

## Chapter 10

# Carboxylic Acids and Their Derivatives

### Chapter Summary

**Carboxylic acids**, the most important class of organic acids, contain the **carboxyl group**,  $\text{—C(=O)—OH}$ . The IUPAC ending for the names of these compounds is *-oic acid* but many common names (such as formic acid and acetic acid) are also used. An **acyl group**,  $\text{R—C(=O)—}$ , is named by changing the *-ic* ending of the corresponding acid to *-yl* [ $\text{CH}_3\text{C(=O)—}$  is acetyl].

The carboxyl group is polar and readily forms hydrogen bonds. A carboxylic acid dissociates to a **carboxylate anion** and a proton. In the carboxylate anion, the negative charge is delocalized equally over both oxygens. The  $\text{p}K_a$ 's of simple carboxylic acids are about 4–5, but the acidity can be increased by electron-withdrawing substituents (such as chlorine) close to the carboxyl function.

Carboxylic acids react with bases to give salts. These are named by naming the cation first and then the carboxylate anion. The name of the anion is obtained by changing the *-ic* ending of the acid name to *-ate* (acetic becomes acetate).

Carboxylic acids are prepared by at least four methods: (1) by oxidation of primary alcohols or aldehydes, (2) by oxidation of an aromatic side chain, (3) from a Grignard reagent and carbon dioxide, or (4) by hydrolysis of a nitrile,  $\text{RC}\equiv\text{N}$ .

**Carboxylic acid derivatives** are compounds in which the carboxyl  $\text{—OH}$  group is replaced by other groups. Examples include **esters**, **acyl halides**, **anhydrides**, and **amides**.

**Esters**,  $\text{RCO}_2\text{R}'$ , are named as salts are; the  $\text{R}'$  group is named first, followed by the name of the carboxylate group (for example,  $\text{CH}_3\text{CO}_2\text{CH}_2\text{CH}_3$  is ethyl acetate). Esters can be prepared from an acid and an alcohol, with a mineral acid catalyst (**Fischer esterification**). The key step of the mechanism is nucleophilic attack by the alcohol on the protonated carbonyl group of the acid. Many esters are used as flavors and perfumes.

**Saponification** is the base-mediated hydrolysis of an ester, yielding its component carboxylate salt and alcohol. **Ammonolysis** of esters gives amides. Esters react with Grignard reagents to give tertiary alcohols. With lithium aluminum hydride, on the other hand, they are reduced to primary alcohols.

Acid derivatives undergo nucleophilic substitution. The mechanism is as follows: the nucleophile adds to the trigonal carbonyl carbon to form a **tetrahedral intermediate**, which, through loss of a leaving group, becomes the trigonal product. The reaction can be regarded as an **acyl transfer**, the transfer of an acyl group from one nucleophile to another. The reactivity order of acid derivatives toward nucleophiles is acyl halides > anhydrides > esters > amides.

**Acyl chlorides** are prepared from acids and either  $\text{SOCl}_2$  or  $\text{PCl}_5$ . They react rapidly with water to give acids, with alcohols to give esters, and with ammonia to give amides. **Acid anhydrides** react similarly but less rapidly. **Thioesters** are nature's acylating agents. They react with nucleophiles less rapidly than anhydrides but more rapidly than ordinary esters.

**Amides** can be prepared from ammonia and other acid derivatives. They can also be prepared by heating ammonium salts. They are named by replacing the *-ic* or *-oic* acid ending with *amide*.

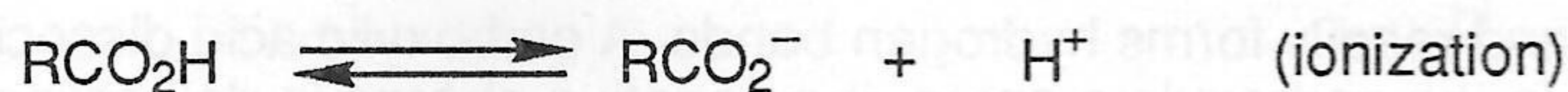
Because of resonance, the C—N bond in amides has considerable C=N character. Rotation about that bond is restricted, and the amide group is planar. Amides are polar, form hydrogen bonds, and have high boiling points considering their molecular weights.

Amides react slowly with nucleophiles (such as water and alcohols). They are reduced to amines by  $\text{LiAlH}_4$ . Urea, made from  $\text{CO}_2$  and  $\text{NH}_3$ , is an important fertilizer.

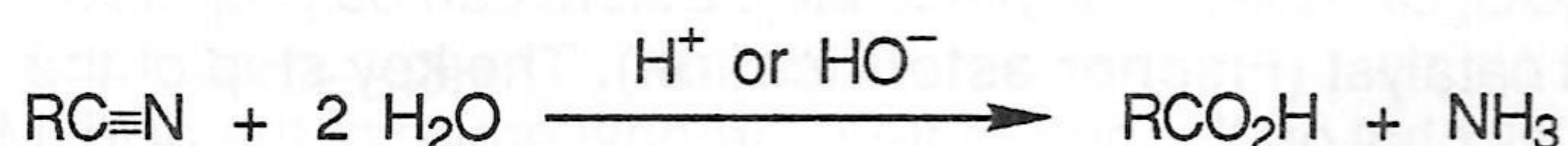
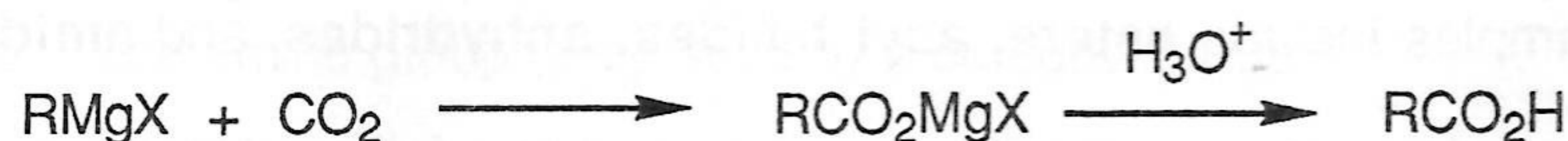
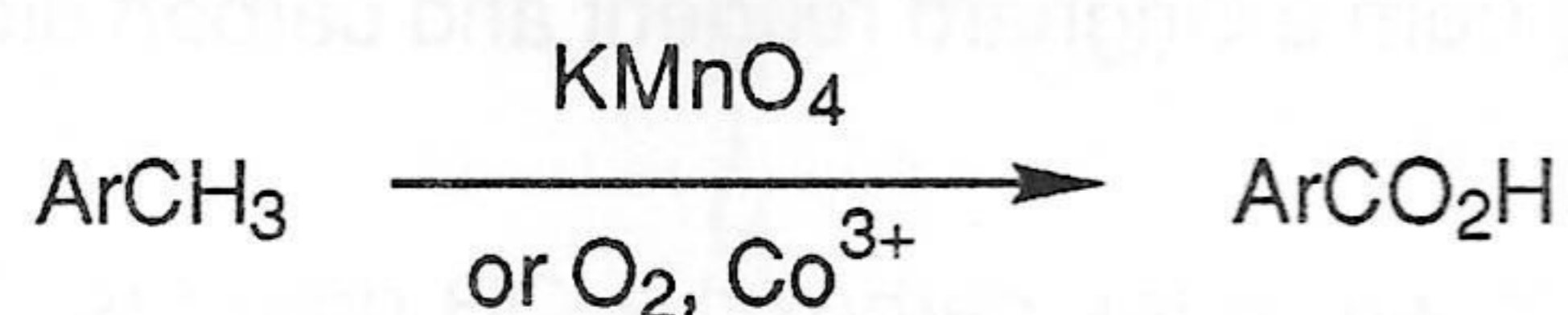
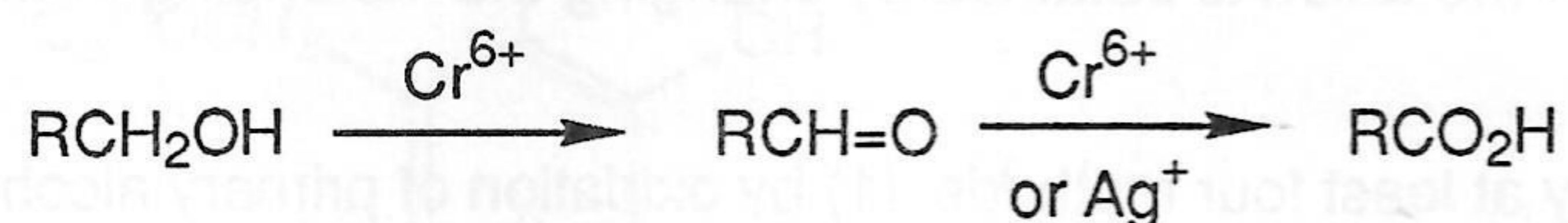
Some reactions of acid derivatives are summarized in Table 10.5.  $\beta$ -Keto esters can be prepared by the **Claisen condensation**, a reaction analogous to the aldol condensation but involving **ester enolates** as the reactive intermediates.

