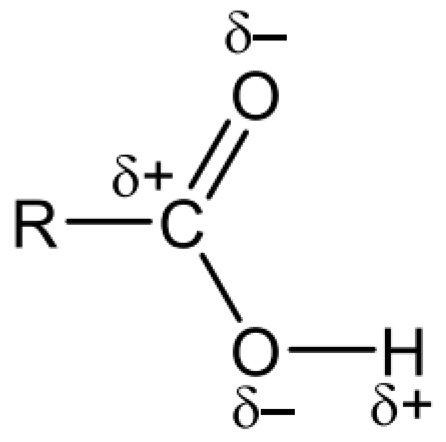
At the end of section 1.3, you should know that:

1. Carboxylic acids can be synthesised by oxidising primary alcohols and aldehydes with $KMnO_4$(aq), H_2SO_4(aq), heat **OR** $K_2Cr_2O_7$(aq), H_2SO_4(aq), heat.
2. Carboxylic acids can be synthesised by oxidative cleavage of alkenes with $KMnO_4$(aq), H_2SO_4(aq), heat.
3. Benzoic acid can be synthesised by oxidation of an alkylbenzene with $KMnO_4$(aq), H_2SO_4(aq), heat.
4. Carboxylic acids can be synthesised by hydrolysing nitriles with H_2SO_4(aq), heat **OR** NaOH(aq), heat, followed by H_2SO_4(aq) or HCl(aq).

1.4 Reactions

LO (b) describe the reactions of carboxylic acids in the formation of
- (i) salts
- (ii) esters on reaction with alcohols, using ethyl ethanoate as an example
- (iii) acyl chlorides, using ethanoyl chloride as an example

Looking at the general structure of a carboxylic acid below, we can identify two main reactive centres:



- The **O—H bond**, which on breaking releases a proton and hence gives rise to the **acidic character** of the carboxyl group and the **formation of ionic salts**. A similar process occurs in alcohols and phenols.
- The **C—O bond**, which may break heterolytically during the **nucleophilic (acyl) substitution of the –OH group**. Again, alcohols take part in similar reactions.
- The **carbonyl group –C=O does not undergo addition reactions which are characteristics of aldehydes and ketones.**

Also, carboxylic acids are generally **stable to oxidation** except for **methanoic acid** and **ethanedioic acid**.

$$HCO_2H + [O] \longrightarrow CO_2 + H_2O$$

Reagents and conditions: $K_2Cr_2O_7$ (aq), H_2SO_4 (aq), heat

OR $KMnO_4$ (aq), H_2SO_4 (aq), heat

Observation: Orange $K_2Cr_2O_7$ turns green

OR Purple $KMnO_4$ decolourises

$$(CO_2H)_2 + [O] \longrightarrow 2CO_2 + H_2O$$

Reagents and conditions: $KMnO_4$ (aq), H_2SO_4 (aq), heat

Observation: Purple $KMnO_4$ decolourises

1.4.1 Fission of the C–O bond

1.4.1.1 Condensation

A carboxylic acid is converted into an ester when heated with an alcohol in the presence of an acid catalyst like concentrated sulfuric acid.

$$RCO_2H + R'OH \xrightleftharpoons{\text{conc. } H_2SO_4\text{, heat}} RCO_2R' + H_2O$$

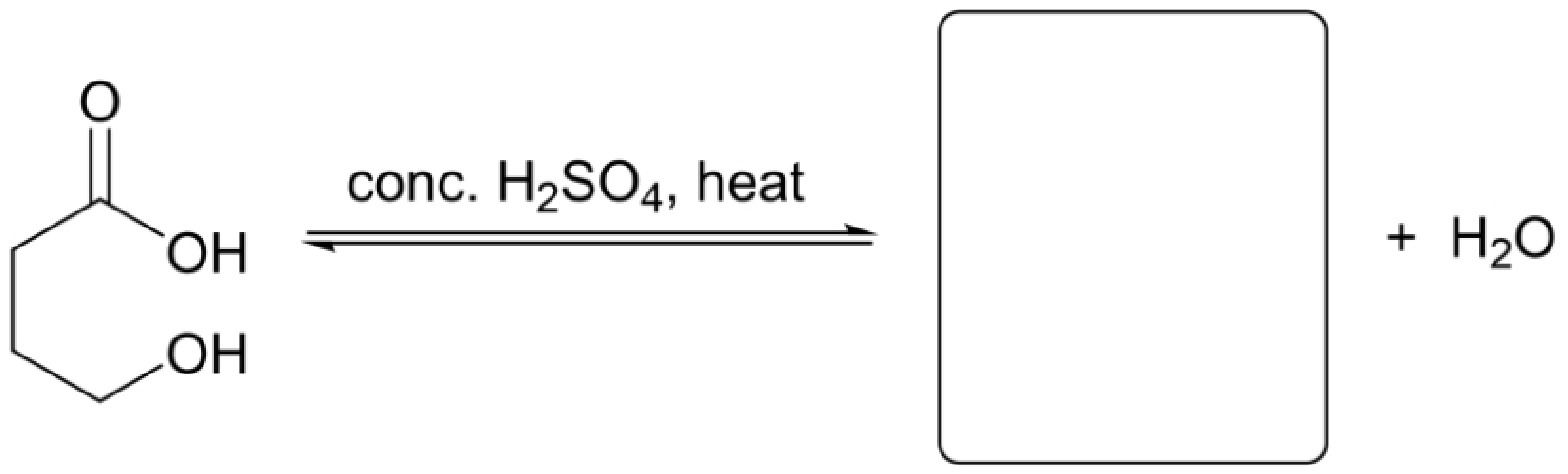
Reagents and conditions: R'OH, conc. H_2SO_4, heat

Example:

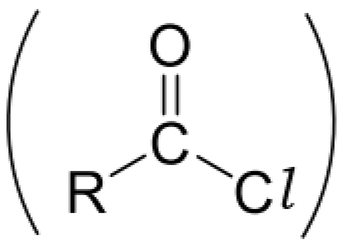
$$CH_3CO_2H + CH_3CH_2OH \xrightleftharpoons{\text{conc. } H_2SO_4\text{, heat}} CH_3CO_2CH_2CH_3 + H_2O$$

Example 1A

Give the structure of the organic product formed.



1.4.1.2 Fission of the C–O bond: Formation of acyl chlorides

A carboxylic acid is converted into an acyl chloride () using **phosphorus trichloride, PCl_3 or phosphorus pentachloride, PCl_5 or thionyl chloride, $SOCl_2$**.

Reagents and conditions: PCl_5 at room temperature, or PCl_3 / $SOCl_2$ with heat

To convert RCO_2H to $RCOCl$

With PCl_3

$3RCO_2H + PCl_3 \rightarrow 3RCOCl + H_3PO_3$

e.g.: $3CH_3CO_2H + PCl_3 \rightarrow 3CH_3COCl + H_3PO_3$

With PCl_5:

$RCO_2H + PCl_5 \rightarrow RCOCl + POCl_3 + HCl$

e.g.: $CH_3CO_2H + PCl_5 \rightarrow CH_3COCl + POCl_3 + HCl$

Observation: White fumes of HCl observed.

With $SOCl_2$:

$RCO_2H + SOCl_2 \rightarrow RCOCl + HCl + SO_2$

e.g.: $CH_3CO_2H + SOCl_2 \rightarrow CH_3COCl + HCl + SO_2$

To convert ROH to RCl:

With PCl_3:

$3ROH + PCl_3 \rightarrow 3RCl + H_3PO_3$

With PCl_5:

$ROH + PCl_5 \rightarrow RCl + POCl_3 + HCl$

With $SOCl_2$:

$ROH + SOCl_2 \rightarrow RCl + SO_2 + HCl$

PCl_5 cannot be used to distinguish between ROH and RCO_2H!

Both will give white fumes of HCl.

The reaction with thionyl chloride is especially convenient ('cleaner') as the two other products are both gaseous and are easily removed from the reaction mixture.

1.4.2 Fission of the O–H bond

1.4.2.1 Acidity

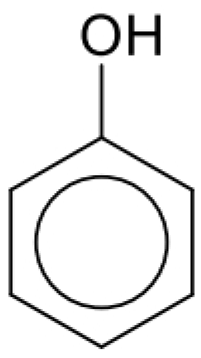
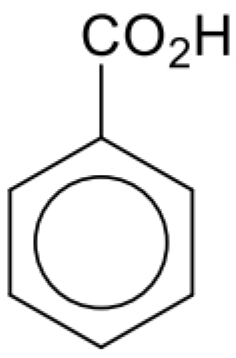
LO (c) explain the acidity of carboxylic acids and of chlorine-substituted ethanoic acids in terms of their structures

Carboxylic acids are weak acids as they dissociate only partially in water.

$$\underset{\text{weak acid}}{RCO_2H} + H_2O \rightleftharpoons \underset{\text{carboxylate anion}}{RCO_2^-} + H_3O^+$$

Carboxylic acids are **<u>stronger acids</u>** than alcohols/phenols.

(I) <u>Comparison of the acid strengths of compounds containing –OH group</u>

compound	CH_3CH_2OH	H_2O		CH_3CO_2H		$ClCH_2CO_2H$
K_a / mol dm^{-3}	1.3×10^{-16}	1.6×10^{-16}	1.0×10^{-10}	1.7×10^{-5}	6.3×10^{-5}	1.4×10^{-3}

Generally, **alcohols < water (reference) < phenols < carboxylic acids**

The relative acidities of organic compounds containing –OH groups may be explained in terms of the **stability of the conjugate base formed** upon dissociation of the acid in water.

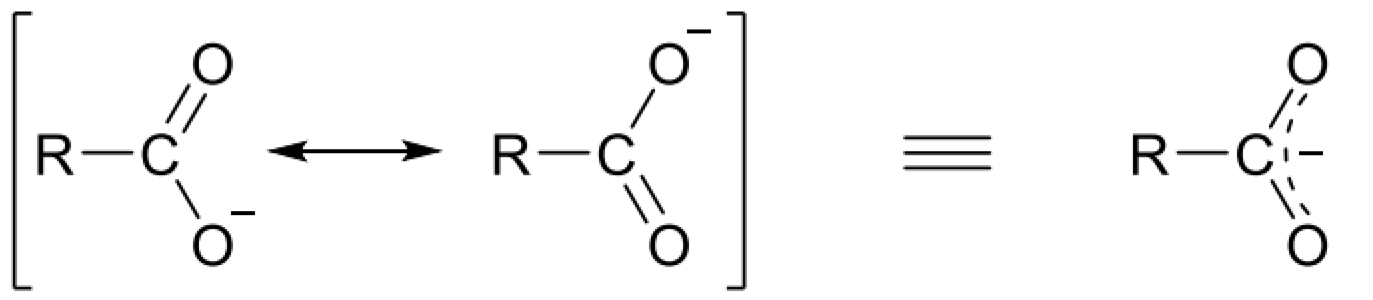
Important:

The more stable the **conjugate base** formed from the dissociation of a proton from the molecule, the less likely it is to accept the proton (backward reaction), and hence the more likely is the forward dissociation reaction to proceed ⇒ stronger acid.

A **carboxylic acid** dissociates to give the **carboxylate** ion, RCO_2^- (conjugate base of RCO_2H).

$$\underset{\text{weak acid}}{RCO_2H} + H_2O \rightleftharpoons \underset{\text{carboxylate anion}}{RCO_2^-} + H_3O^+$$

- RCO_2^- forms **<u>2 equivalent resonance structures</u>** with **<u>delocalisation of the negative charge over 2 highly electronegative O atoms</u> (resonance effect)**.
- This results in the carboxylate anion being **greatly stabilised** compared to phenoxide and alkoxide ions and its formation is energetically favoured.

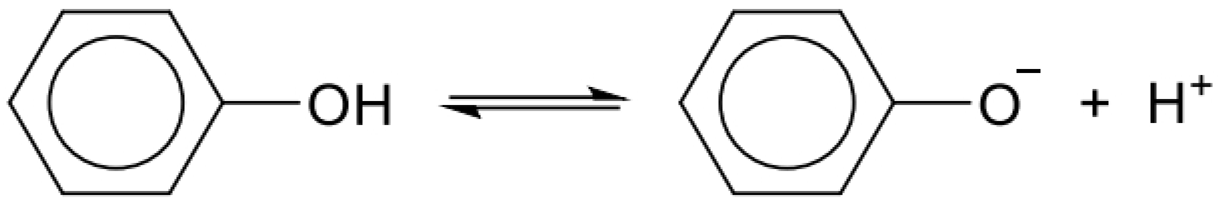


2 equivalent resonance structures

resonance-stabilised carboxylate ion

Note: The C–O bonds in the resonance-stabilised carboxylate ion are equal in length. **<u>The negative charge is equally distributed</u>** between the two oxygen atoms.

Phenol dissociates to give the **phenoxide** ion, $C_6H_5O^-$ (conjugate base of C_6H_5OH).



- The p-orbital of O **overlaps** with the π-electron cloud of the benzene ring so that the **negative charge on O delocalises into the benzene ring**.
- This resonance stabilisation is **not as effective** as that in the RCO_2^- ion **because the negative charge is delocalised over the carbon atoms** while the negative charge is delocalised over 2 highly electronegative O atoms in the RCO_2^- ion.
- The **dispersal** of negative charge **stabilises** the phenoxide ion so that it is more stable than the alkoxide ion.

An **alcohol** dissociates to give the **alkoxide** ion**, RO^-** (conjugate base of ROH).

$$ROH + H_2O \rightleftharpoons RO^- + H_3O^+$$

- The electron-donating alkyl group **intensifies** the negative charge on the O atom.
- Charge on RO^- ion also remains **localised** on a single electronegative O.
- The alkoxide ion is, therefore, the **least stable** and most likely to accept a proton.

When we spread a charge over **more than one atom**, we call the charge “delocalised”.

(II) Effect of substituents on acidity

The strength of the carboxylic acid RCO_2H depends on the following factors:

(i) Nature of R group

carboxylic acid	**pK_a**
HCO_2H	3.75
CH_3CO_2H	4.76
$CH_3CH_2CO_2H$	4.87
CH_2ClCO_2H	2.86

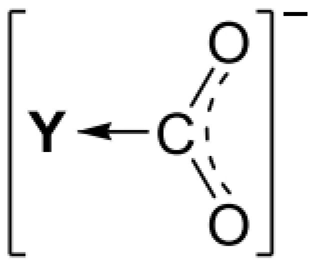
Electron-donating substituents, such as alkyl groups, **decrease** the acidic strength of carboxylic acids.

Electron-withdrawing substituents, such as groups with electronegative atoms like halogen, O or N atoms **increase** the acidic strength of carboxylic acids.

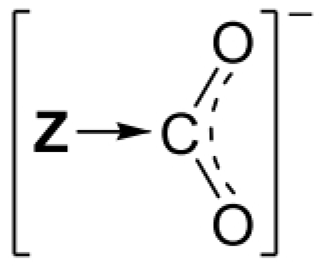
Electron-donating substituents
- **intensify** the negative charge on the carboxylate anion.
- **destabilise** the conjugate base of the acid.
- cause a **decrease** in acidity.

Electron-withdrawing substituents
- **disperse** the negative charge on the carboxylate anion.
- **stabilise** the conjugate base of the acid.
- cause an **increase** in acidity.

Example: **C*l***–CH_2CO_2H (pK_a = 2.86) is a stronger acid than **CH_3**–CH_2CO_2H (pK_a = 4.87).



Y withdraws electron density, stabilises the anion and increases acidity



Z donates electron density, destabilises the anion and decreases acidity

(ii) Number of substituents

carboxylic acid	**pK_a**
CH_2ClCO_2H	2.86
$CHCl_2CO_2H$	1.29
CCl_3CO_2H	0.65

The strength of the carboxylic acid also depends on the **number** of electron-withdrawing (or electron-donating) substituents next to the $–CO_2H$ group.

The **greater** the number of **electron-withdrawing** substituent groups, the **greater the extent of negative charge dispersal on RCO_2^-**. The conjugate base of the acid is **stabilised** and the acidity is **increased**.

The **greater** the number of **electron-donating** groups, the **more intensified the negative charge on RCO_2^-**. The conjugate base of the acid is **destabilised** and the acidity is **decreased**.

Example: Cl_3CCO_2H (pK_a = 0.65) is a stronger acid than $ClCH_2CO_2H$ (pK_a = 2.86).

(iii) Positions of substituents

carboxylic acid	**pK_a**
$CH_3CH_2CHClCO_2H$	2.86
$CH_3CHClCH_2CO_2H$	4.05
$CH_2ClCH_2CH_2CO_2H$	4.52

The strength of the carboxylic acid also depends on the **position** of electron-withdrawing (or electron-donating) substituents in the vicinity of the $–CO_2H$ group.

Because inductive effects operate through **σ bonds** and are dependent on **distance**, the effect of the electron-withdrawing (or electron-donating) substituents decreases as the substituent is further from the CO_2H group. The **closer** the electron-withdrawing substituents are to the $–CO_2H$, the **more** acidic the carboxylic acid.

E.g. $CH_3CH_2CHClCO_2H$ (pK_a = 2.86) is a stronger acid than $CH_2ClCH_2CH_2CO_2H$ (pK_a = 4.52).

An increase in distance between the Cl atom and carboxyl group disperses the negative charge on the anion to a smaller extent.

Example 1B

In which sequence is it correctly stated that the value of pK_a **increases**?

A $C_6H_5OH < C_2H_5OH < CCl_3CO_2H < CH_3CO_2H$

B $C_6H_5OH < C_2H_5OH < CH_3CO_2H < CCl_3CO_2H$

C $CCl_3CO_2H < CH_3CO_2H < C_6H_5OH < C_2H_5OH$

D $CCl_3CO_2H < CH_3CO_2H < C_2H_5OH < C_6H_5OH$

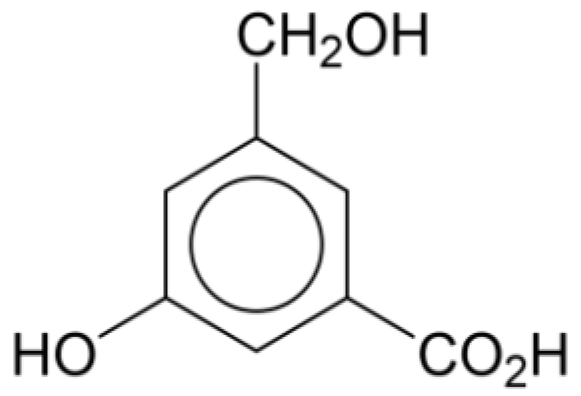
1.4.2.2 Salt formation

Due to its ability to act as an acid, carboxylic acids react with **metals, alkalis, carbonates, hydrogen carbonates** and **aq NH_3** to form salts.

reaction with	**alcohol, ROH**	**phenol, C_6H_5OH**	**carboxylic acid, RCO_2H**
Na(s)	Redox reaction with effervescence of hydrogen: $ROH(l) + Na(s) \rightarrow RO^-Na^+(alc) + ½H_2(g)$	Vigorous redox reaction with effervescence of hydrogen: $C_6H_5OH(l) + Na(s)$ $\rightarrow C_6H_5O^-Na^+ + ½H_2(g)$	Explosive redox reaction with effervescence of hydrogen: $RCO_2H(l) + Na(s)$ $\rightarrow RCO_2^-Na^+(s) + ½H_2(g)$
NaOH(aq)	**No reaction**. Alcohol is not acidic enough to react with the reagent	Acid-base reaction and phenol dissolves $C_6H_5OH(l) + NaOH(aq)$ $\rightarrow C_6H_5O^-Na^+(aq) + H_2O(l)$	Acid-base reaction: $RCO_2H(aq) + NaOH(aq)$ $\rightarrow RCO_2^-Na^+(aq) + H_2O(l)$
Na_2CO_3(aq)		Acid-base reaction and phenol dissolves $C_6H_5OH(l) + Na_2CO_3(aq)$ $\rightarrow C_6H_5O^-Na^+(aq) + NaHCO_3(aq)$	Acid-base reaction with effervescence of CO_2: $2RCO_2H(aq) + Na_2CO_3(aq)$ $\rightarrow 2RCO_2^-Na^+(aq) + H_2O(l) + CO_2(g)$
$NaHCO_3$(aq)		**No reaction**. Phenol is not acidic enough to react with the reagent	Acid-base reaction with effervescence of CO_2: $RCO_2H(aq) + NaHCO_3(aq)$ $\rightarrow RCO_2^-Na^+(aq) + H_2O(l) + CO_2(g)$
NH_3(aq)			Acid-base reaction: $RCO_2H(aq) + NH_3(aq)$ $\rightarrow RCO_2^-NH_4^+(aq)$

Example 1C

Excess NaOH(aq) is added to the compound below.



Give the structure of the organic compound formed.

1.4.3 Reduction to alcohols

Carboxylic acids can be **reduced to primary alcohols** by using lithium aluminium hydride ($LiA\mathit{l}H_4$) in dry ether at room temperature.

Please refer to Appendix for a detailed experimental procedure.

$$RCO_2H + 4\,[H] \xrightarrow{LiA\mathit{l}H_4 \text{ in dry ether}} RCH_2OH + H_2O$$

Reagents and conditions: LiA/H_4 in dry ether, room temperature

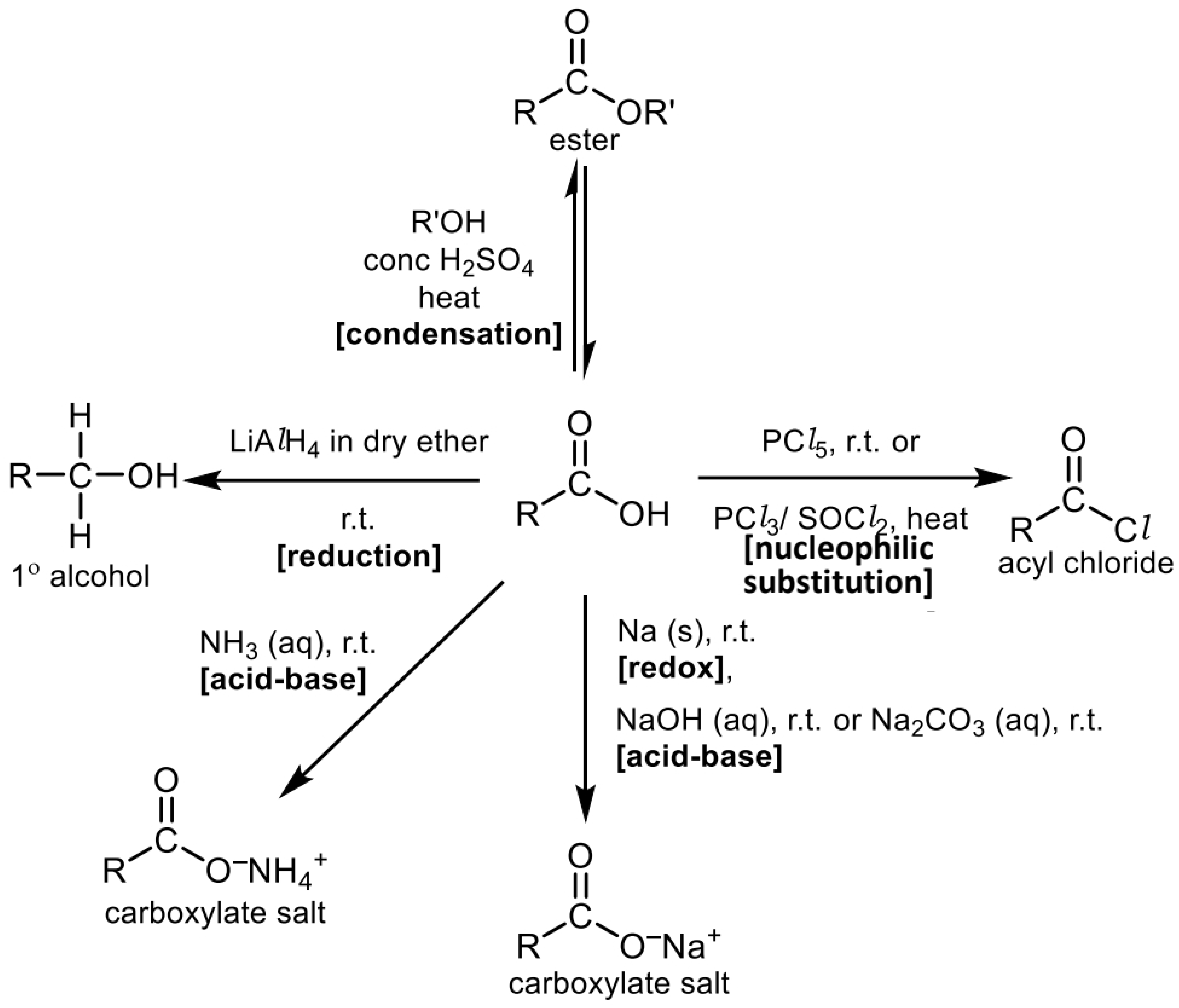
1.4.4 Distinguishing test for carboxylic acids

Procedure: Add **aqueous** sodium carbonate, Na_2CO_3(aq) (or $NaHCO_3$(aq)) at room temperature.

Observation: Effervescence of CO_2 observed. Gas evolved forms white precipitate in $Ca(OH)_2$ solution.

Note: Phenols and aliphatic alcohols **DO NOT** react with Na_2CO_3(aq) and $NaHCO_3$(aq) to give CO_2 gas.

Reactions of carboxylic acids



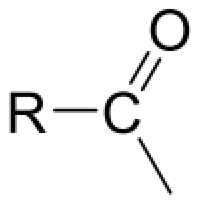
At the end of section 1.4, you should know that:

1. Carboxylic acids are resistant to oxidation, except methanoic acid and ethanedioic acid.
2. Methanoic acid and ethanedioic acid can be further oxidised to carbon dioxide and water with $KMnO_4$(aq), H_2SO_4(aq), heat.
3. Aliphatic carboxylic acids react with aliphatic alcohols in the presence of concentrated H_2SO_4 and heat to form esters.
4. Carboxylic acids can be converted to acyl chlorides by heating them with PCl_3 **OR** heating them with $SOCl_2$ **OR** stirring them with PCl_5 at room temperature.
5. The general trend in acidity when comparing aliphatic alcohols, phenols and carboxylic acids is **aliphatic alcohol < phenol < carboxylic acid**.
6. Na_2CO_3(aq) is a useful reagent as a chemical test for carboxylic acids as only carboxylic acids are acidic enough to react with Na_2CO_3(aq) to give CO_2(g). Effervescence is observed and the gas evolved forms a white precipitate in $Ca(OH)_2$(aq).
7. The greater the number of electron-withdrawing substituents and the closer these substituents are to the COOH group, the stronger the carboxylic acid will be.
8. Carboxylic acids can be reduced to primary alcohols by reacting them with $LiAlH_4$ in dry ether at room temperature.

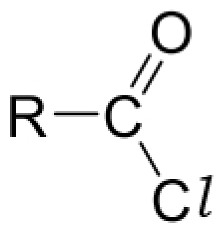
2 Carboxylic Acid Derivatives

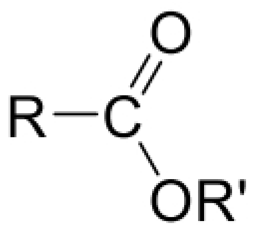
2.1 Structure and Nomenclature

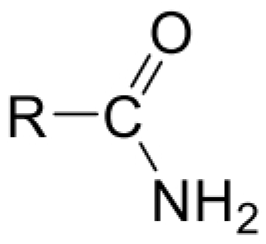
Acid derivatives are formed when the –OH portion of the carboxyl group is replaced by another functional group (which usually includes an electronegative atom).