## Reaction Summary

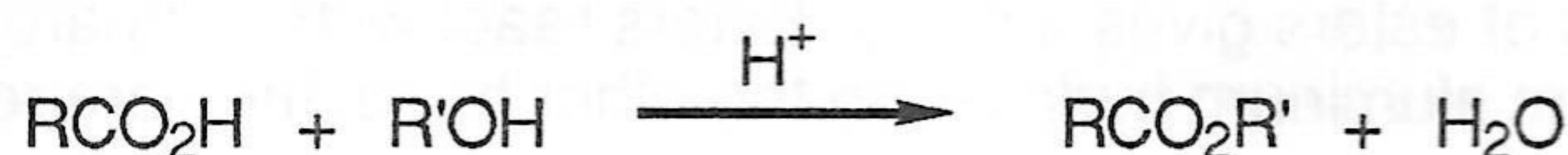
### Acids



### Preparation of Acids



### Fischer Esterification

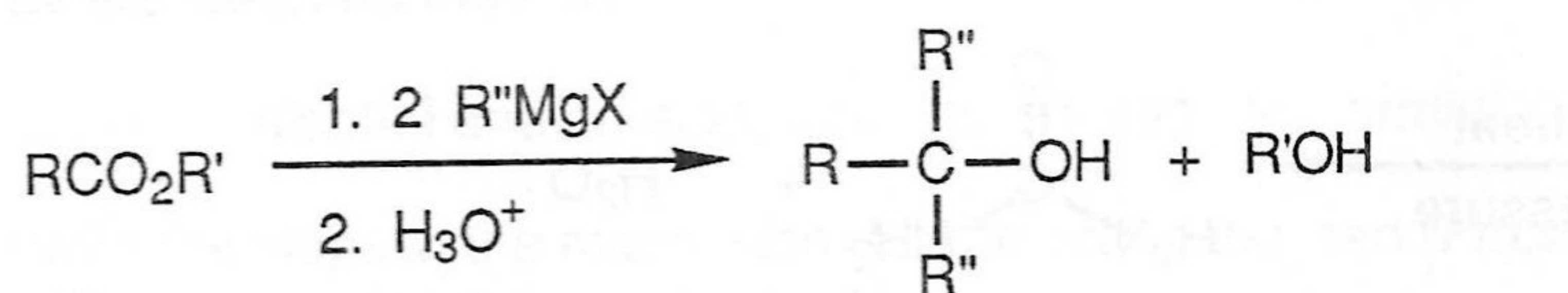
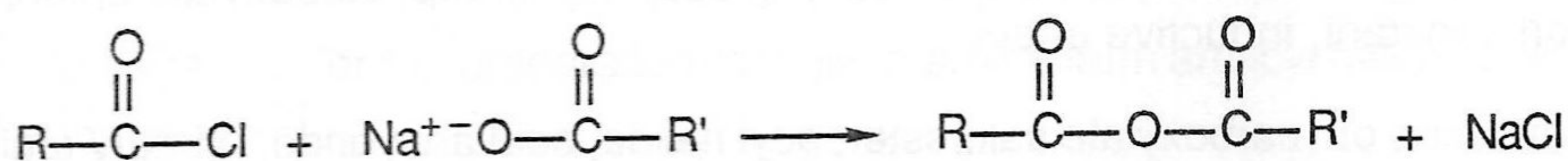
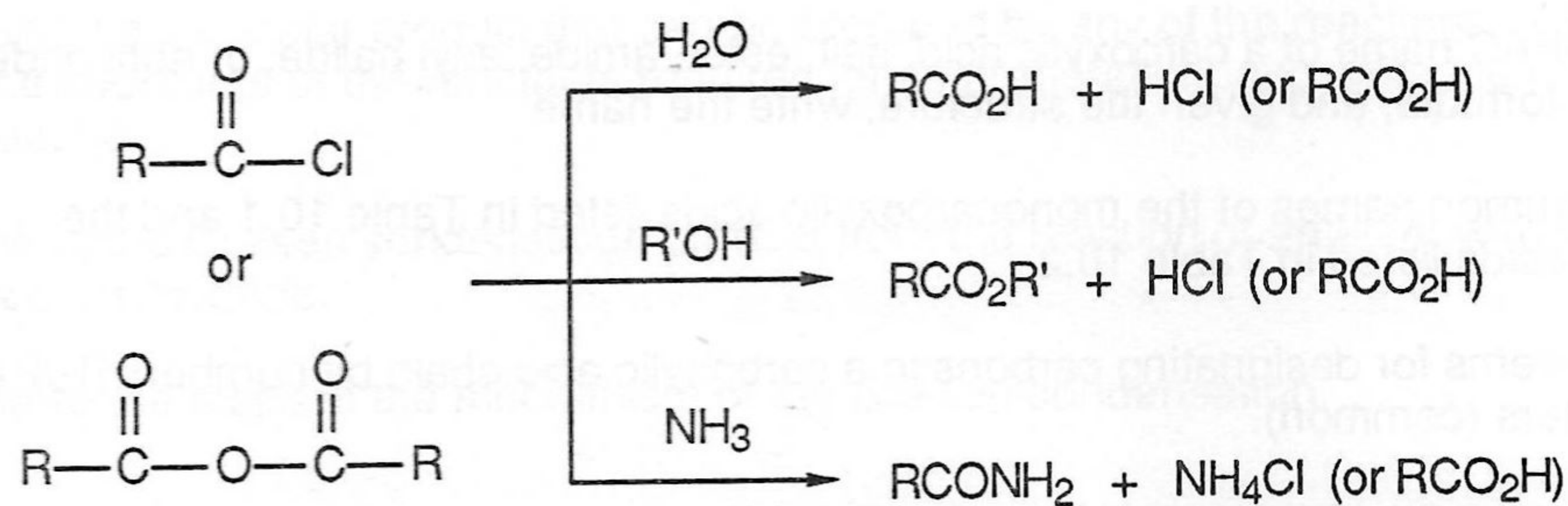
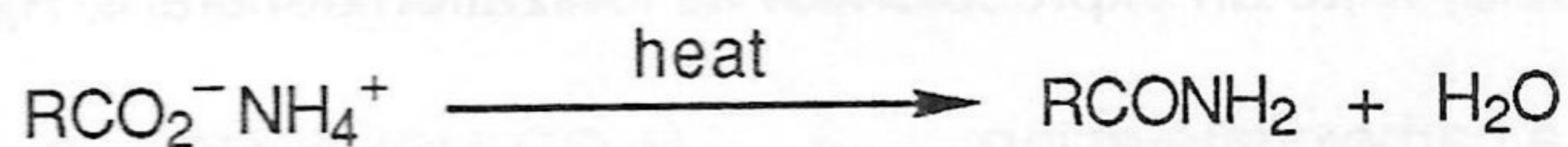
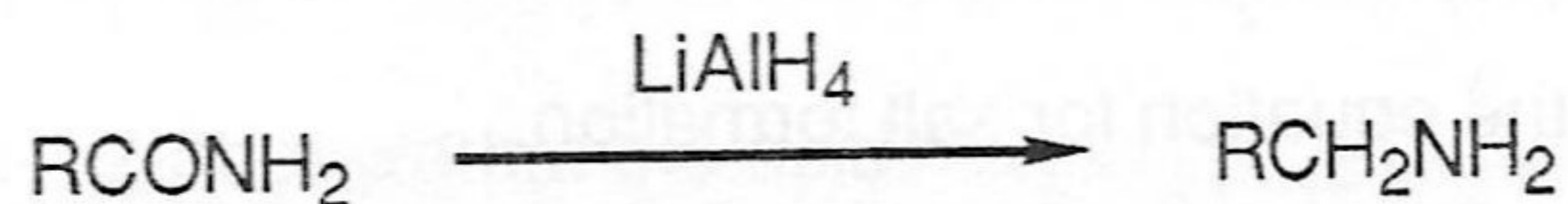
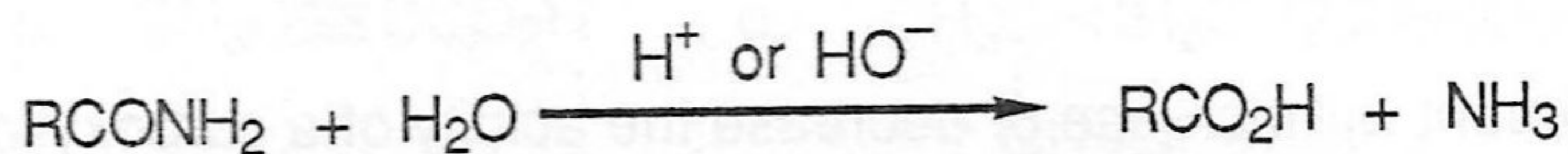


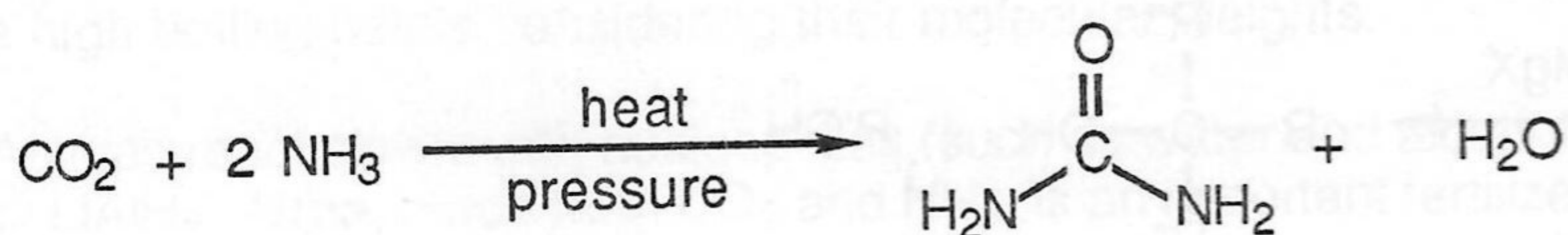
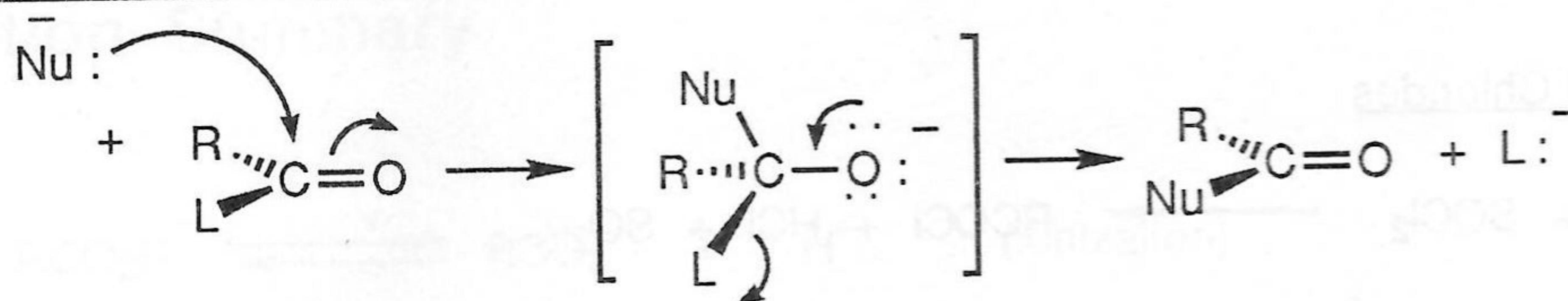
### Saponification



### Ammonolysis of Esters



Esters and Grignard ReagentsReduction of EstersPreparation of Acyl ChloridesPreparation of AnhydridesReactions of Acyl Halides (or Anhydrides)Amides from Ammonium SaltsReactions of Amides

Urea**Mechanism Summary**Nucleophilic Addition–Elimination**Learning Objectives**

1. Know the meaning of: carboxylic acid, carboxyl group, acyl group, carboxylate anion, acidity or ionization constant, inductive effect.
2. Know the meaning of: carboxylate salt, ester, acyl halide, acid anhydride, primary amide.
3. Know the meaning of: Fischer esterification, nucleophilic addition–elimination, tetrahedral intermediate, saponification, ammonolysis, acyl transfer.
4. Given the IUPAC name of a carboxylic acid, salt, ester, amide, acyl halide, or anhydride, write its structural formula, and given the structure, write the name.
5. Know the common names of the monocarboxylic acids listed in Table 10.1 and the dicarboxylic acids listed in Table 10.2.
6. Know the systems for designating carbons in a carboxylic acid chain by numbers (IUPAC) or by Greek letters (common).
7. Know how to name acyl groups and how to write a formula given a name that includes acyl group nomenclature.
8. Given the formula of a carboxylic acid, write an expression for its ionization constant,  $K_a$ .
9. Write the resonance structures of a carboxylate anion.
10. Given two or more carboxylic acids with closely related structures, rank them in order of increasing (or decreasing) acidities ( $pK_a$ 's).
11. Tell whether a particular substituent will increase or decrease the acidity of a carboxylic acid.
12. Given a carboxylic acid and a base, write the equation for salt formation.
13. Given a carboxylic acid, tell what aldehyde or primary alcohol is needed for its preparation by oxidation.
14. Given an aromatic compound with alkyl substituents, tell what aromatic acid would be obtained from its oxidation.