These derivatives all contain the acyl group, 

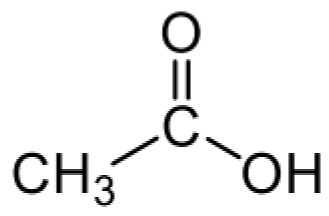
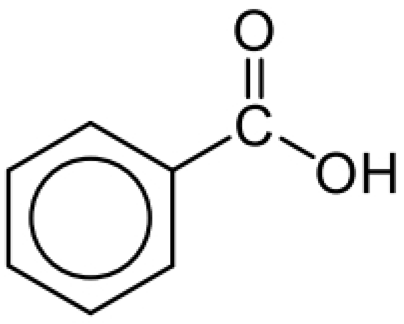
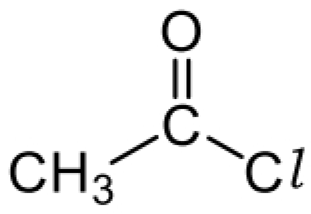
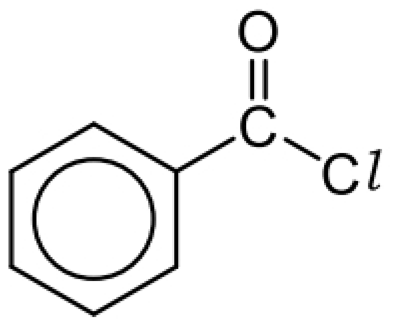
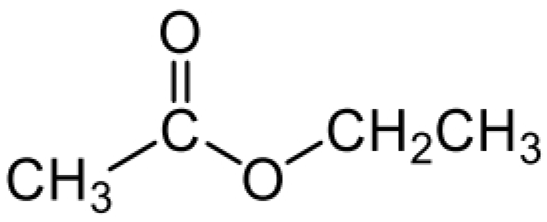
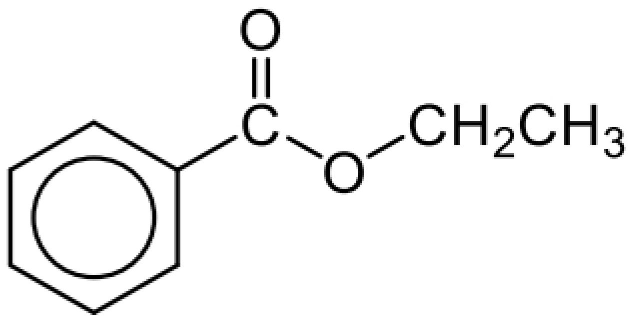
The following are some classes of acid derivatives:


acyl chloride


ester


amide (to be covered in *Organic Nitrogen Compounds*)

The names are taken in simple ways from the name of the corresponding carboxylic acid.

			change
acid	 ethanoic acid	 benzoic acid	
acid chloride/ acyl chloride (under the family of acid halides)	 ethanoyl chloride	 benzoyl chloride	-***ic acid*** to -***yl chloride***
ester	 ethyl ethanoate	 ethyl benzoate	-***ic acid*** to ***–ate*** (preceded by alcohol)

2.2 Physical Properties

2.2.1 Volatility

Acid chlorides and esters have **lower** boiling points than the **parent carboxylic acids**. They are **unable to form hydrogen bonds with their own molecules** as they lack an H atom bonded to a highly electronegative O atom. Their predominant intermolecular forces are **permanent dipole-permanent dipole** interactions, which are weaker than the hydrogen bonding between RCO_2H molecules.

Acyl chlorides which have lower M_r possess a sharp pungent smell and have an irritating effect on the eyes and mucous membrane, partly due to their rapid hydrolysis in air to form HCl and carboxylic acids. **Volatile esters** have strong, pleasant and fruity odours.

2.2.2 Solubility

Solubilities of carboxylic acid derivatives are dependent on the **size of the hydrocarbon chain**. As the **length of the non-polar hydrocarbon chain increases**, solubility in water **decreases**. The **permanent dipole-induced dipole interactions** between the larger non-polar alkyl group and water molecules **do not release sufficient energy** to overcome the strong **hydrogen bonds** between the water molecules. In addition, the larger alkyl group also **hinders the formation of hydrogen bonds between the carboxylic acid derivative's functional group and water molecules**.

Esters are **insoluble in polar solvents** but are **soluble in non-polar solvents**.

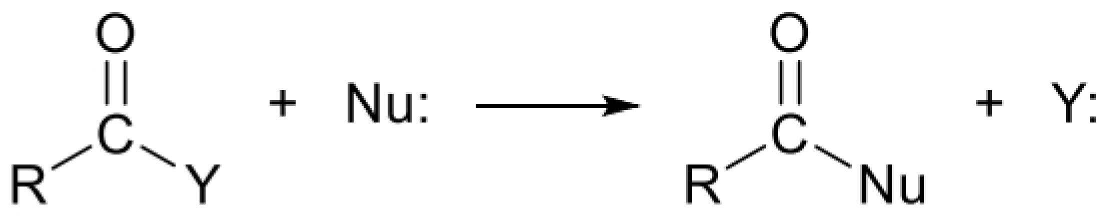
Acid chlorides are **soluble in non-polar solvents** and **soluble in water**. They hydrolyse rapidly in water to form strong acids (HCl) which then ionise. (See Section 2.3.1)

2.3 Reactions

Acid derivatives, like carboxylic acids, contain the carbonyl group C=O, and the reactions of acid derivatives typically proceed via **nucleophilic (acyl) substitution** at the carbonyl carbon.

This type of reaction occurs readily because of the presence of good leaving groups (Y) and the partial positive charge on the carbonyl carbon which attracts nucleophiles.

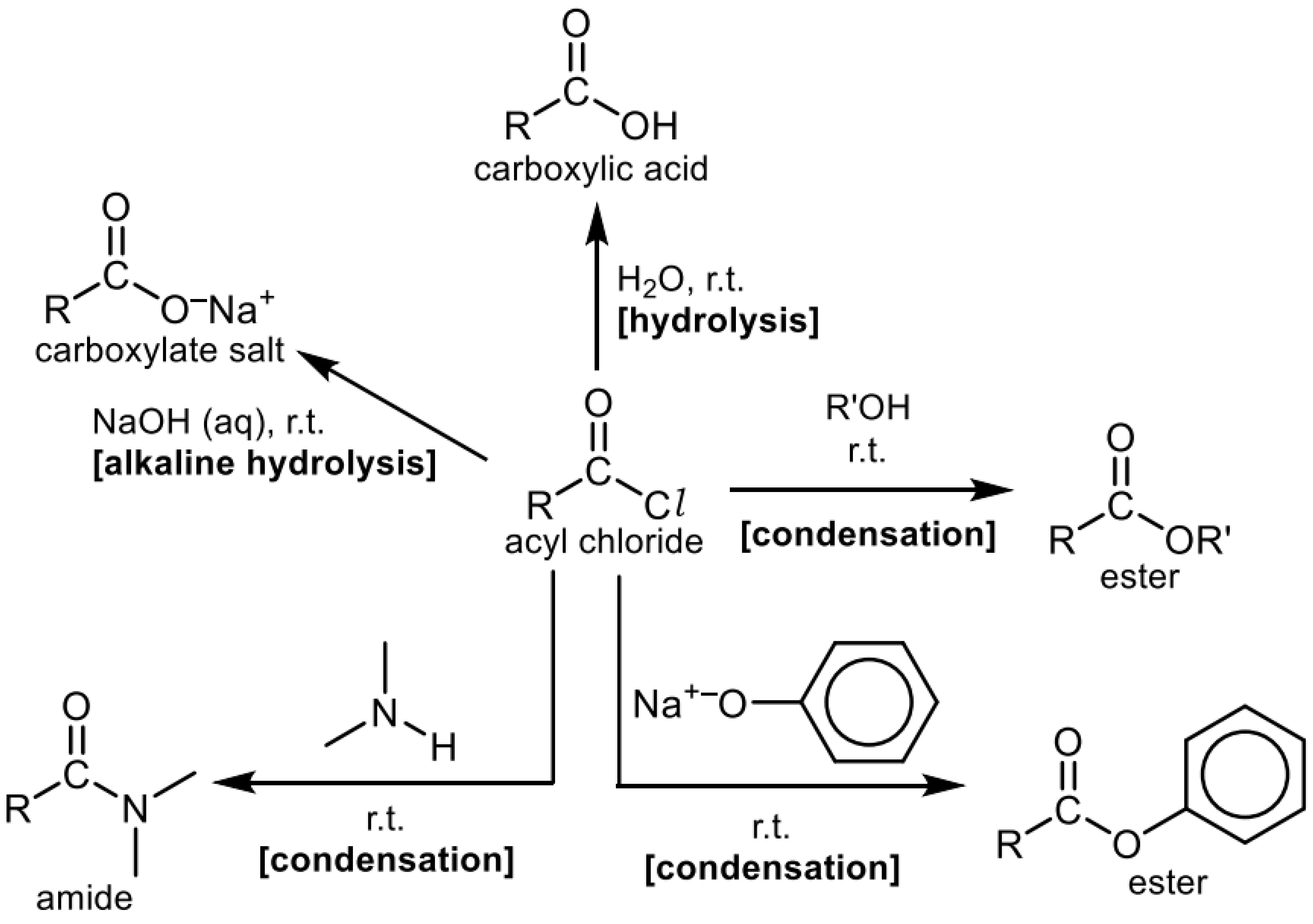
Y is replaced by a nucleophile (Nu:):



where
Y = OH acid
Cl acyl chloride
OR' ester

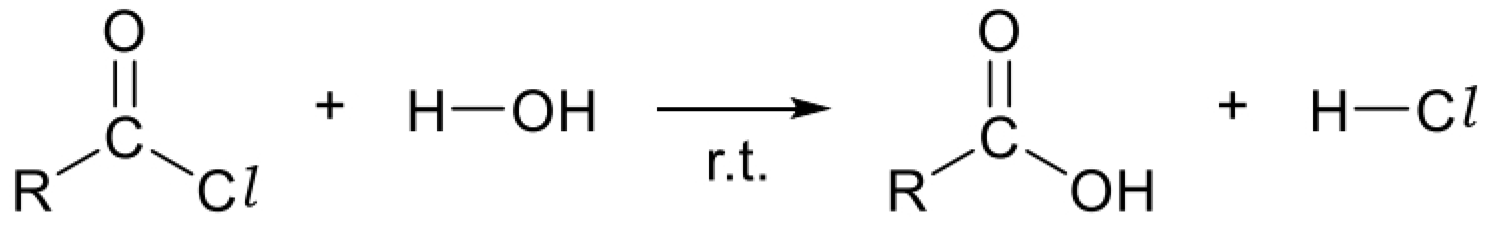
2.3.1 Reactions of acyl chlorides

Reactions of acyl chlorides



2.3.1.1 Hydrolysis

LO (d) describe the hydrolysis of acyl chlorides.



- ➢ Acid chlorides are the most reactive of the derivatives of carboxylic acids.
- ➢ Acid chlorides are hydrolysed on contact with water.
- ➢ White fumes of hydrogen chloride are evolved.
- ➢ Since HCl is very soluble, some remained dissolved in solution so that when $RCOCl$ is reacted with water, the resultant solution is strongly acidic (pH ~ 1, due to complete ionisation of HCl).

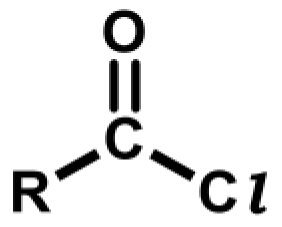
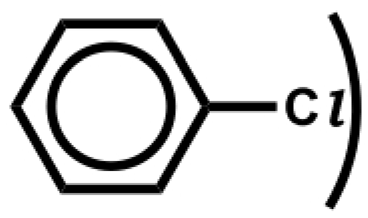
LO (f) explain the relative ease of hydrolysis of acyl chlorides, alkyl chlorides and aryl chlorides.

<u>Relative ease of hydrolysis of acyl chlorides, alkyl chlorides and aryl chlorides</u>

The ease of hydrolysis is dependent on two factors:

1. **Electronic factor**:
   - electron deficiency of C centre
   - ease of cleavage of C–Cl
2. **Steric factors** can also facilitate or hinder nucleophilic attack at the carbonyl carbon.

***Ease of hydrolysis*:** **$R–COCl$ > $R–CH_2–Cl$ > $Ar–Cl$**

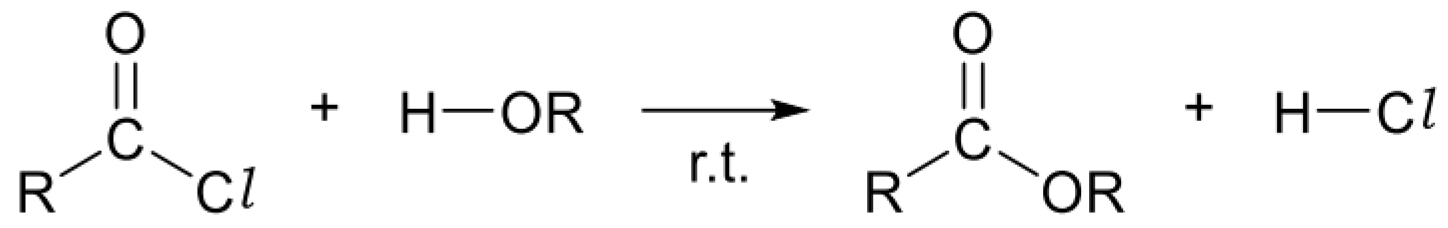
compound		**RCH_2Cl**	**ArCl** (e.g. )
electronic factor	**higher δ+ charge on C** (bonded to 2 strongly electronegative atoms, O and Cl) ➢ attracts nucleophile more strongly **Highly polarized C–Cl bond cleaves easily** without heating	**lower δ+ charge on C** (bonded to 1 electronegative Cl atom) ➢ attracts nucleophile less strongly **C–Cl bond cleaves only with heating**	overlapping of p–orbital on Cl atom with π-electron cloud of the benzene ring ➢ attracts nucleophile less strongly **C–Cl bond** has **partial double bond** character ➢ no cleavage occurs due to strengthening of the C–Cl bond electron-rich benzene ring **repels** nucleophile
steric factor	**sp^2** hybridised C (**less** steric hindrance since Nu attacks trigonal planar C)	**sp^3** hybridised C (**more** steric hindrance since Nu attacks tetrahedral C)	attack of Nu **blocked** by the aromatic ring
reaction with aq. $AgNO_3$	White ppt of $AgCl$ is observed immediately.	White ppt of $AgCl$ is observed only after prolonged boiling. The white ppt observed appears faster when heated with ethanolic $AgNO_3$.	No ppt even after prolonged boiling. No ppt is observed when heated with ethanolic $AgNO_3$.