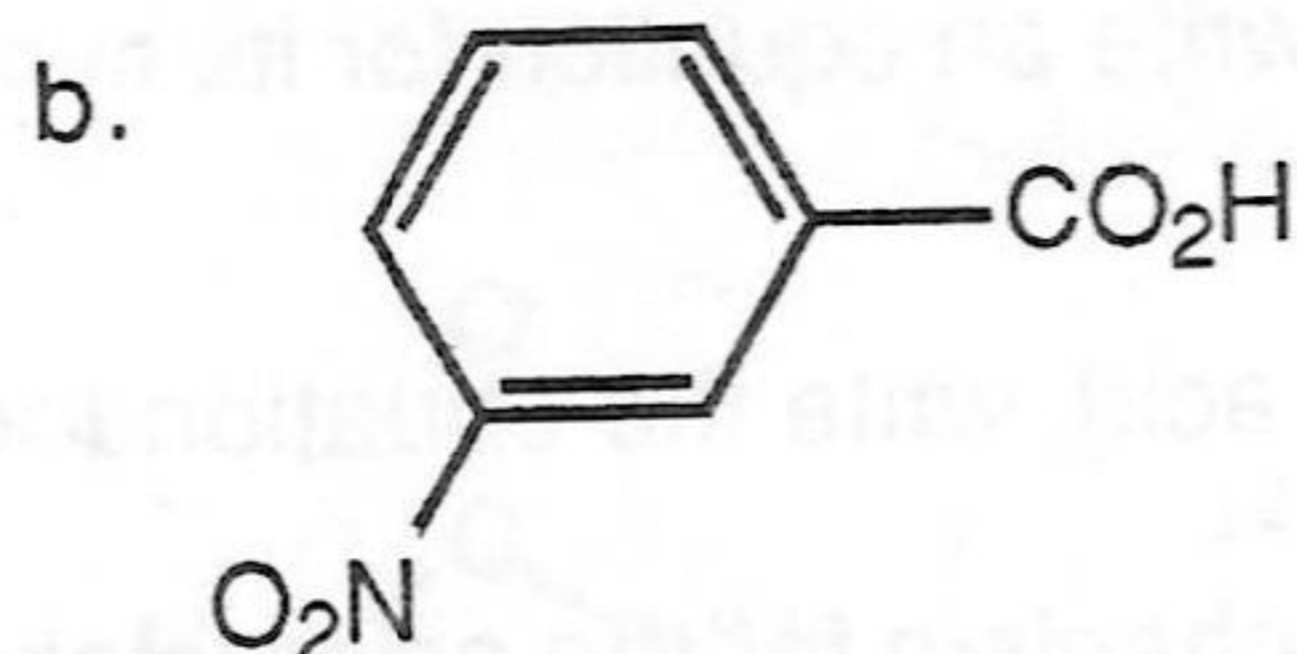
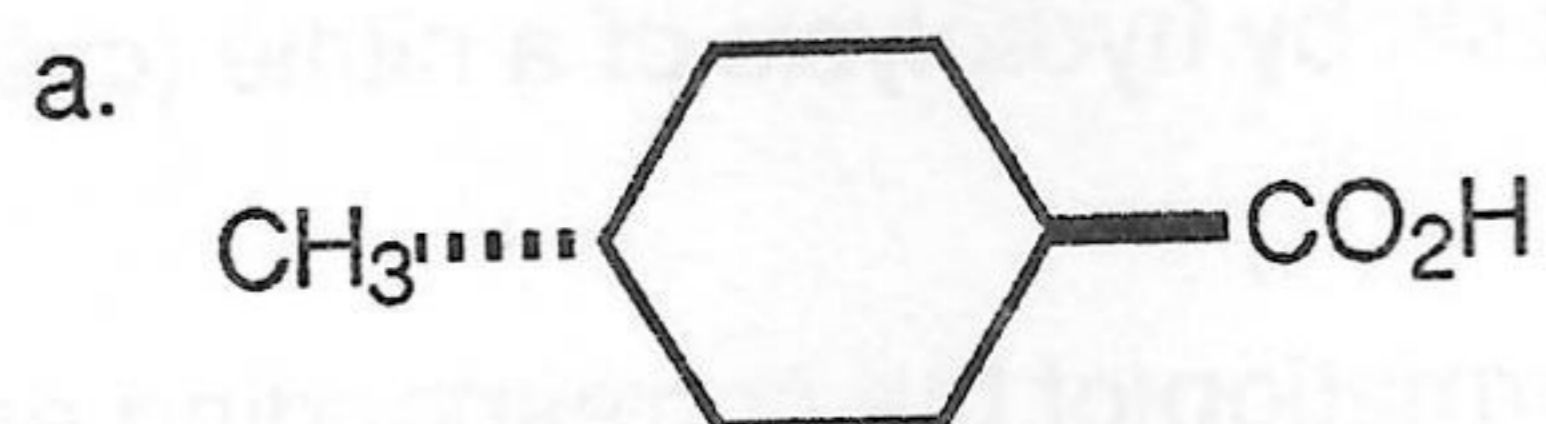
15. Given a carboxylic acid, write an equation for its synthesis by hydrolysis of a nitrile (cyanide) or by the Grignard method.
16. Given an alcohol and an acid, write the equation for formation of the corresponding ester.
17. Write the steps in the mechanism for the acid-catalyzed (Fischer) esterification of a given carboxylic acid with a given alcohol.
18. Given the name or the structure of an ester, write the structure of the alcohol and acid from which it is derived.
19. Write an equation for the reaction of a given ester with aqueous base (saponification).
20. Write an equation for the reaction of a given ester with ammonia, a Grignard reagent, or lithium aluminum hydride.
21. Given a particular acid halide, write an equation for its preparation from an acid.
22. Given a particular anhydride, write an equation for its preparation from an acid chloride and a carboxylic acid salt.
23. Write the equation for the reaction of a given acid halide or anhydride with a given nucleophile (especially with water, an alcohol, or ammonia).
24. Write equations for the preparation of a given amide from an acyl halide, acid anhydride, or ammonium salt.
25. Given a particular amide, write equations for its hydrolysis and reduction with lithium aluminum hydride.
26. Given a particular product that can be prepared by any of the reactions in this chapter, deduce the structures of the reactants required for its preparation, and write the equation for the reaction.
27. Write the Claisen condensation product from the reaction of an ester with an alkoxide or sodium hydride.
28. Write the steps in the mechanism of the Claisen condensation.

## Answers to Problems

### Problems Within the Chapter

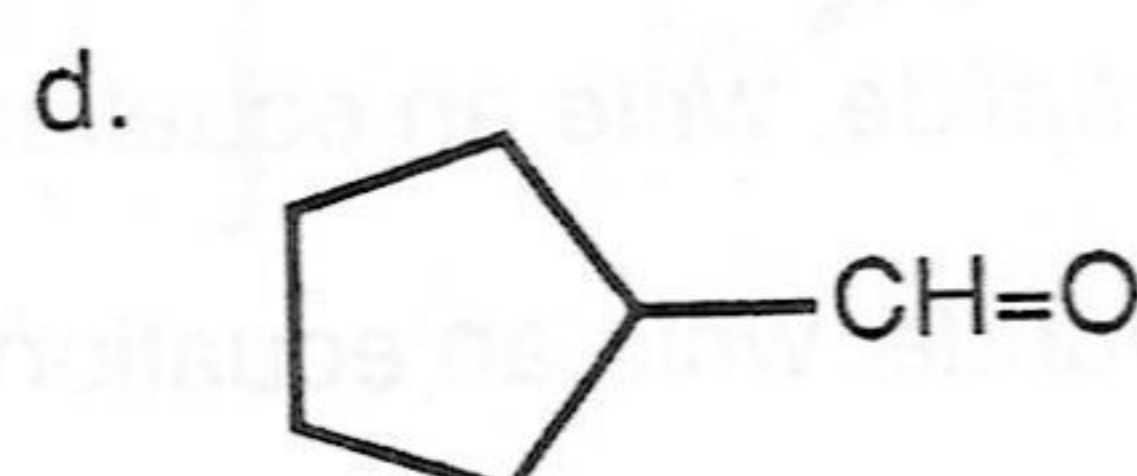
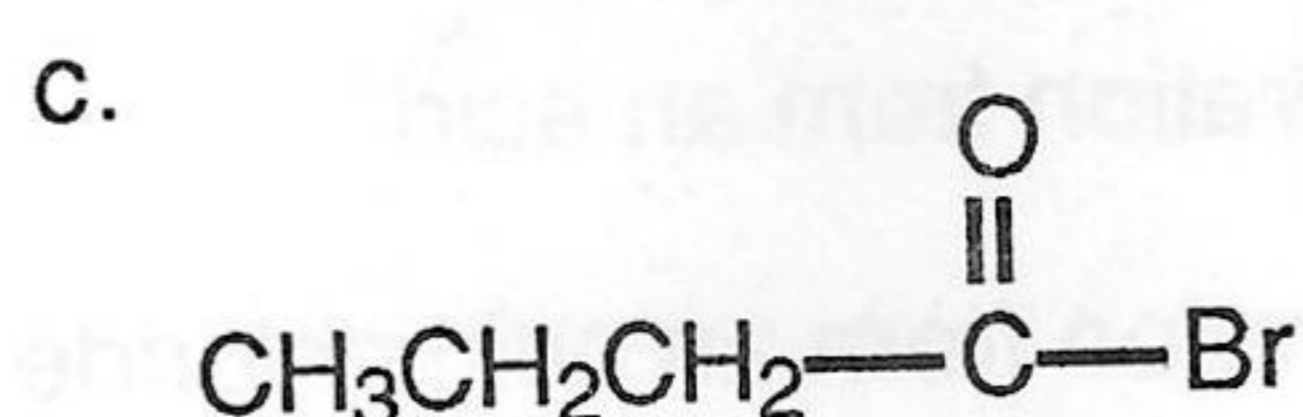
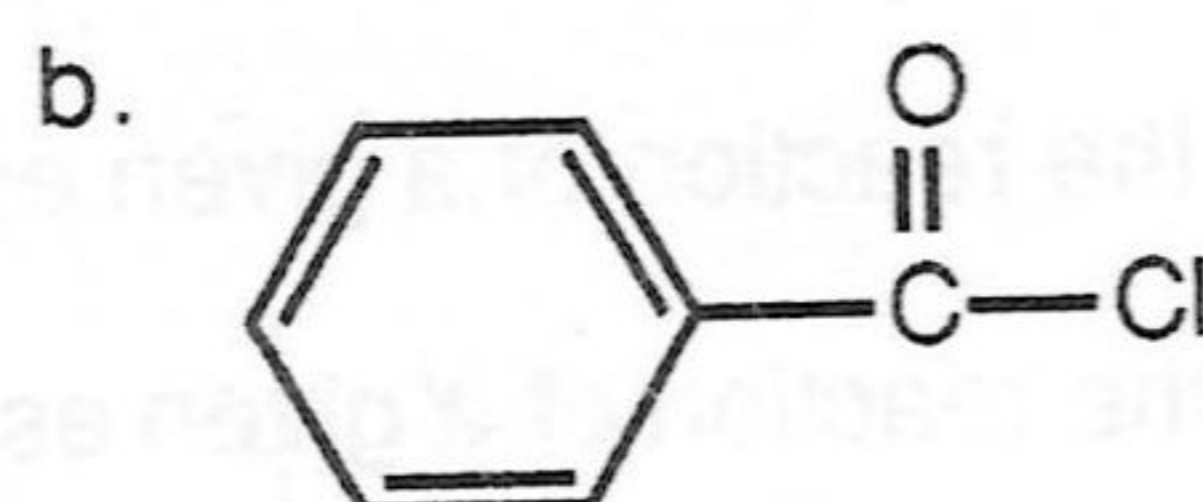
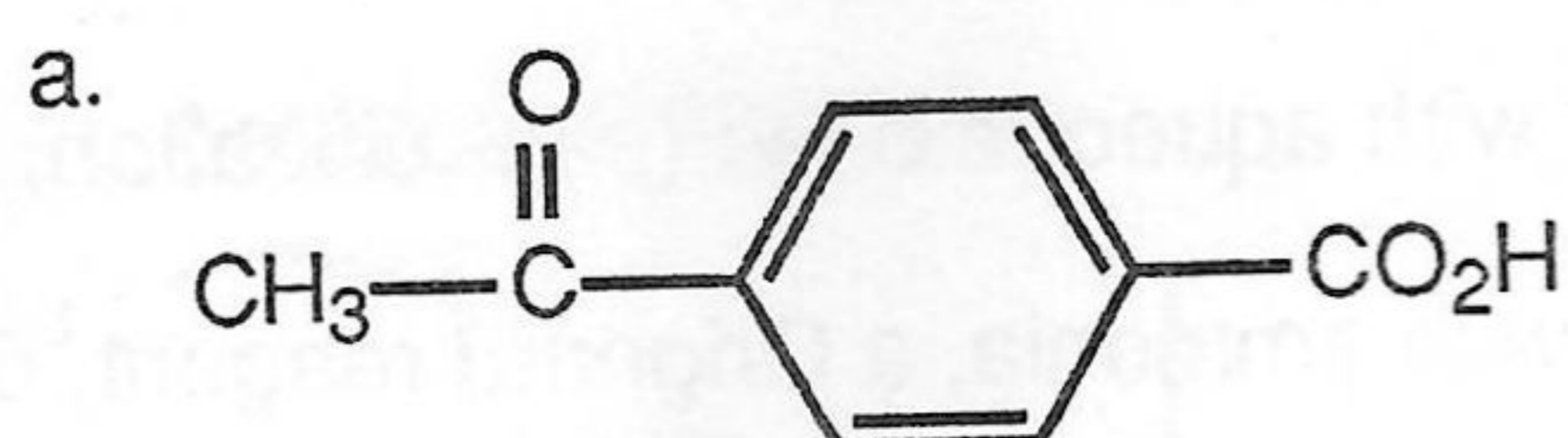
- 10.1
- |   |  |
|---|--|
| a. $\text{CH}_3\underset{\text{Br}}{\text{CH}}\text{CH}_2\text{CO}_2\text{H}$ | b. $(\text{CH}_3)_2\underset{\text{OH}}{\text{C}}\text{CO}_2\text{H}$  |
| c. $\text{CH}_3\text{C}\equiv\text{CCO}_2\text{H}$                            | d. $\text{CH}_3\underset{\text{CH}=\text{O}}{\text{CH}}\text{CH}_2\text{CH}_2\text{CH}_2\text{CO}_2\text{H}$ |
- 10.2
- a. 2-phenylethanoic acid
  - b. dichloroethanoic acid
  - c. 2-butenoic acid
  - d. 2,2-dimethylpropanoic acid

10.3



- 10.4 a. cyclopropanecarboxylic acid  
b. *p*-toluic acid (or *p*-methylbenzoic acid)

10.5

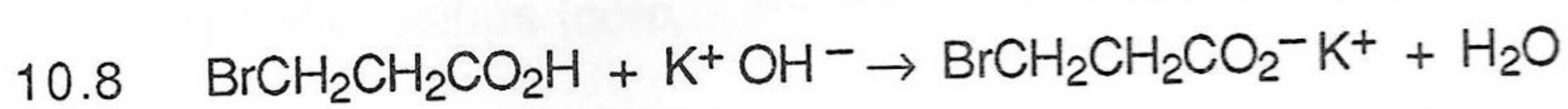


- 10.6  $K_a$  is  $1.8 \times 10^{-5}$  for acetic acid and  $1.5 \times 10^{-3}$  for chloroacetic acid.  $K_a$  is larger for chloroacetic acid; it is the stronger acid. The ratio is:

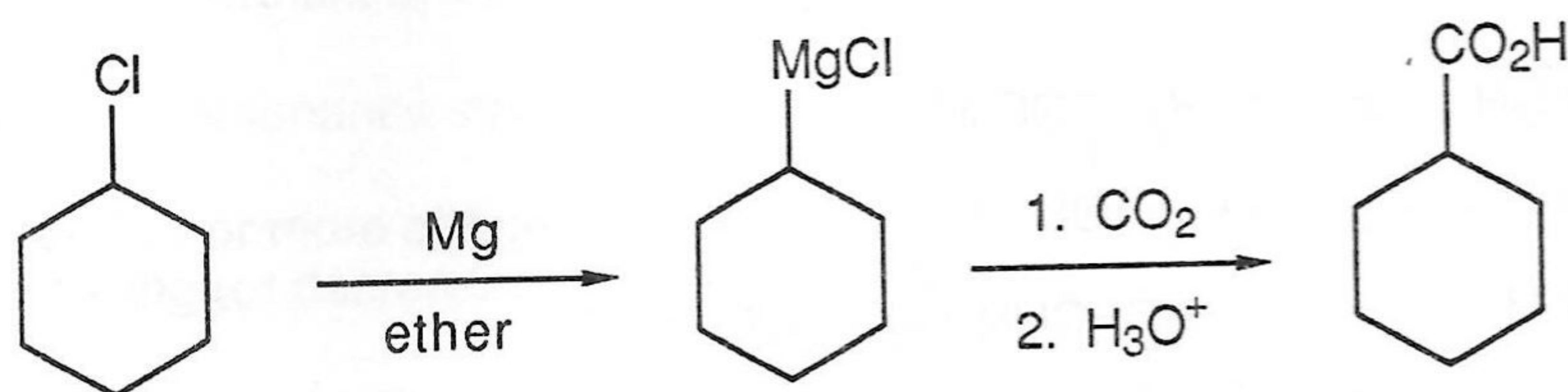
$$\frac{1.5 \times 10^{-3}}{1.8 \times 10^{-5}} = 0.83 \times 10^2$$

In other words, chloroacetic acid is 83 times stronger than acetic acid.

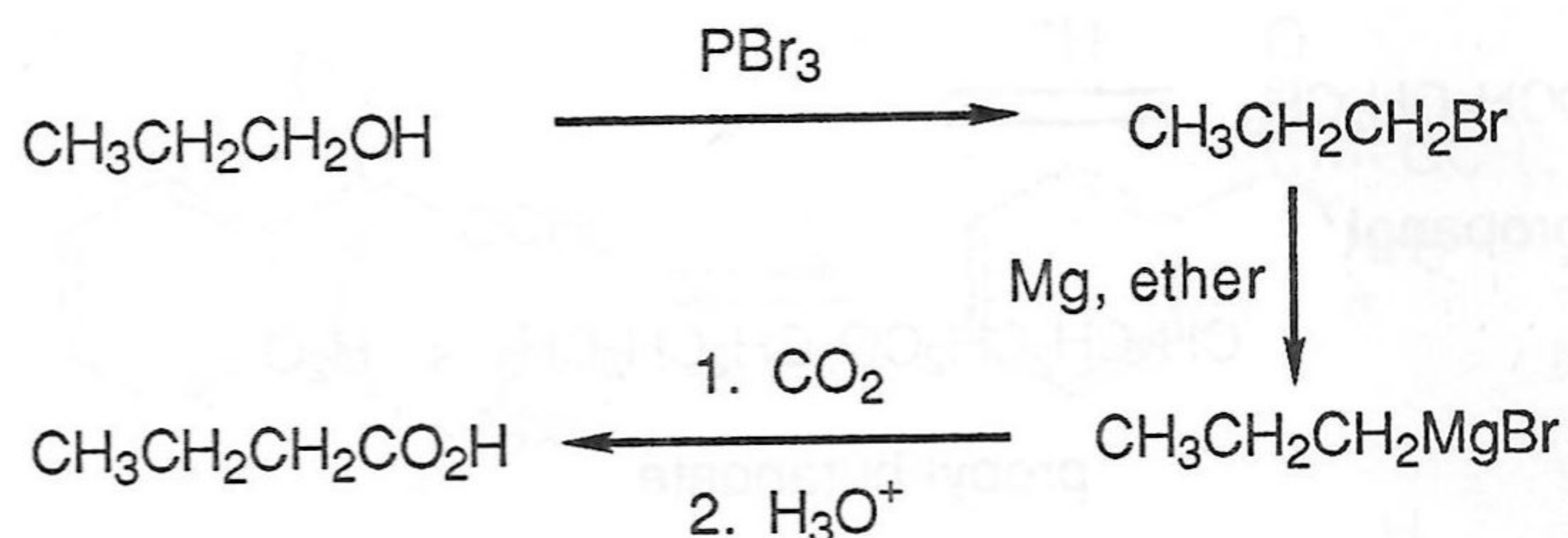
- 10.7  $K_a$  for benzoic acid is  $6.6 \times 10^{-5}$  or  $0.66 \times 10^{-4}$ . For *o*-, *m*-, and *p*-chlorobenzoic acids,  $K_a$  is 12.5, 1.6, and  $1.0 \times 10^{-4}$ , respectively. All three chloro acids are stronger than benzoic acid. However, the difference is greatest for the *ortho* isomer since in this isomer the chloro substituent is closest to the carboxyl group and exerts the maximum electron-withdrawing inductive effect. The effect decreases as the distance between the chloro substituent and the carboxyl group increases.



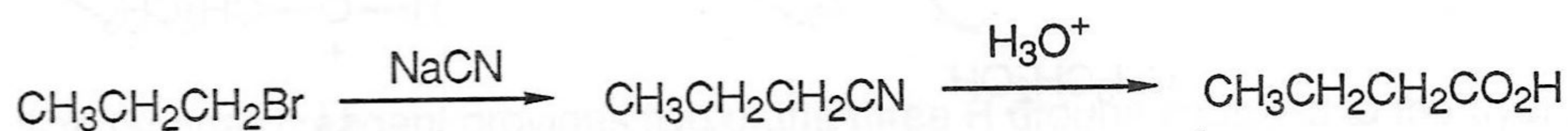
- 10.9 The halide can be converted to the corresponding Grignard reagent, which can be reacted with carbon dioxide to give the carboxylic acid.