2.3.1.2 Reactions with alcohols, phenols, ammonia and amines

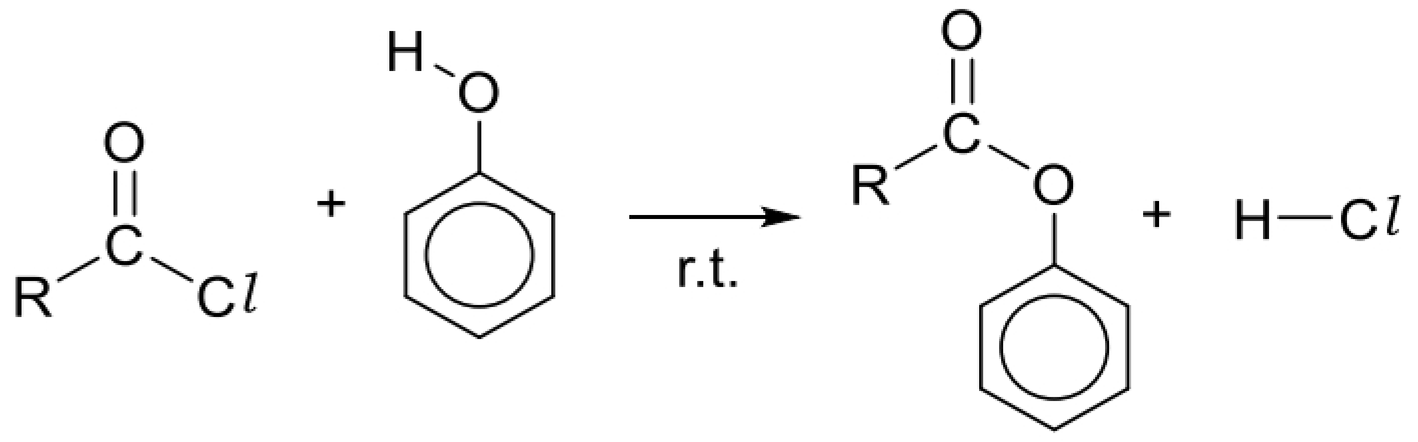
LO (e) describe the reactions of acyl chlorides with alcohols, phenols and primary amines.
(g) describe the formation of esters from acyl chlorides, using phenyl benzoate as an example.

Acid chlorides react with **alcohols** and **phenols** to form **esters**.

With alcohols:



With phenols:



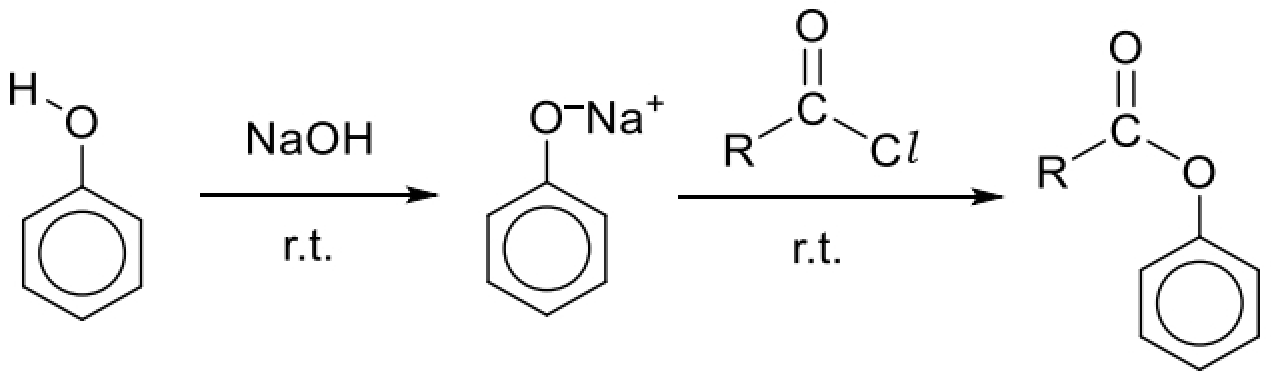
Comparing with RCO_2H,

$$RCO_2H + R'OH \xrightleftharpoons[\text{heat}]{\text{conc. } H_2SO_4} RCO_2R' + H_2O$$

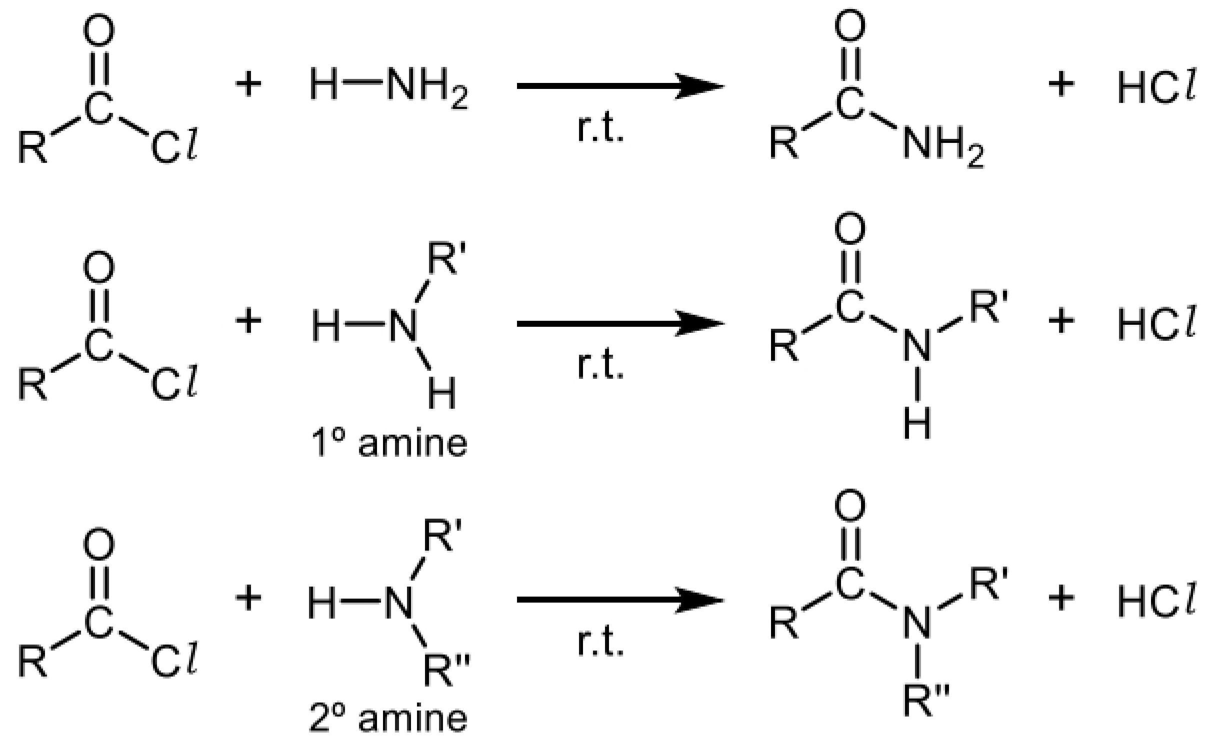
Phenols cannot react with carboxylic acids to form esters! They can only react with acid chlorides to form esters!

Note:
The formation of esters from the reaction of an acyl chloride and a phenol proceeds via an **alkaline medium** to first convert the **less nucleophilic phenol to a more nucleophilic phenoxide ion**.

However, this reaction can also proceed even if an acyl chloride is mixed with phenol without first converting the phenol to the phenoxide anion.



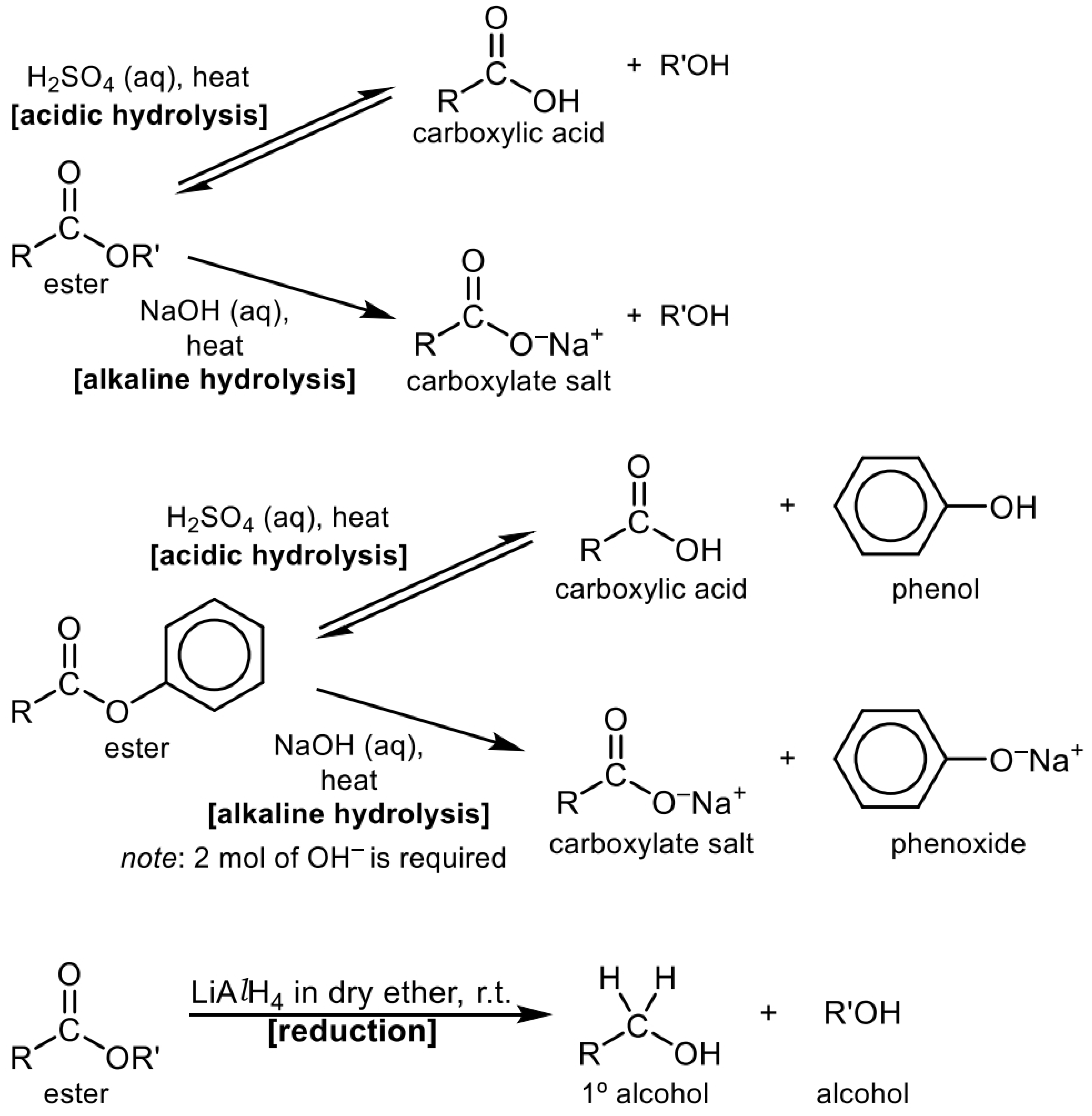
Acyl chlorides react with **ammonia** and **amines** to give **amides**.



Note:
Tertiary amines, NR'₃, **do** not react with acyl chlorides to give amides. **(WHY?)**

2.3.2 Reactions of esters

Reactions of esters



2.3.2.1 Laboratory preparation of esters

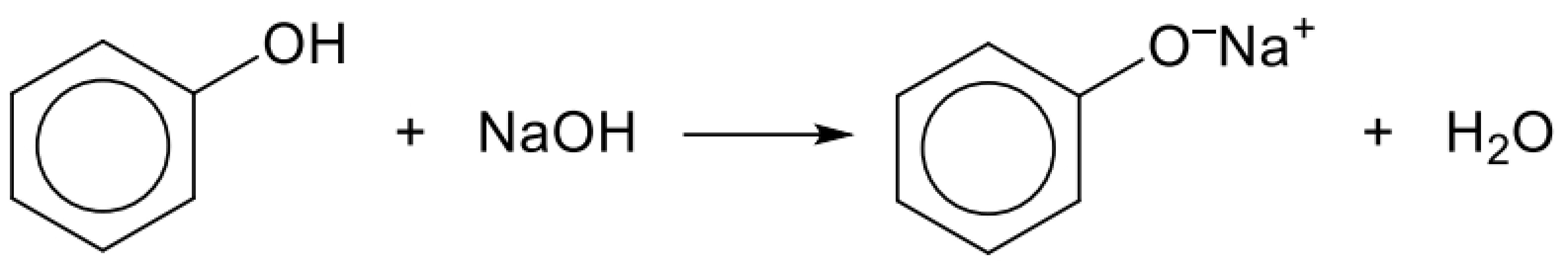
Ethyl ethanoate can be prepared by the reaction between concentrated ethanoic acid and ethanol in the presence of concentrated H_2SO_4 as a catalyst.

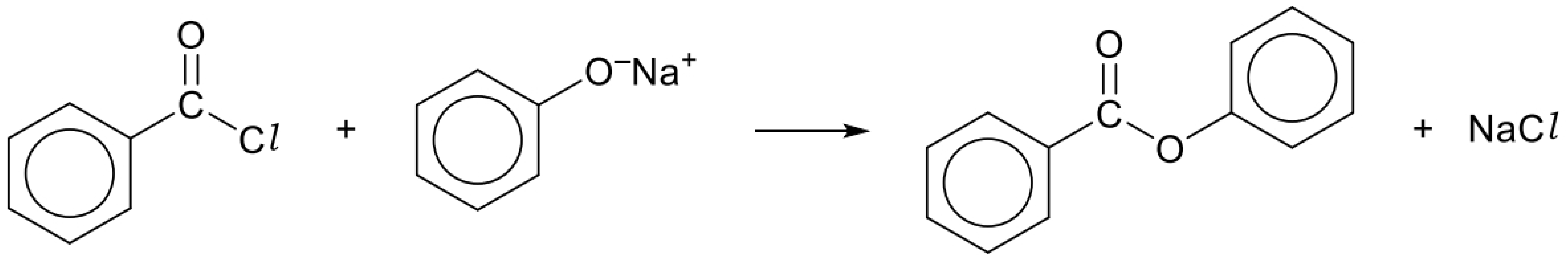
Please refer to the Appendix for a detailed procedure of this preparation.

$$CH_3CO_2H + CH_3CH_2OH \overset{\text{conc. } H_2SO_4\text{, heat}}{\rightleftharpoons} CH_3CO_2CH_2CH_3 + H_2O$$

- The reaction is **reversible**.
- As the equilibrium constant is not very large (about 3.4), equilibrium is reached only after many days of heating.
- Therefore, **concentrated sulfuric acid is used:**
  - It acts **as <u>catalyst</u>** to enhance nucleophilic attack on carbonyl carbon (See Appendix).
  - It also acts as a **<u>dehydrating agent</u>** to remove water, shifting position of equilibrium to the right.
- The equilibrium position is driven to the right by using an excess of one of the reactants.

Phenyl benzoate can be prepared by the reaction between benzoyl chloride and phenol in the presence of sodium hydroxide.





Note:

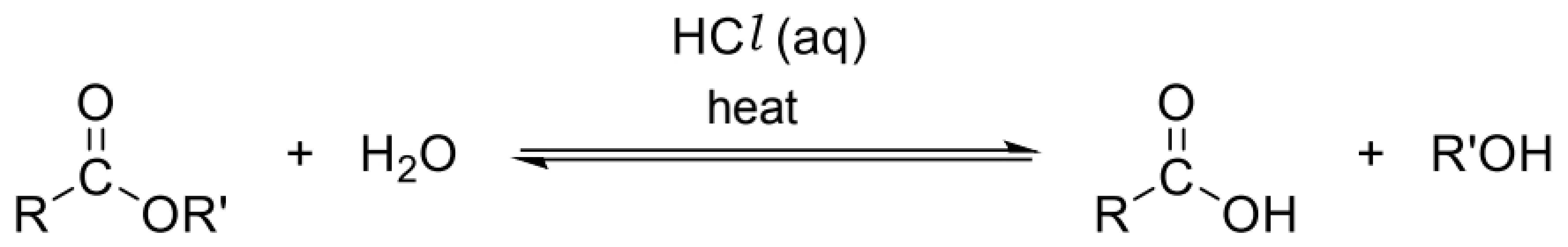
To form phenolic esters, we can only use **RCOCl** and sodium phenoxide, or **RCOCl** and phenol. RCOOH **CANNOT** be used.

2.3.2.2 Hydrolysis

LO (h) describe the acid and base hydrolyses of esters.

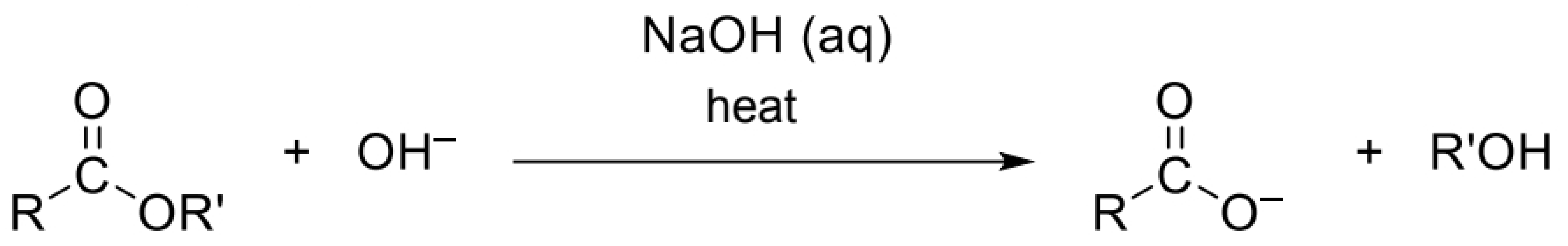
The hydrolysis of esters by heating with water alone occurs very, very slowly. This hydrolysis can be sped up by **heating with acid or alkali**.

(I) Acidic hydrolysis



The hydrolysis of esters is nucleophilic in nature, where the nucleophile is H_2O (for acidic hydrolysis). The reaction is **reversible**.

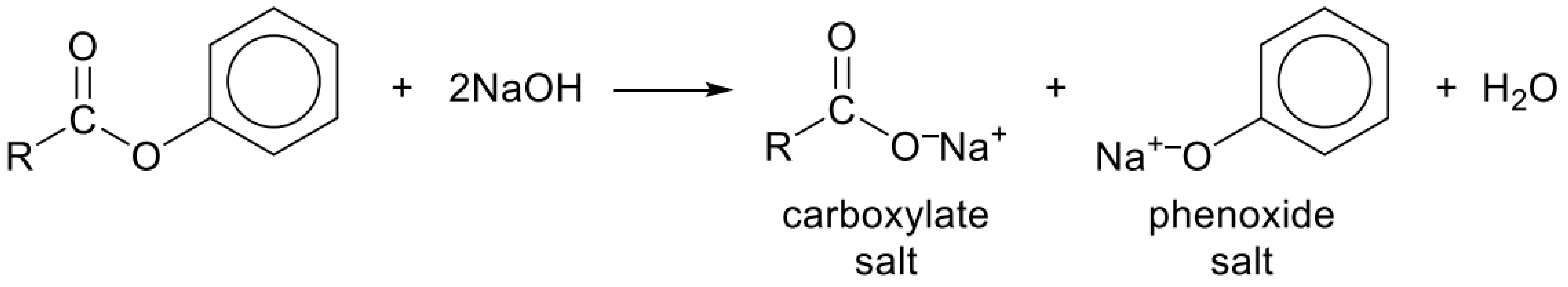
(II) Alkaline/Basic hydrolysis



Alkalis promote hydrolysis of esters by providing the strong nucleophile OH^-. Under alkaline conditions, the carboxylic acid is obtained in the form of the carboxylate salt. The reaction is essentially **irreversible**, since a resonance stabilised carboxylate anion shows little tendency to react with an alcohol. Alkaline hydrolysis is often referred to as *saponification*.

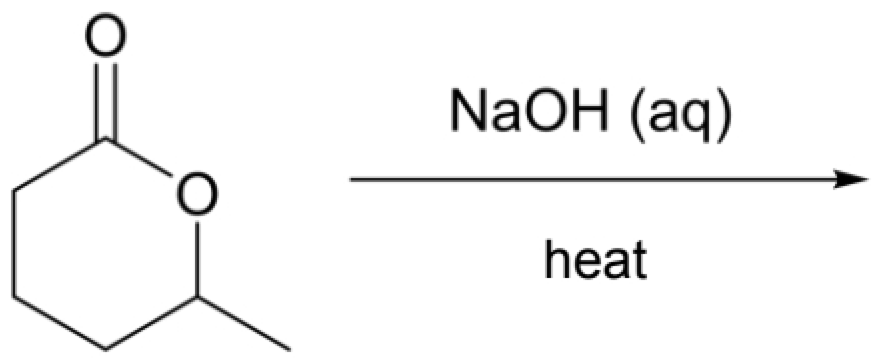
Note:
If the hydroxy compound formed is a phenol or substituted phenol, then the phenoxide salt is obtained.

Example:



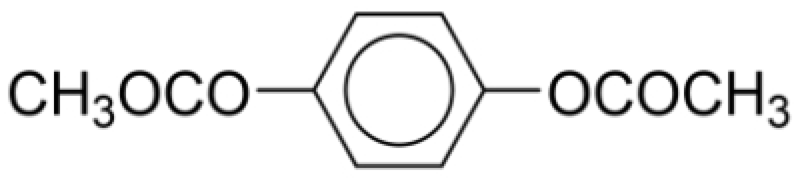
Example 2A

Draw the structure of the organic product formed.

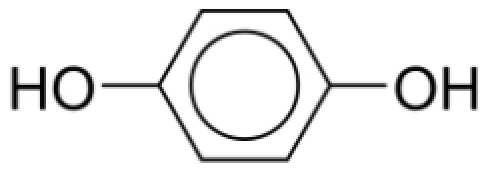


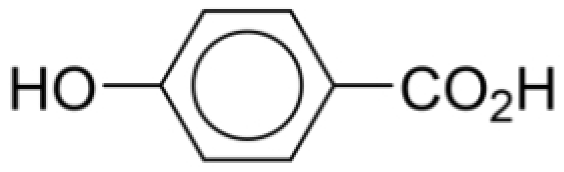
Example 2B

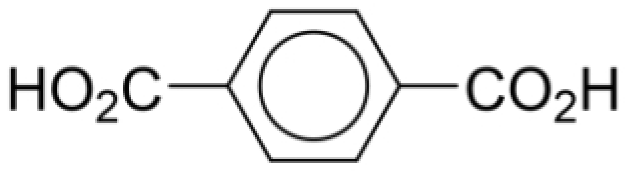
What are the products formed when compound **J** is heated with dilute sulfuric acid?

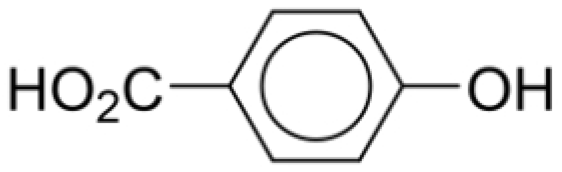


J

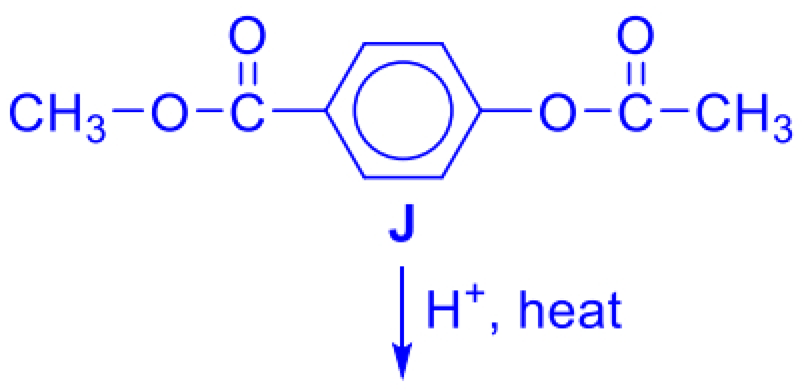
A  and CH_3CO_2H

B  and CH_3OH

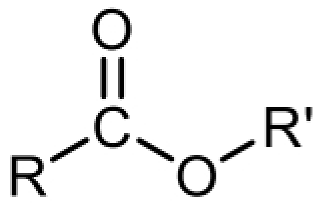
C CH_3CH_2OH,  and HCO_2H

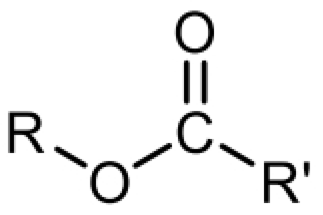
D CH_3OH,  and CH_3CO_2H

Working for Example 2 Option C:



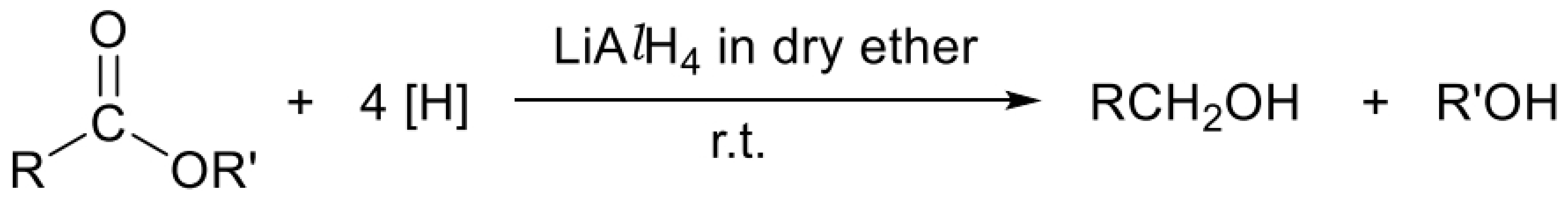
Note :

RCO_2R' is 

$ROCOR'$ is 

2.3.2.3 Reduction to alcohols

Esters can be **reduced to primary alcohols** by using lithium aluminium hydride ($LiAlH_4$) in dry ether.



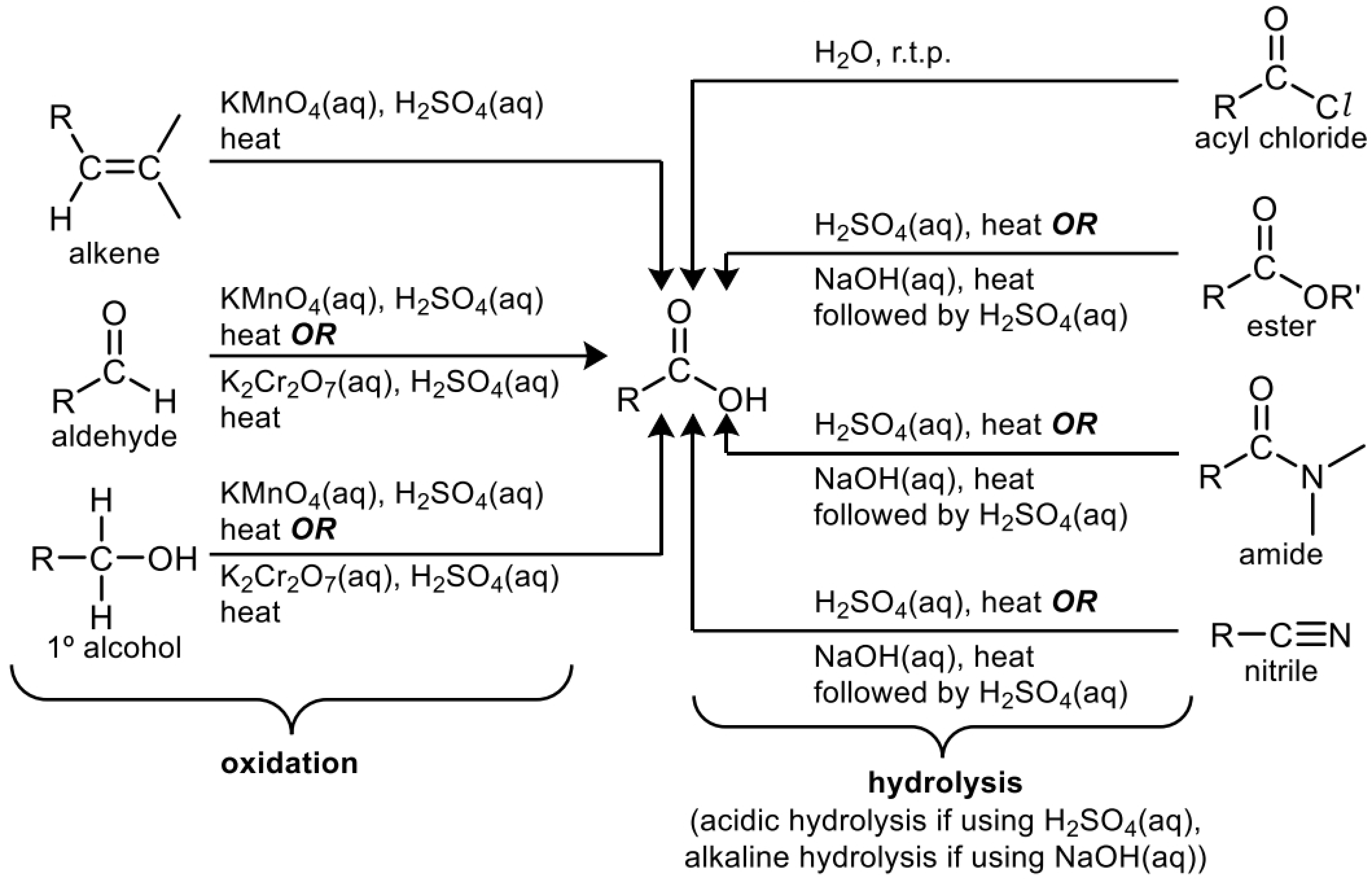
Reagents and conditions: $LiAlH_4$ in dry ether, room temperature