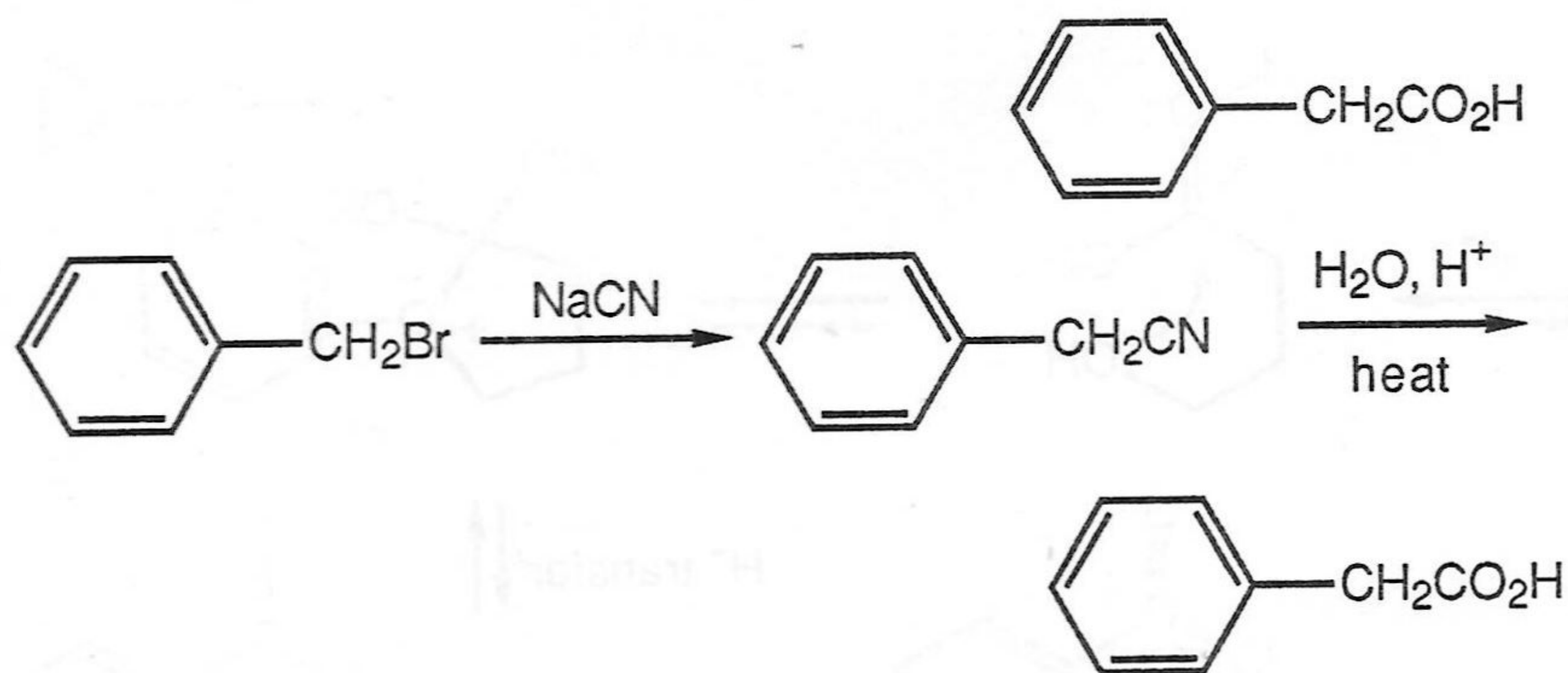
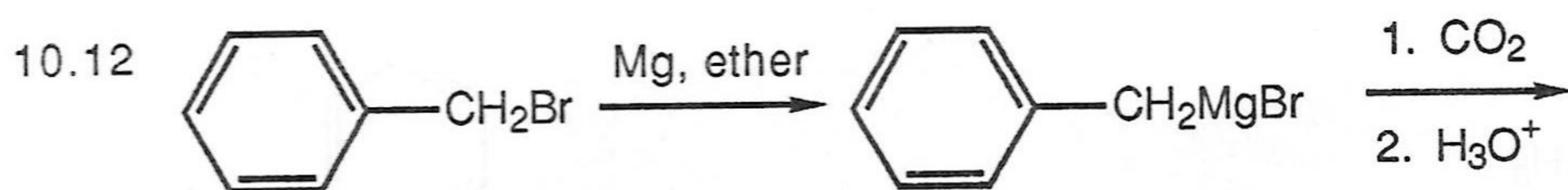
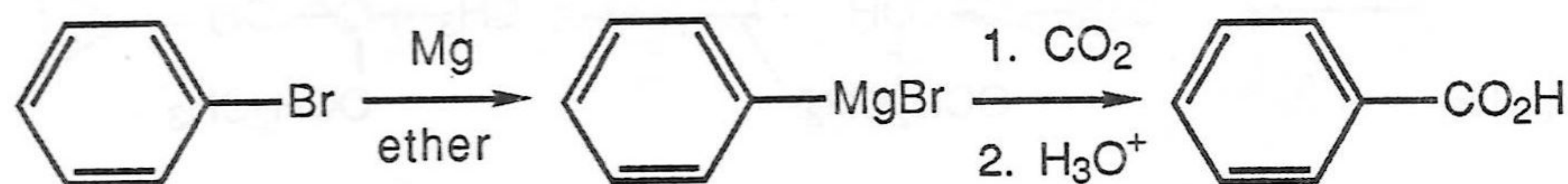
- 10.10 There are several possible approaches. First the alcohol must be converted to a halide. The halide can then be converted to the corresponding Grignard reagent, which can be reacted with carbon dioxide to provide the carboxylic acid.



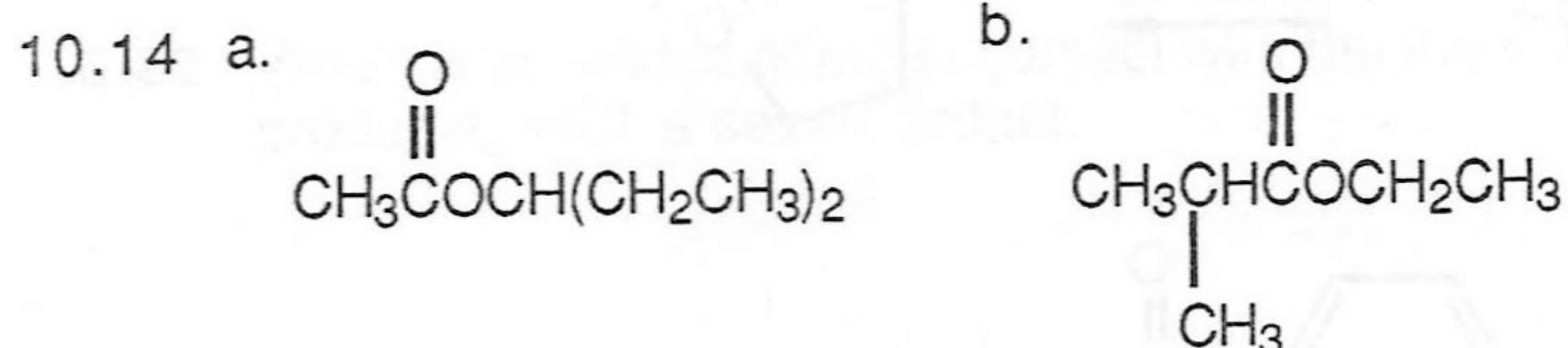