At the end of section 2, you should know that:

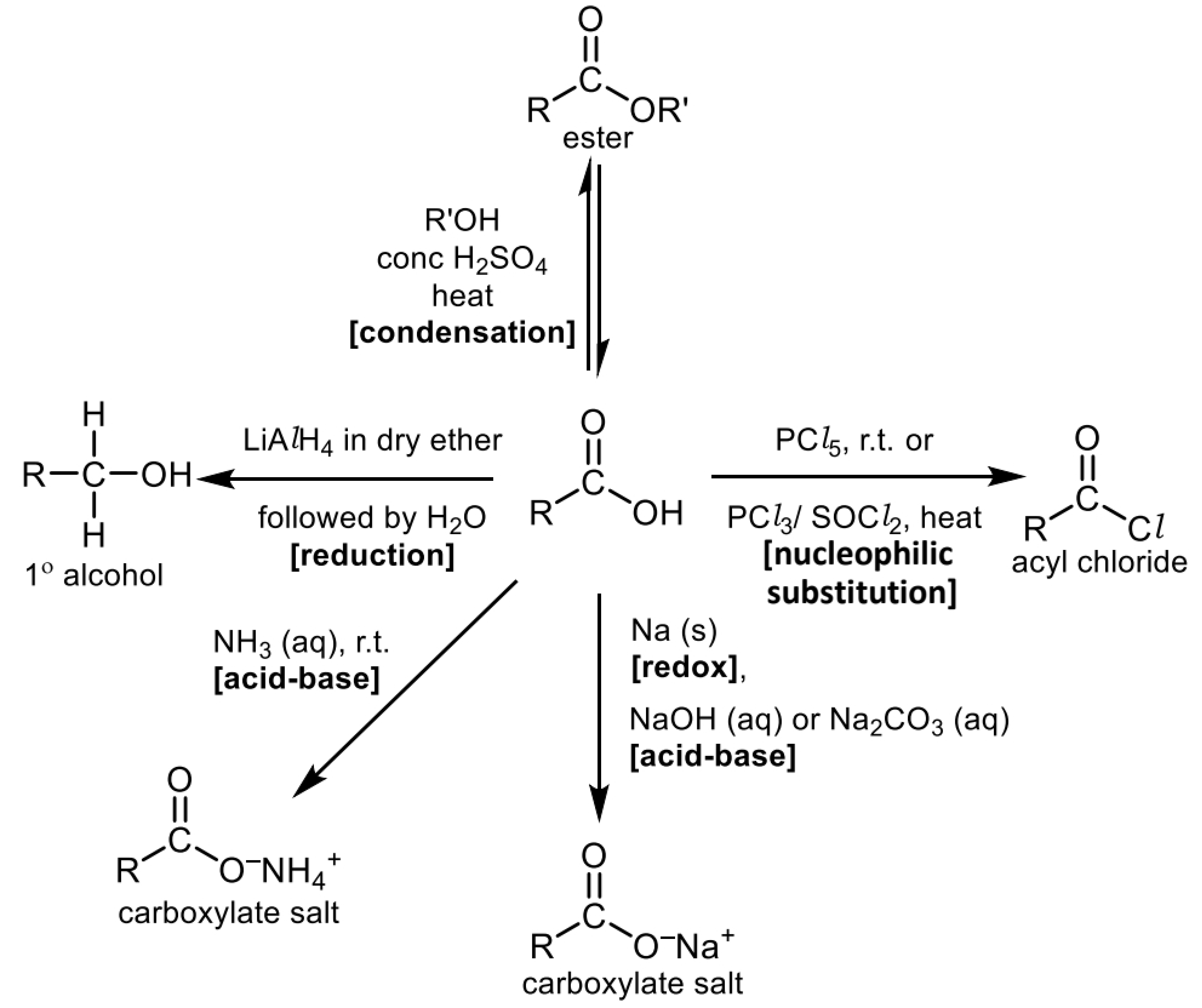
1. Acid chlorides, esters and amides are derivatives of carboxylic acids.
2. Acid chlorides and esters have lower boiling points than their parent carboxylic acids due to their lack of ability to form hydrogen bonds between molecules.
3. Esters with large molar masses are soluble in non-polar solvents and insoluble in polar solvents.
4. Acid chlorides are soluble in both non-polar solvents and water.
5. Acid chlorides hydrolyse rapidly in water to form the corresponding carboxylic acid and $HC\mathit{l}$(aq).
6. Acid chlorides react readily with nucleophiles, such as OH^-, primary and secondary amines, alcohols, and phenol.
7. Esters can be hydrolysed by heating with acids to give the corresponding carboxylic acid and alcohol. This reaction is reversible.
8. Esters can be hydrolysed by heating with alkalis to give the corresponding carboxylate salt and alcohol. This reaction is irreversible.
9. Esters can be reduced by $LiA\mathit{l}H_4$ in dry ether at room temperature to give the two corresponding alcohols.
10. Esters can be synthesized by heating a carboxylic acid with an alcohol in the presence of concentrated H_2SO_4.
11. Esters can be synthesized by mixing an acid chloride with an alcohol at room temperature.

Summary of Carboxylic Acids & Derivatives

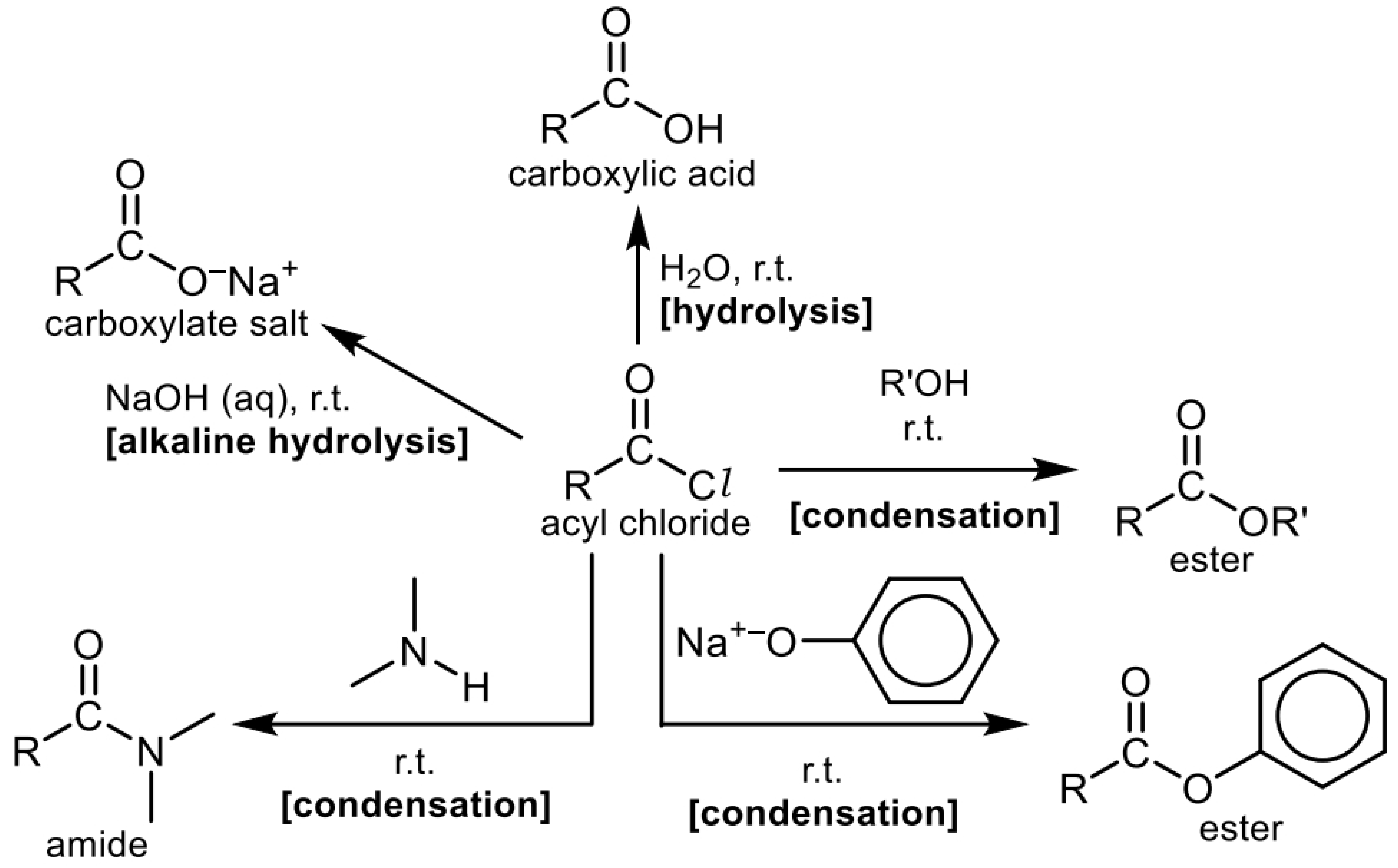
Preparation of carboxylic acids



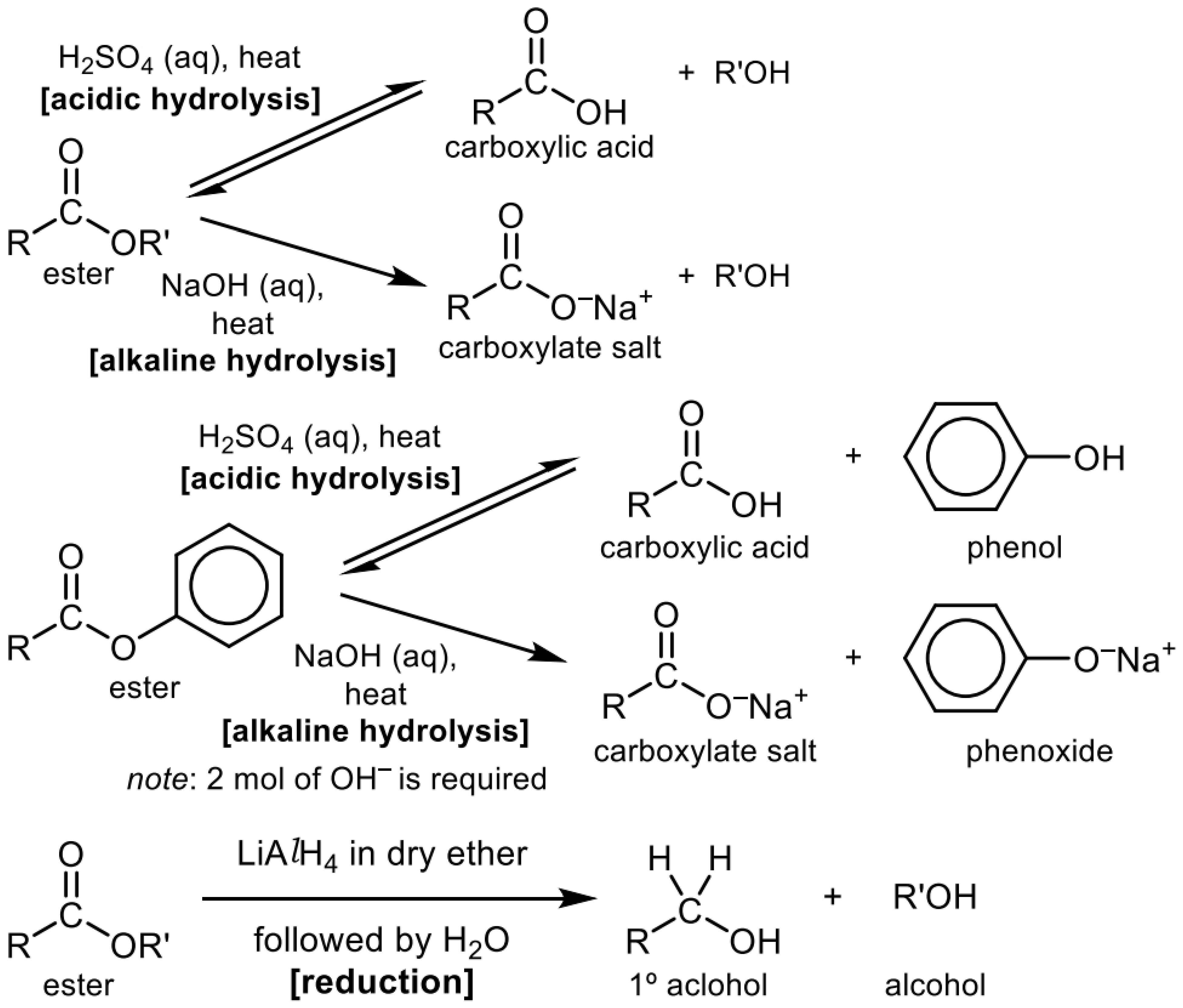
Reactions of carboxylic acids



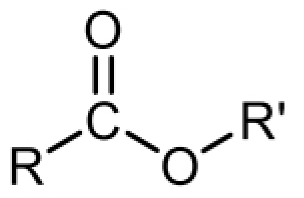
Reactions of acyl chlorides



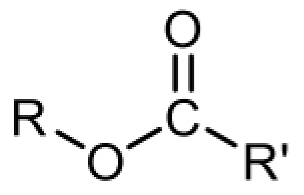
Reactions of esters

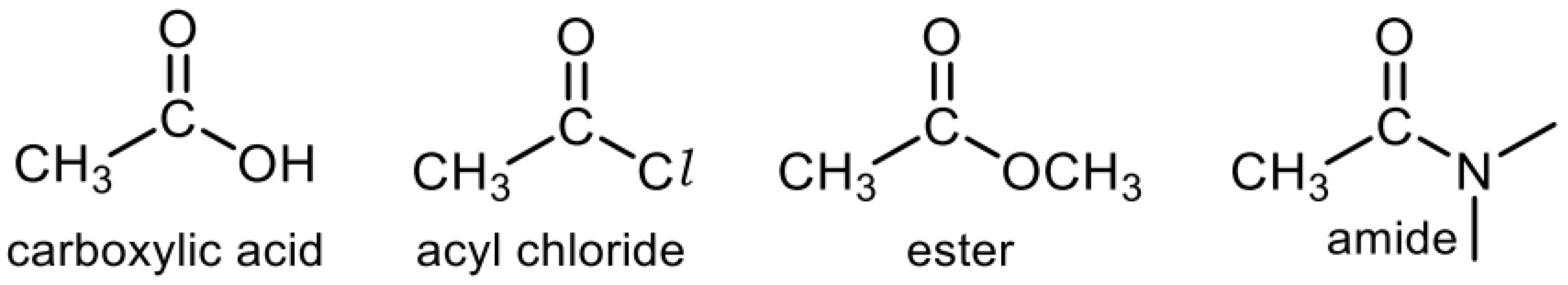


RCO$_2$R' is



ROCOR' is

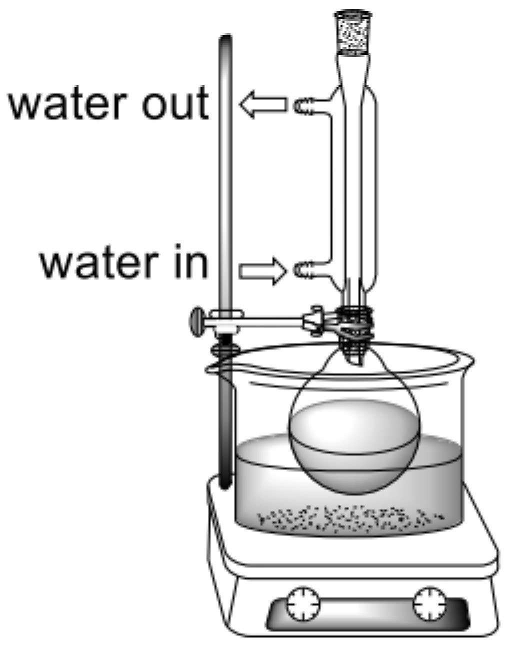
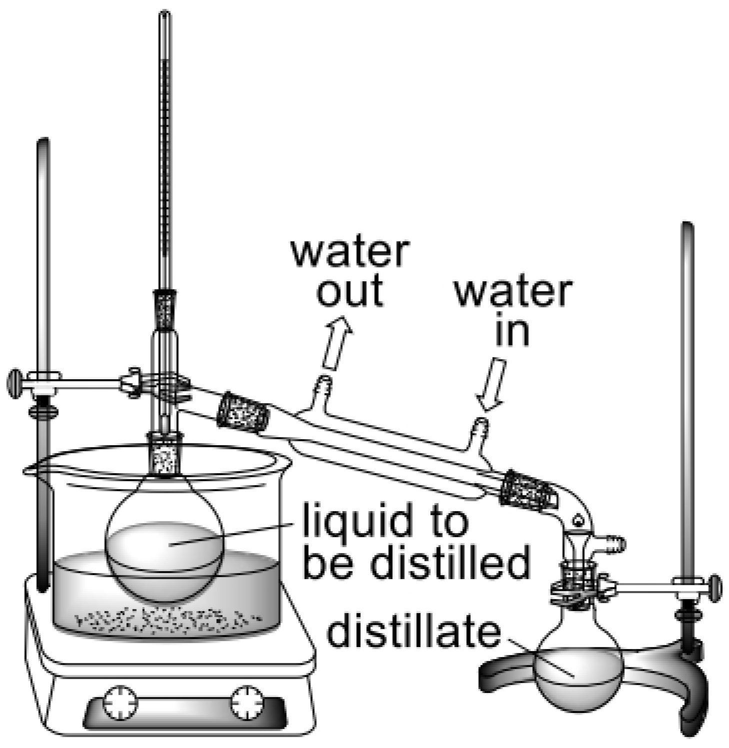
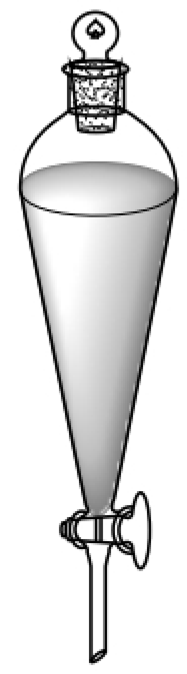




do not give positive iodoform test

4 Annex

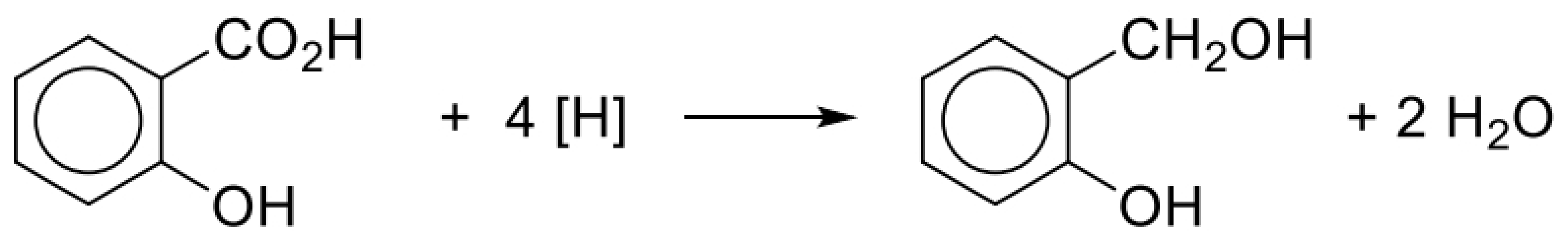
4.1. PREPARATION OF ETHYL ETHANOATE

- Mix 50 cm^3 of ethanol and 50 cm^3 of *glacial* ethanoic acid thoroughly in a 250 cm^3 round-bottomed flask.	- **Explain the meaning of the term *glacial* as applied to ethanoic acid.** ⇒ Glacial ethanoic acid is pure ethanoic acid CH_3CO_2H. It is called glacial because on cooling it forms glassy crystals.
- Add *slowly with cooling* and shaking 10 cm^3 of *concentrated sulfuric acid*.	- **Why is concentrated sulfuric acid used in this procedure?** ⇒ Concentrated sulfuric acid is a ***catalyst*** for the esterification reaction and to remove water. $CH_3CH_2OH + CH_3CO_2H \rightleftharpoons CH_3CO_2CH_2CH_3 + H_2O$ - **Why must the concentrated sulfuric acid be added slowly and with cooling?** ⇒ The concentrated sulfuric acid on dilution gives out a lot of heat; the slow addition with cooling is necessary to avoid splashing if the mixture gets hot.
- Ensure that the mixture is *homogeneous*, then fit the flask with a *reflux water-condenser* and boil the mixture gently *for 10 minutes*. Rearrange the position of the condenser for distillation, and distil off about two-thirds of the mixture.  **reflux setup**  **distillation setup**	- **Why must the mixture be homogeneous?** ⇒ Concentrated sulfuric acid is much denser than any of the other reagents. If not well mixed initially, the solution is liable to get too hot and boil uncontrollably when mixing occurs later in the reaction. - **What is a reflux water-condenser?** ⇒ A reflux water condenser is a Liebig condenser arranged vertically above the reaction flask; vapors are condensed and returned to the flask, the contents of which can therefore be boiled for long periods without any loss of material. - **Why is the reaction comparatively slow?** ⇒ Most organic reactions are slow since they involve the breaking of strong covalent bonds. The proportion of molecular collisions that have the necessary activation energy is usually fairly low.
- Transfer the distillate to a separating funnel and add about 25 cm^3 of 30% *sodium carbonate solution*. Stopper the funnel, invert it, and shake, *opening the tap from time to time*  separatory funnel - Allow the two layers to separate and carefully run off and reject the lower layer, ensuring that the sodium carbonate is removed as completely as possible.	- **What is the function of the sodium carbonate solution?** ⇒ The distillate contains traces of ethanoic acid and perhaps some sulfuric acid. Sodium carbonate solution removes this. - **Why do you need to open the tap from time to time?** ⇒ The neutralisation with sodium carbonate produces carbon dioxide gas; opening the tap releases this and avoids a build-up of pressure that might blow the stopper out of the funnel.

• Prepare a solution of 25 g of calcium chloride in 25 cm^3 of water, *add it to the crude ethyl ethanoate* in the funnel, and shake vigorously. Allow the mixture to separate, and run off the lower aqueous layer as completely as possible.	• **What is the function of the calcium chloride at this stage of the preparation?** ⇒ The crude ethyl ethanoate contains traces of ethanol; the calcium chloride solution removes this since it complexes with the ethanol
• Run the ethyl ethanoate into a small conical flask, add a few lumps of granular *anhydrous calcium chloride*, and shake occasionally until the *liquid is clear*.	• **What is the function of the calcium chloride at this stage of the preparation?** ⇒ The solid calcium chloride is a dehydrating agent; it removes any remaining traces of water from the product.
• Then decant the liquid into a *clean, dry* 100 cm^3 round-bottom flask, add some *anti-bumping granules*, and arrange for distillation including a 0–100 ºC thermometer in the apparatus. The distilling flask should be placed in a cold water bath, which is gradually heated. *The ether that is always formed* in this reaction will distil off at 35–40 ºC, and may be discarded. Continue to heat, and collect the fraction that boils between 74 ºC and 79 ºC.	• **What is the nature and purpose of anti-bumping granules?** ⇒ Anti-bumping granules are small pieces of silica; broken unglazed pottery works as well. This provides a nucleus on which gas bubbles grow, therefore avoiding the sudden production of large gas bubbles which can lead to 'bumping'. This, properly called succussion, causes liquid to splash over into the condenser and therefore produce an impure product. Severe bumping can even lead to loss of material through vents or can blow a distillation apparatus apart. • **Why is an ether formed in this reaction?** ⇒ An ether is formed because sulfuric acid can cause the elimination of a molecule of water between two alcohol molecules. The water causes the ionisation of the sulfuric acid: $CH_3CH_2OH + HOCH_2CH_3 + H_2SO_4 \rightarrow CH_3CH_2OCH_2CH_3 + H_3O^+ + HSO_4^-$

4.2. A LITHIUM ALUMINUM HYDRIDE REDUCTION

The reaction concerned is the reduction of 2-hydroxybenzoic acid (salicylic acid) to give (2-hydroxyphenyl)methanol (saligenin):

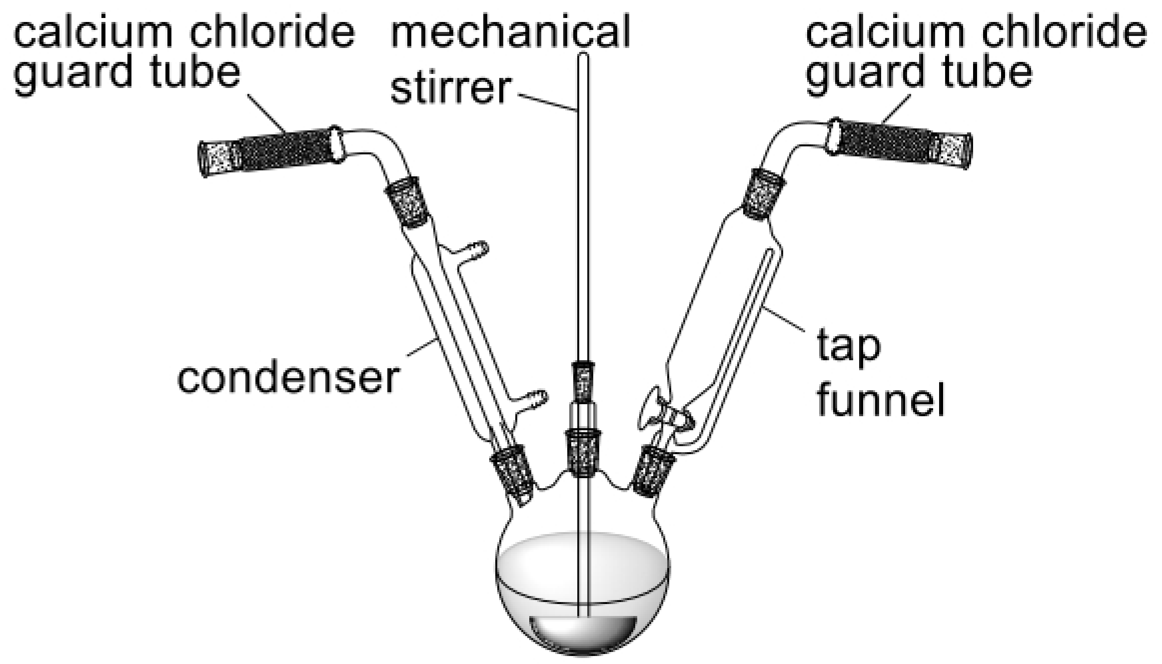


This preparation should only be attempted by a professionally-trained chemist.