Conversion of the halide to a nitrile followed by hydrolysis would also provide the carboxylic acid. This reaction is introduced in the next section (10.7d), so do not be concerned if it did not occur think of it when initially working this problem.

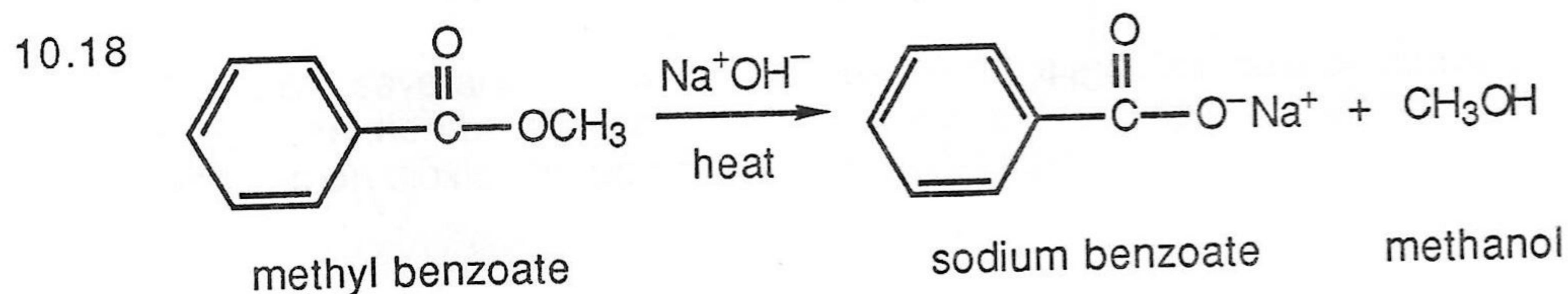
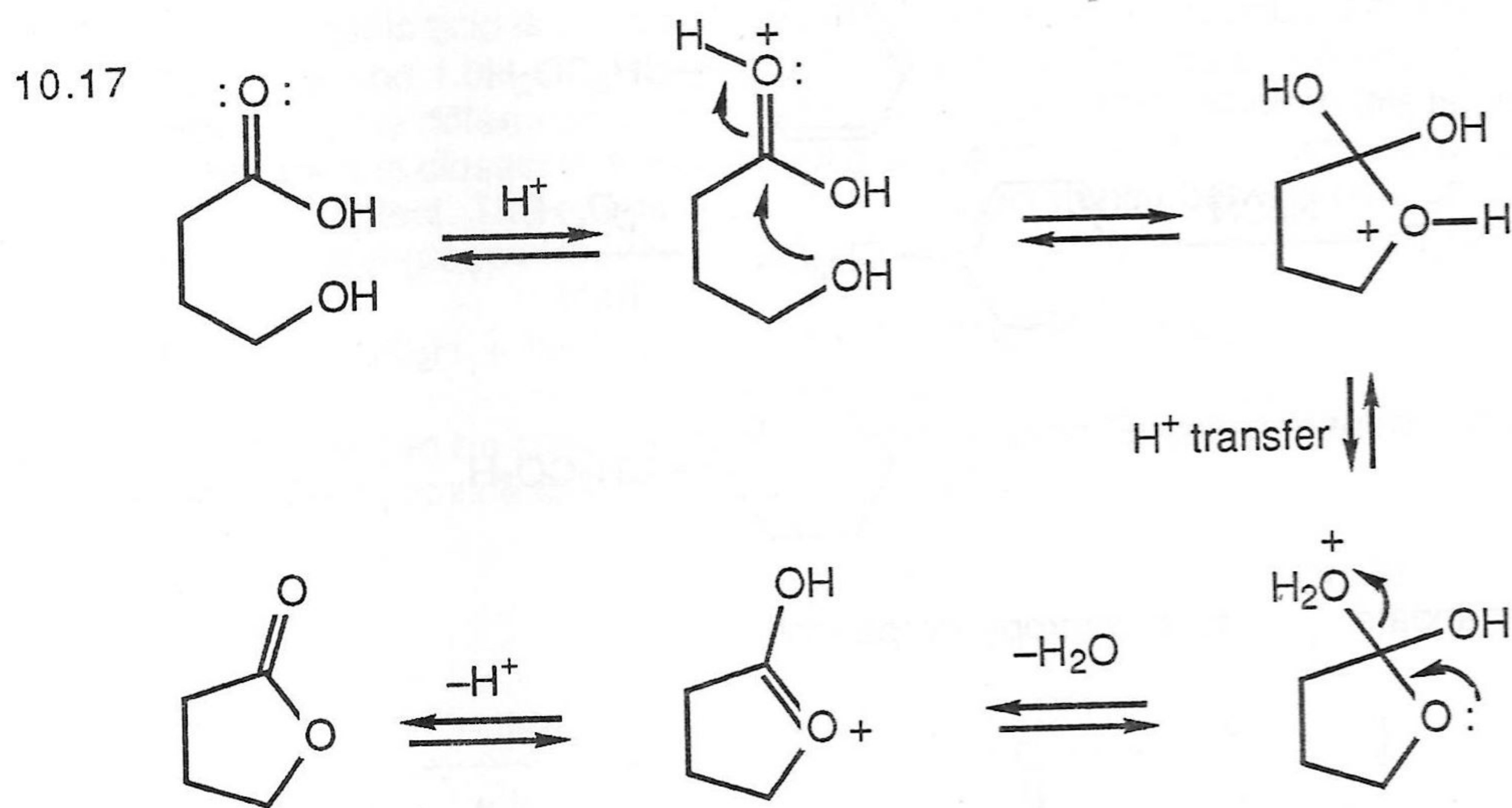
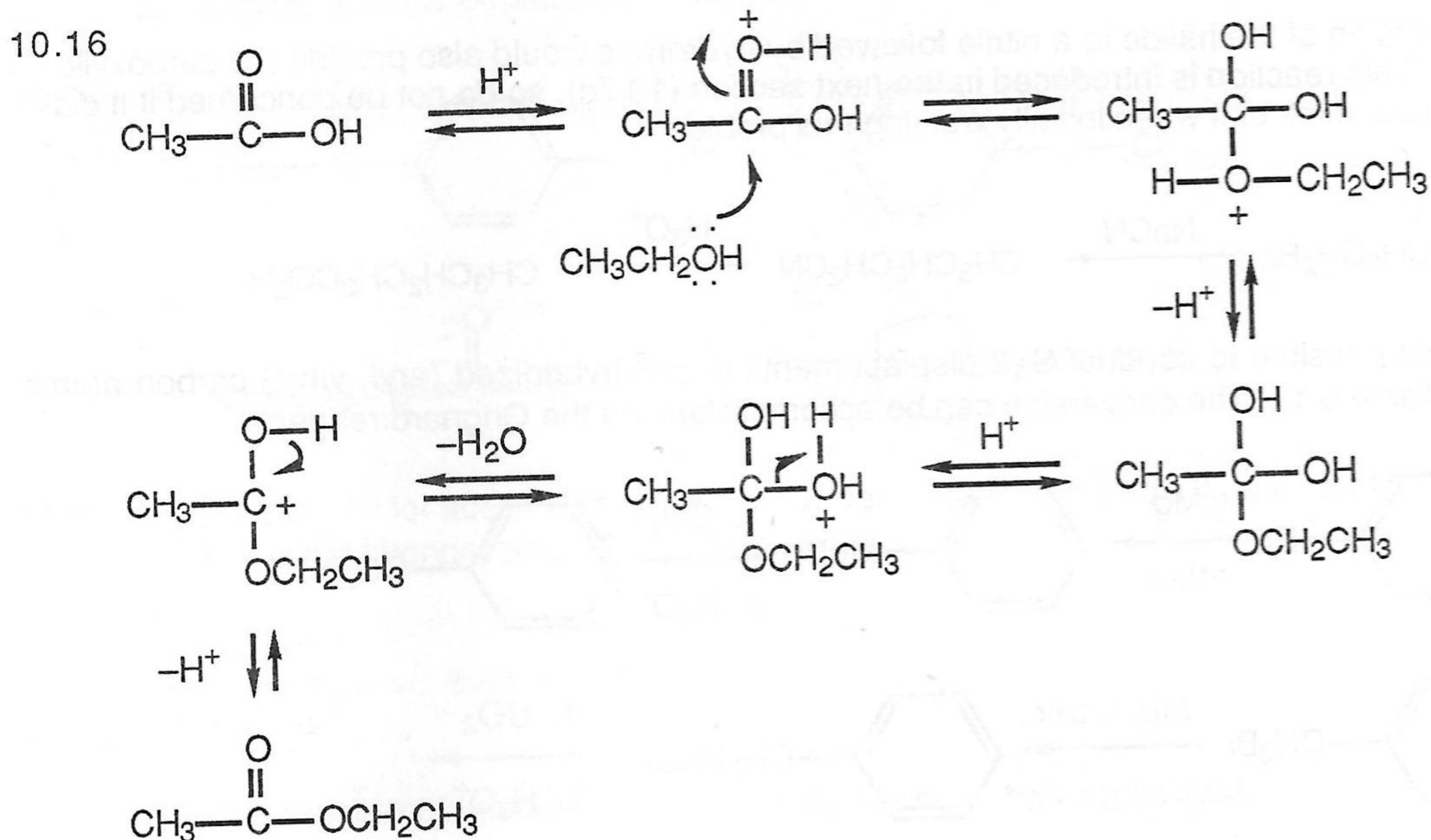
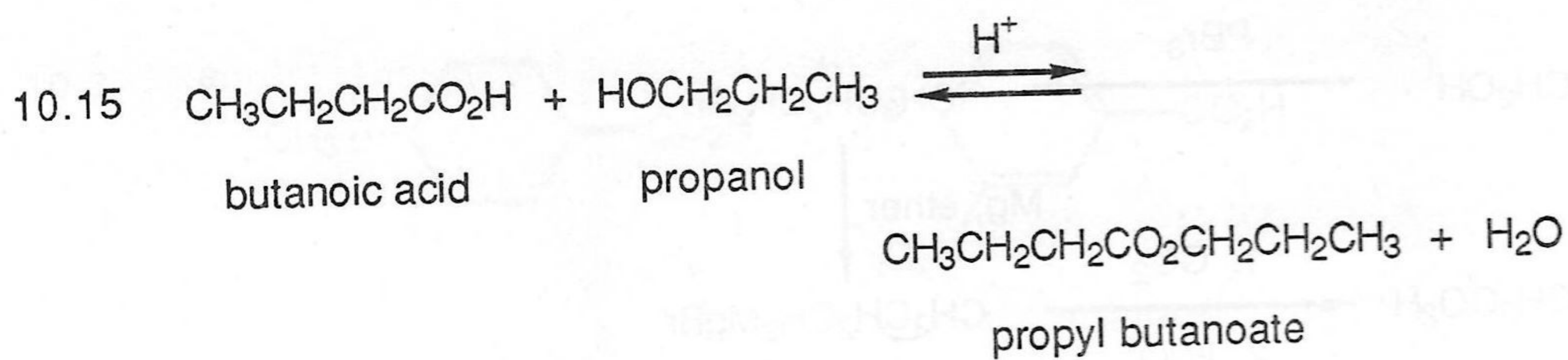