Hazards:

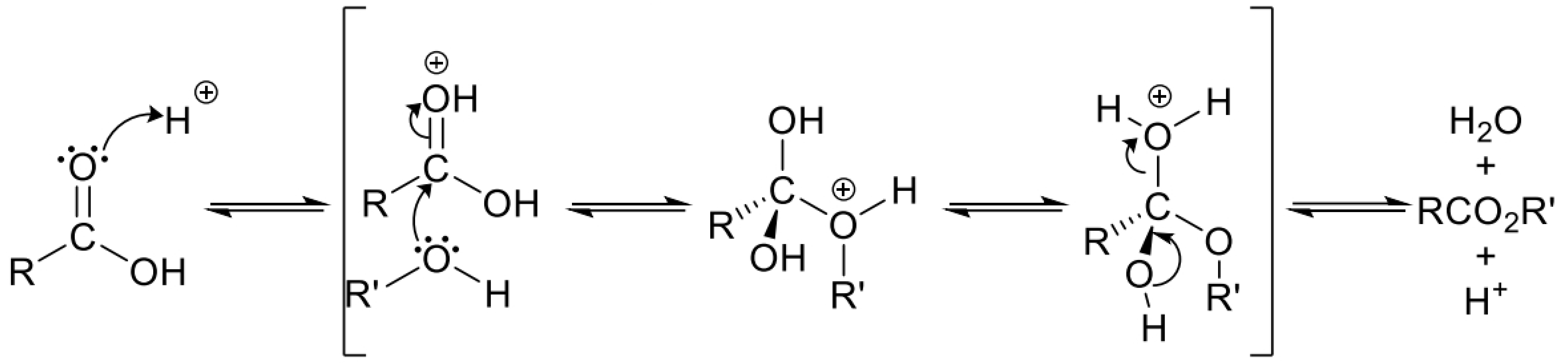
Lithium aluminium hydride reacts extremely violently with water; the hydrogen liberated may be ignited by a fragment of the hydride and cause an explosion. The powder is extremely caustic, and must be kept away particularly from the lips, nostrils and eyes. Therefore it must only be handled in an efficient fume cupboard. For these reasons, and the fact that reductions are performed in dry ethoxyethane ($C_2H_5OC_2H_5$, ether) which is extremely flammable and forms an explosive mixture with air, $LiA\ell H_4$ is an unsuitable reagent for school use.

A slight excess of the hydride is employed, which is destroyed after the reaction by the addition either of ordinary undried ethoxyethane which contains enough water for the purpose and adds it gradually and in small amounts; or by addition of ethyl ethanoate which is reduced to ethanol.

• Assemble in a fume cupboard a 3-necked flask fitted with a stirrer, a reflux condenser and a tap funnel, the apparatus being thoroughly dry, and the condenser and the funnel closed by calcium chloride guard tubes.  	• **Why must the apparatus be thoroughly dry?** ⇒ Much of the preparation technique is concerned with preventing the dangerous reaction of lithium aluminium hydride with water - the reaction is exothermic and generates hydrogen, so the danger of explosion is evident. • **What is the function of calcium chloride guard tubes?** ⇒ Anhydrous calcium chloride is hygroscopic (has a high affinity for water), and the guard tubes prevent water vapour from entering from the atmosphere. Lithium aluminium hydride dust can even catch fire on a damp day.
• Run 90 cm^3 of *dry* ethoxyethane into the flask and start the stirring. Weigh out 2.5 g of lithium aluminium hydride, and then divide 0.5 g of this amount into *very small portions*: add these portions in turn cautiously to the stirred ethoxyethane. Then add the remaining 2.0g of the hydride more rapidly.	• **How is ethoxyethane dried?** ⇒ Sodium wire is used. • **What is the reason for adding a small portion of lithium aluminium hydride initially?** ⇒ This is to remove any traces of water which in spite of the precautions taken may be present in the reaction flask.
• When the addition is complete, continue stirring the mixture for 15 minutes.	• **What is the reason for this stirring?** ⇒ To ensure that the lithium aluminium hydride is dissolved.
• Now cool the mixture thoroughly in an ice-water bath, and run in over a period of 45 minutes a solution of 6.0 g of *dry* 2-hydroxybenzoic acid in *dry* ethoxyethane.	• **Why is the mixture cooled?** ⇒ The reduction is exothermic; the boiling temperature of ethoxyethane is 34.5 ºC and the reaction must at this stage be kept cold to prevent thermal runaway and loss of the ethoxyethane.
• When the addition of the solution of 2-hydroxybenzoic acid is complete, heat the mixture under reflux on the water bath for 15 minutes.	• **Why is the mixture heated for 15 minutes?** ⇒ This is to ensure completion of the reduction and the consumption of the lithium aluminium hydride.

• Thoroughly chill the mixture in ice-water, and hydrolyse any unused hydride by the *slow* addition of 50 cm^3 of ordinary undried ethoxyethane, followed by the *slow* addition of 75 cm^3 of dilute sulphuric acid.	• **Why does the mixture have to be chilled?** ⇒ The reaction of lithium aluminium hydride with water is very exothermic. • **Why is the addition of the undried ethoxyethane slow?** ⇒ To ensure that the reaction with water is not violent. • **Why is the addition of sulfuric acid slow?** ⇒ This precautionary, in case any lithium aluminium hydride still remains. • **What is the purpose of the sulfuric acid?** ⇒ The hydrolysis of lithium aluminium hydride also gives lithium hydroxide, which is not very soluble in ethoxyethane and gives a white sludge. Sulfuric acid forms water-soluble lithium sulfate which passes into the aqueous layer.
• Transfer the reaction mixture to a separating funnel, run off and keep the lower aqueous layer and retain the ethoxyethane layer in the funnel. Shake the aqueous layer successively with two 25 cm^3 portions of ethoxyethane, and add these to the main ethoxyethane solution. Dry the ethoxyethane solution with anhydrous sodium sulfate.	• **Why is the aqueous layer shaken with ethoxyethane?** ⇒ This extracts any of the organic product that remains in the aqueous layer. • **Why is the organic product significantly soluble in the aqueous layer?** ⇒ The two hydroxyl groups make it significantly soluble since they can hydrogen bond with water. • **Why are two 25 cm^3 portions of ethoxyethane used, rather than one of 50 cm^3?** ⇒ The process of solvent extraction is more efficient if several extractions are made rather than just one. • **How would you know when the solution is dry?** ⇒ It would be clear rather than cloudy.
• Filter the ethoxyethane solution, which is then distilled to remove ethoxyethane. Arrange a distillation apparatus using a 100 cm^3 distilling flask heated with a hot water bath (NO naked flames should be anywhere in the laboratory) and fitted with a tap funnel. The ethoxyethane solution is placed in the funnel, and added to the heated distillation flask as fast as the ethoxyethane distils over. When all the ethoxyethane has distilled over, cool the oily residue of crude product, which will rapidly crystallise.	• **Why is the solution filtered?** ⇒ This removes any particles of sodium sulfate. • **Why should there not be flames *anywhere* in the laboratory?** ⇒ The vapour of ethoxyethane is very dense, and can creep along bench surfaces or along the floor. It is possible to ignite it if there are flames on the other side of the room.
Re-crystallise the product twice from the minimum amount of boiling pure water; cool the saturated solution to about 70 ºC, then in ice-water. Filter the final product and dry in a desiccator. The product gives fine white crystalline plates, m.p. 84–85 ºC.	• **Why is the minimum amount of boiling water used?** ⇒ The solution needs to be saturated at the boiling temperature of the solvent to minimise losses. • **Why is a dessicator used rather than drying the crystals in an oven?** ⇒ The melting temperature of the product is low and it would melt; a desiccator is in any case much more efficient.

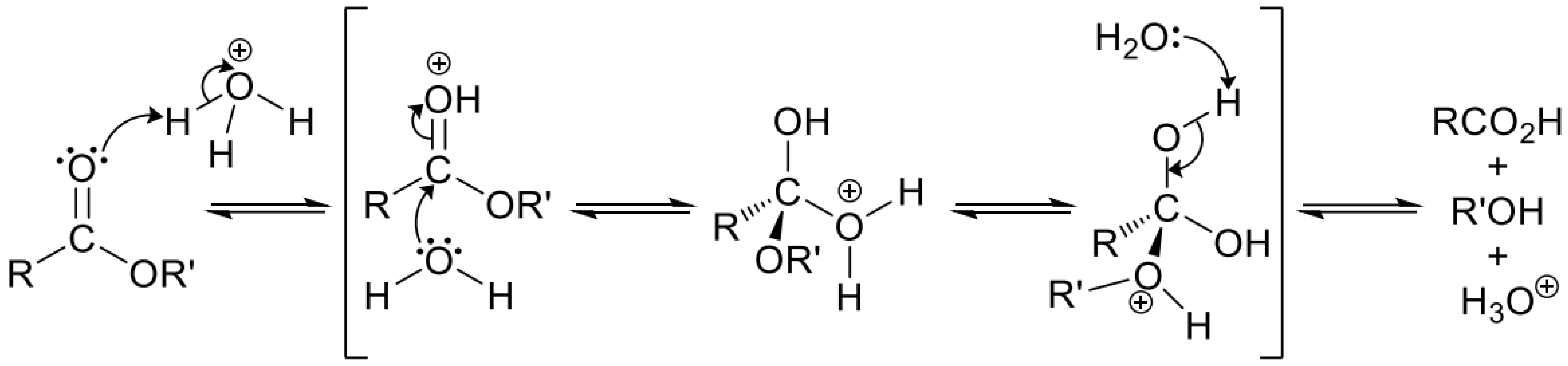
5A. Mechanism of esterification [not required for H2 Chemistry]



- Protonation of carbonyl group activates it for nucleophilic attack by alcohol to yield a tetrahedral intermediate.
- Transfer of a proton then converts the –OH into a good leaving group (H_2O).
- Expulsion of water yields the ester, and acid catalyst is regenerated.

5B. Mechanism of acidic hydrolysis of esters

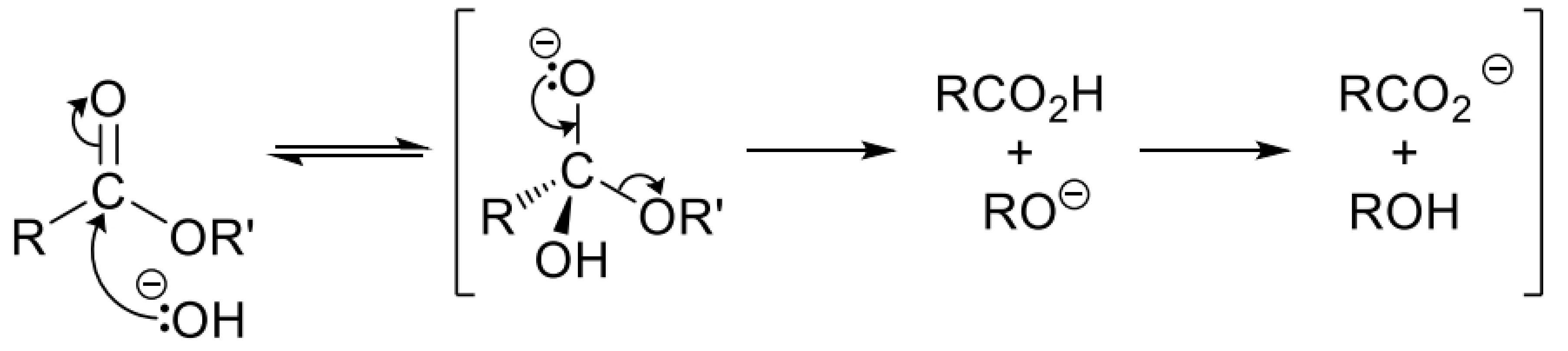
Mechanism of acidic hydrolysis: [not required for H2 Chemistry]



- Protonation of carbonyl group activates it for nucleophilic attack by water to yield a tetrahedral intermediate.
- Transfer of a proton then converts the –OR into a good leaving group (R'OH).
- Expulsion of alcohol yields the carboxylic acid and acid catalyst is regenerated.

5C. Mechanism of alkaline hydrolysis of esters

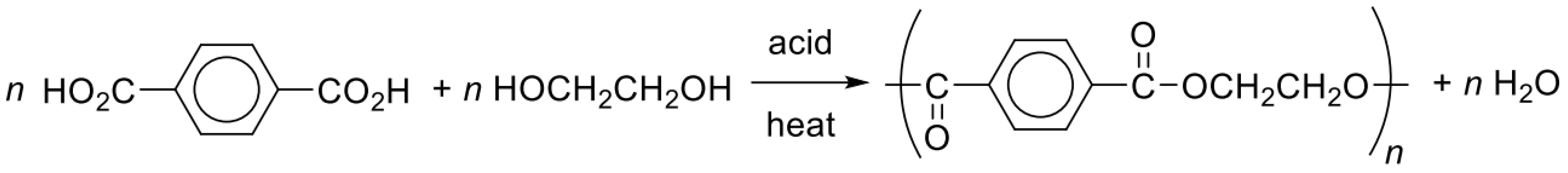
Mechanism of alkaline hydrolysis: nucleophilic acyl substitution [not required for H2 Chemistry]



- The OH^- attacks the electron deficient carbonyl carbon to give a tetrahedral intermediate.
- Expulsion of the alkoxide ion then generates the carboxylic acid.
- A proton transfer occurs to give the carboxylate ion and the alcohol.
- Protonation of the carboxylate ion by addition of aqueous mineral acid gives the free carboxylic acid.

6. Formation of Polyesters

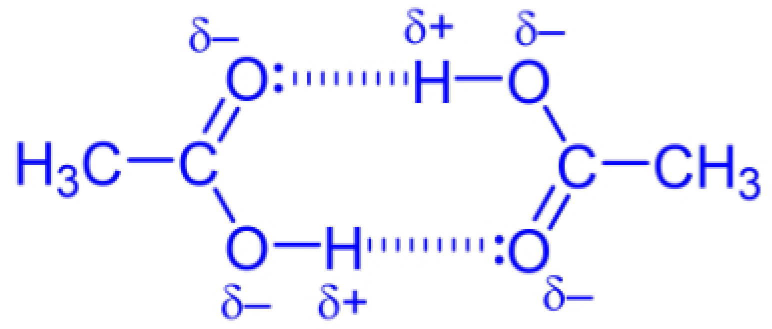
- Polyesters are formed by the interaction of a dicarboxylic acid and a diol.
- A small molecule (H_2O) is eliminated ⇒ ***Condensation polymerisation.***
- Polyesters are long-chain molecules that are unreactive and that have great tensile strength.



- *Terylene* (also called Dacron polyester) has properties which have certain advantages over those of natural fibres. For example, fabrics containing *Terylene* and cotton are soft and capable of retaining an almost permanent crease.
- *Terylene* may also be obtained in the form of transparent sheets – a common material for recording tape, computer diskettes and packaging for frozen foods.

7 Solution to Self-Check

Self Check 1A



Ethanoic acid (CH_3CO_2H, M_r = 60.0) has an **apparent M_r of 120.0** which **doubles** the expected value. Each acid molecule pairs up to form a **cyclic** (closed ring) **dimer** via intermolecular **hydrogen bonding.**