10.11 It is not possible to conduct  $\text{S}_{\text{N}}2$  displacements at  $sp^2$ -hybridized (aryl, vinyl) carbon atoms (see Table 6.1). The conversion can be accomplished via the Grignard reagent:

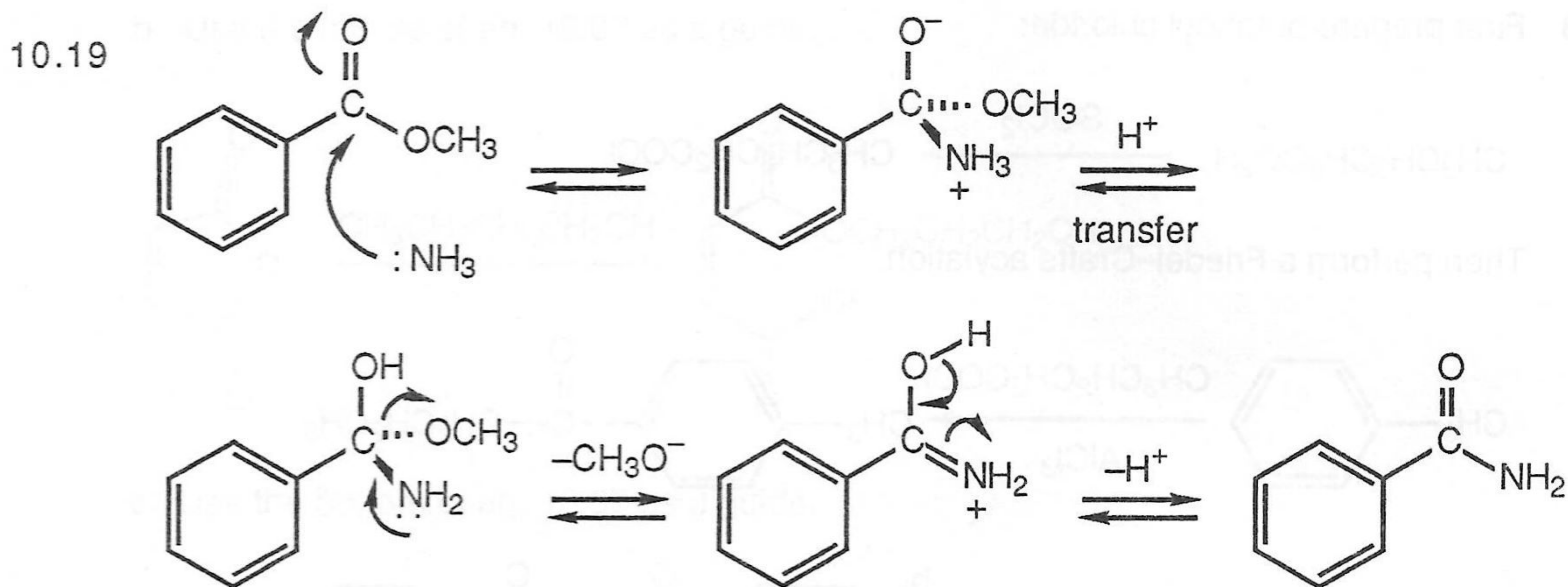


10.13 a. methyl methanoate      b. cyclopropyl propanoate

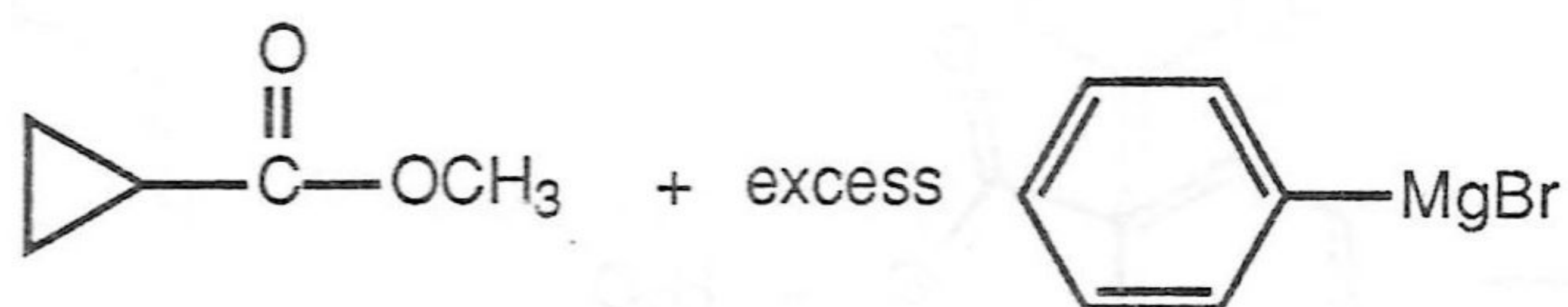




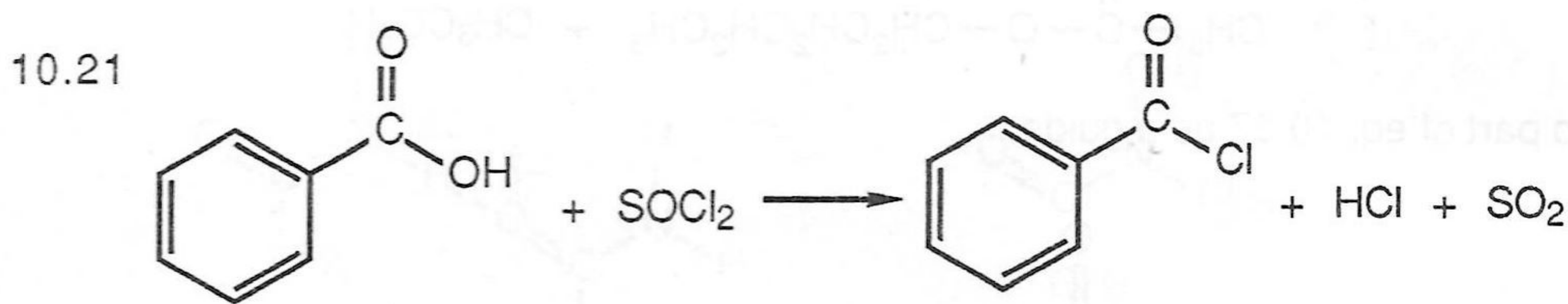
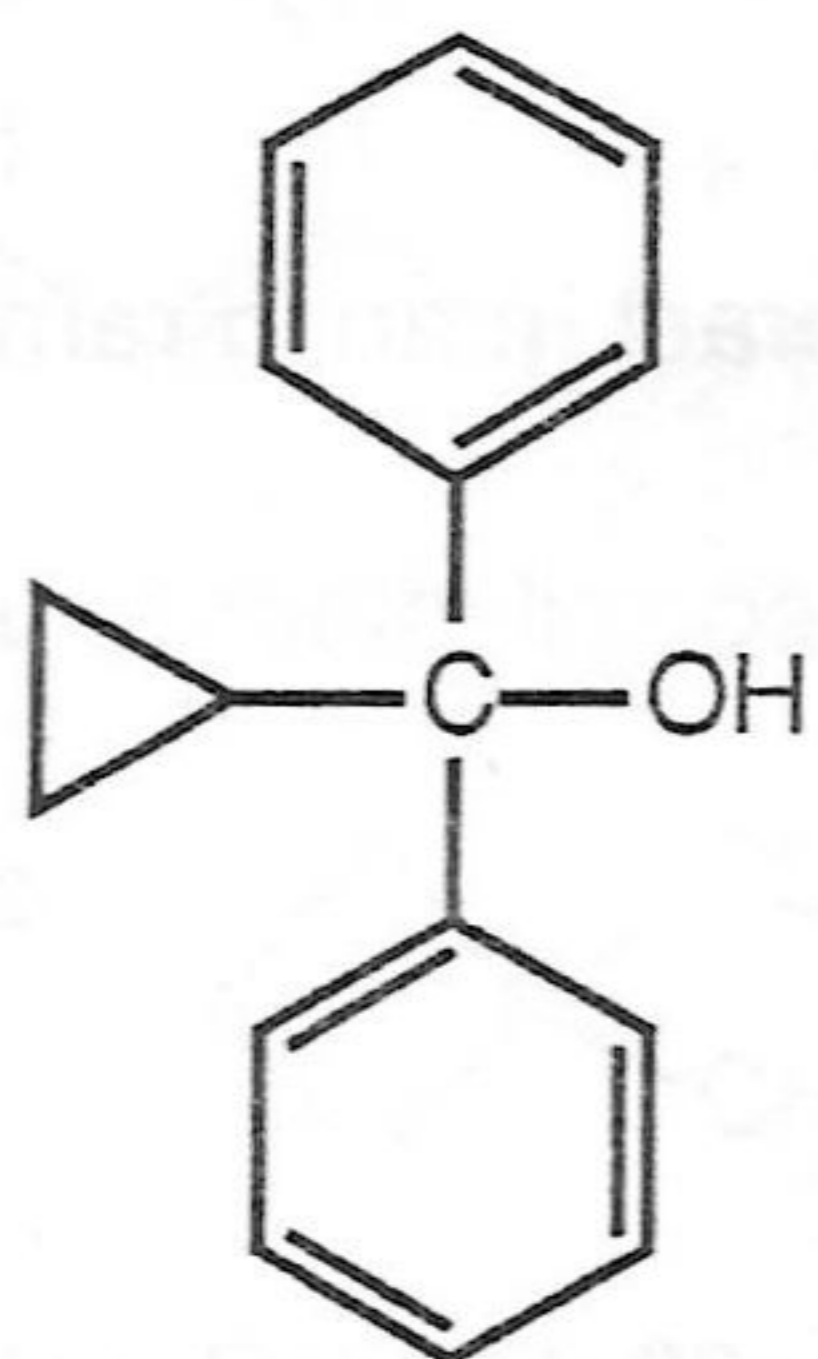




10.20 The Grignard reagent provides two of the three R groups attached to the hydroxyl-bearing carbon of the tertiary alcohol. The ester provides the third R group. So, from

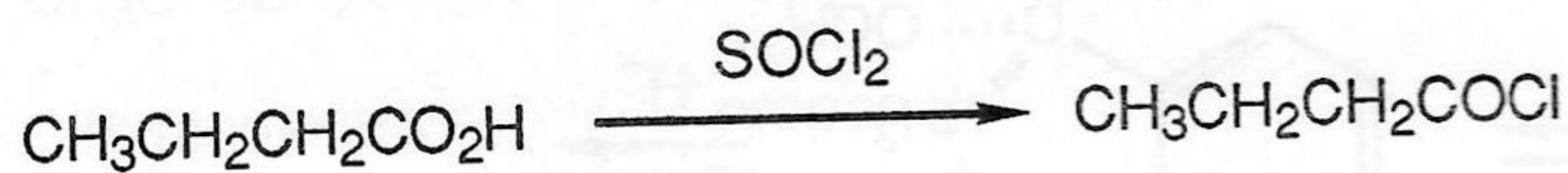


we get the tertiary alcohol

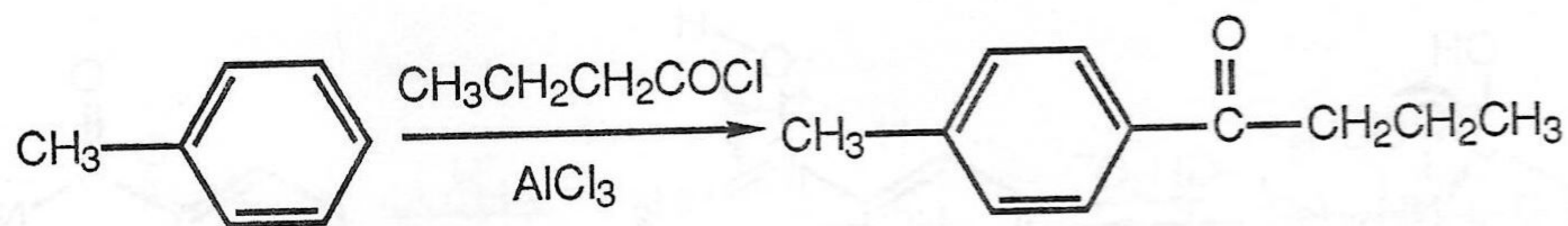


10.22 When acyl halides come in contact with the moist membranes of the nose, they hydrolyze, producing HCl, a severe irritant.

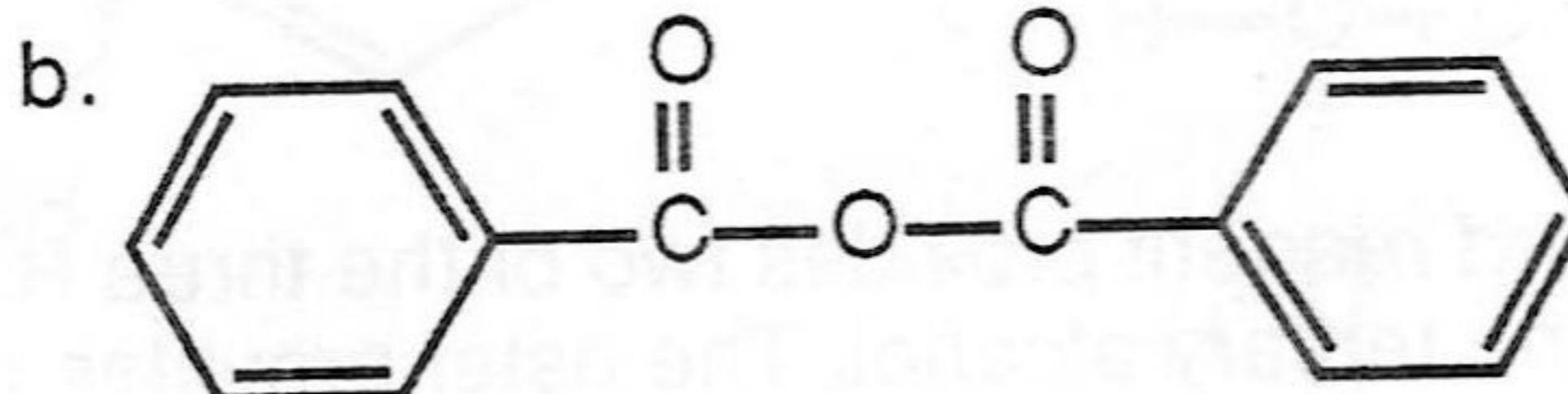
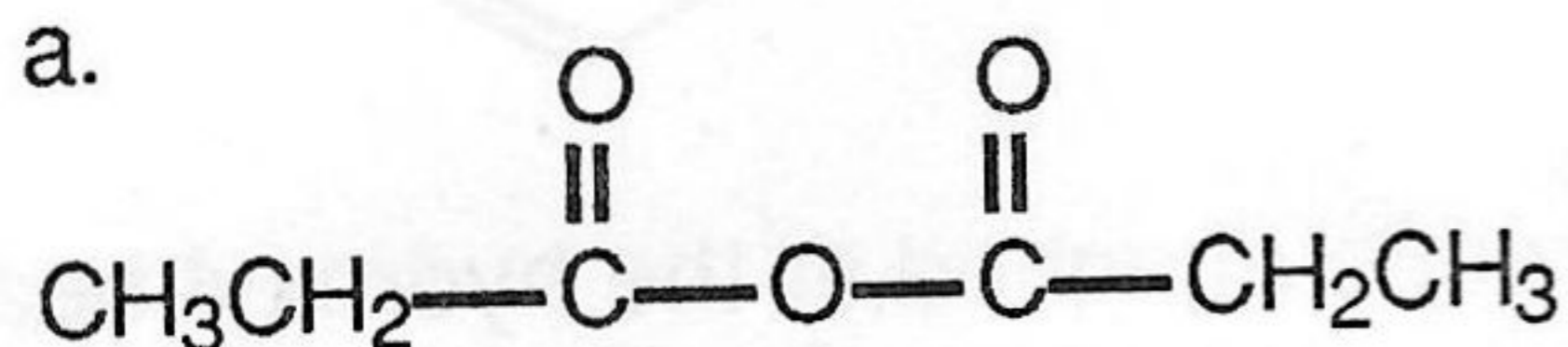
10.23 First prepare butanoyl chloride:



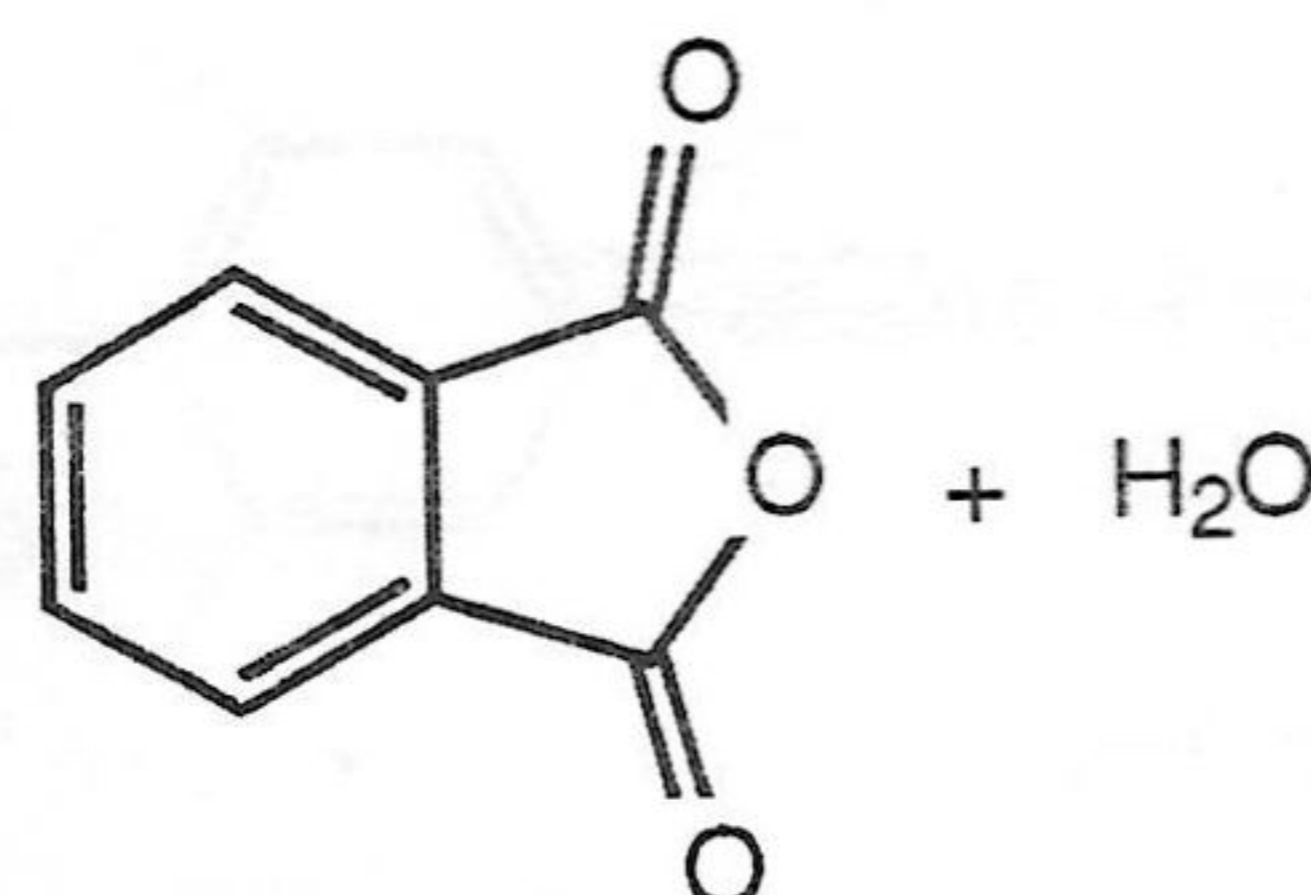
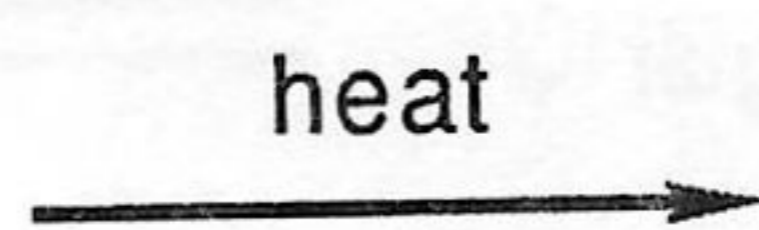
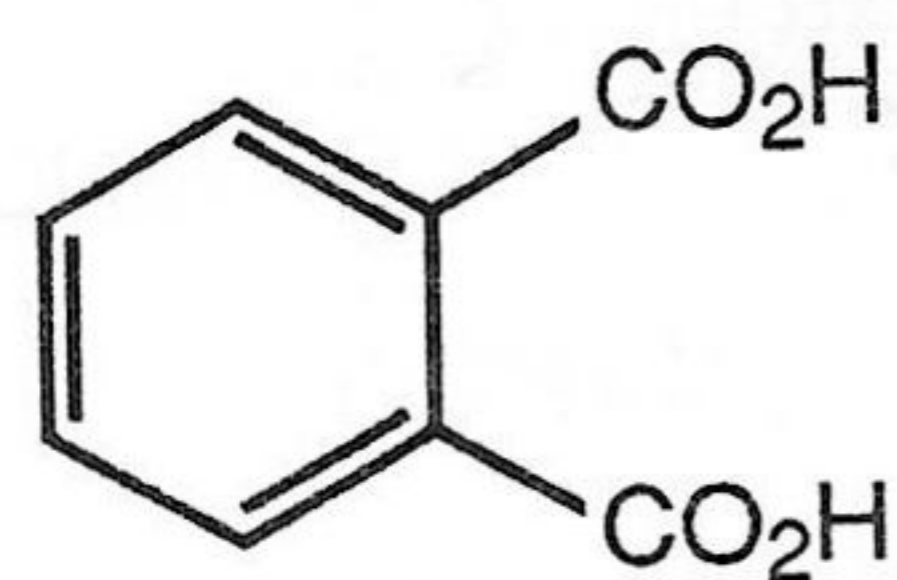
Then perform a Friedel–Crafts acylation:



10.24



10.25

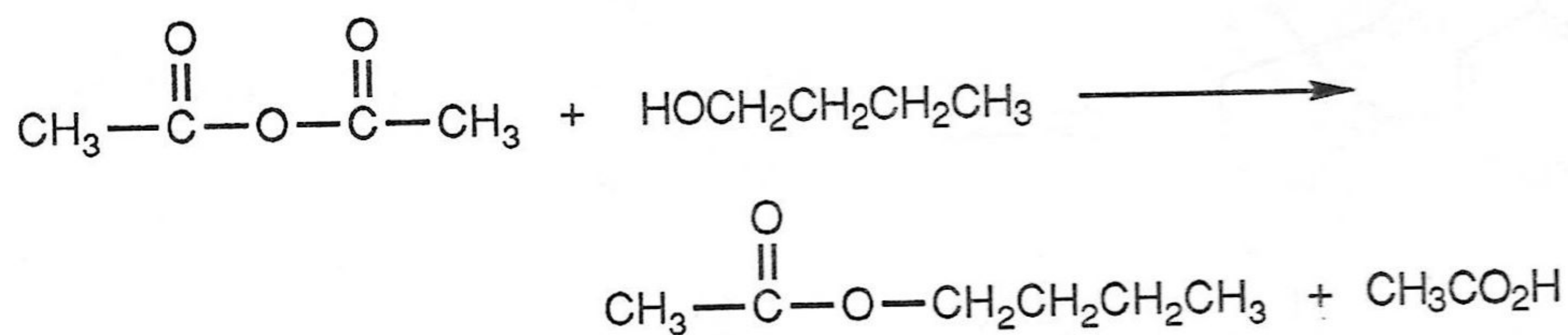


phthalic acid

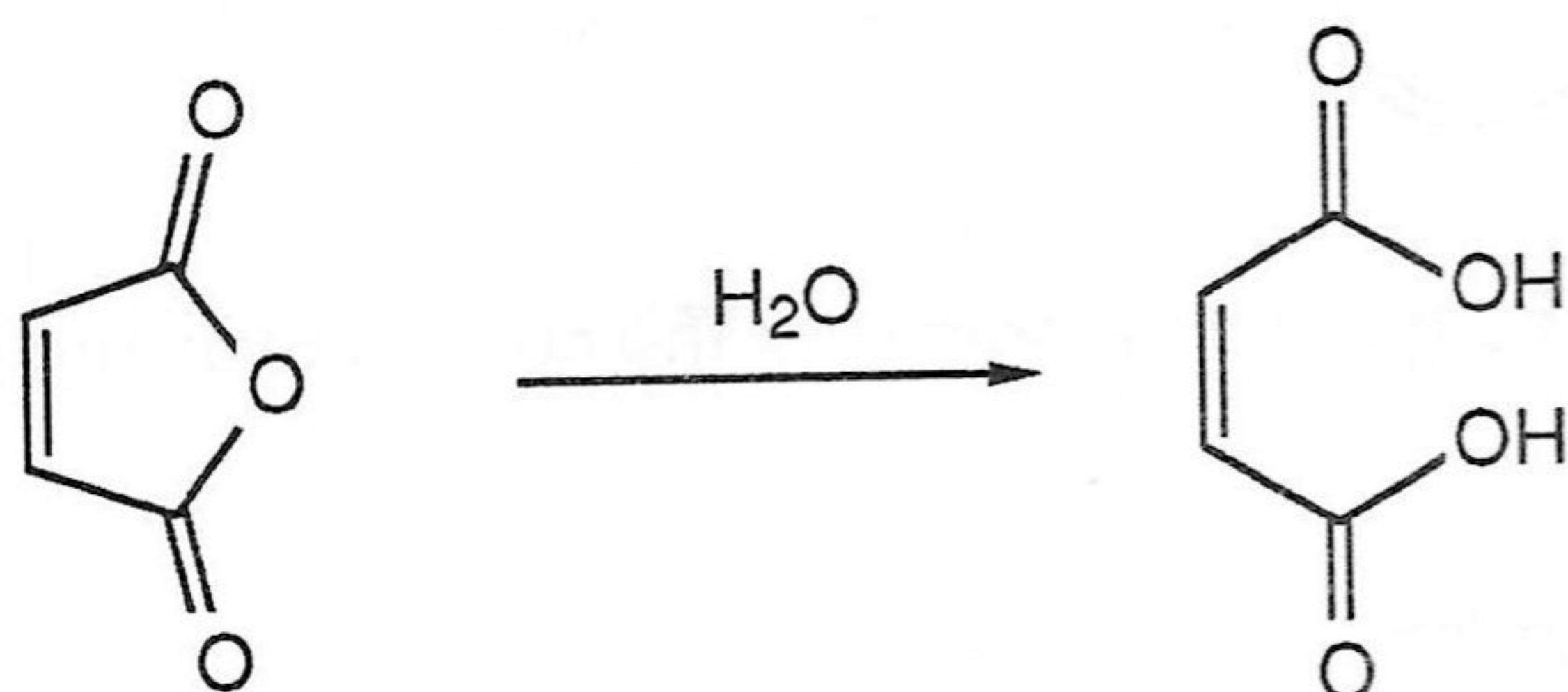
phthalic anhydride

10.26 No. The two carboxyl groups are *trans* to one another and cannot interact in an intramolecular fashion.

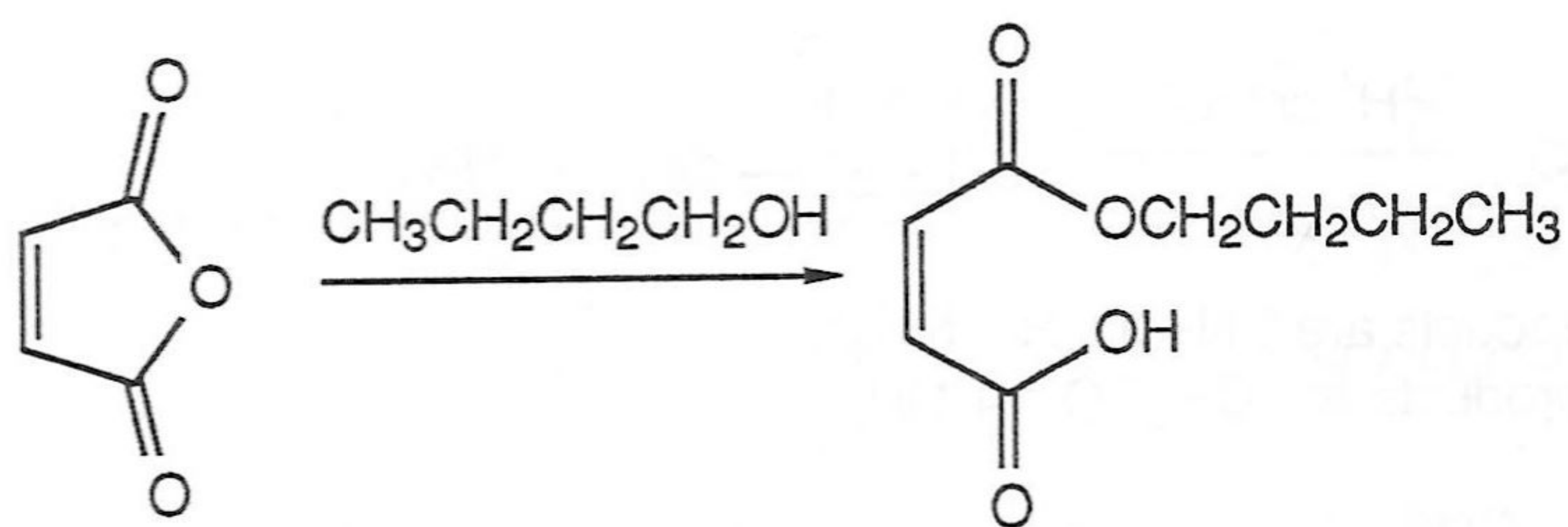
10.27 Use the middle part of eq. 10.37 as a guide:



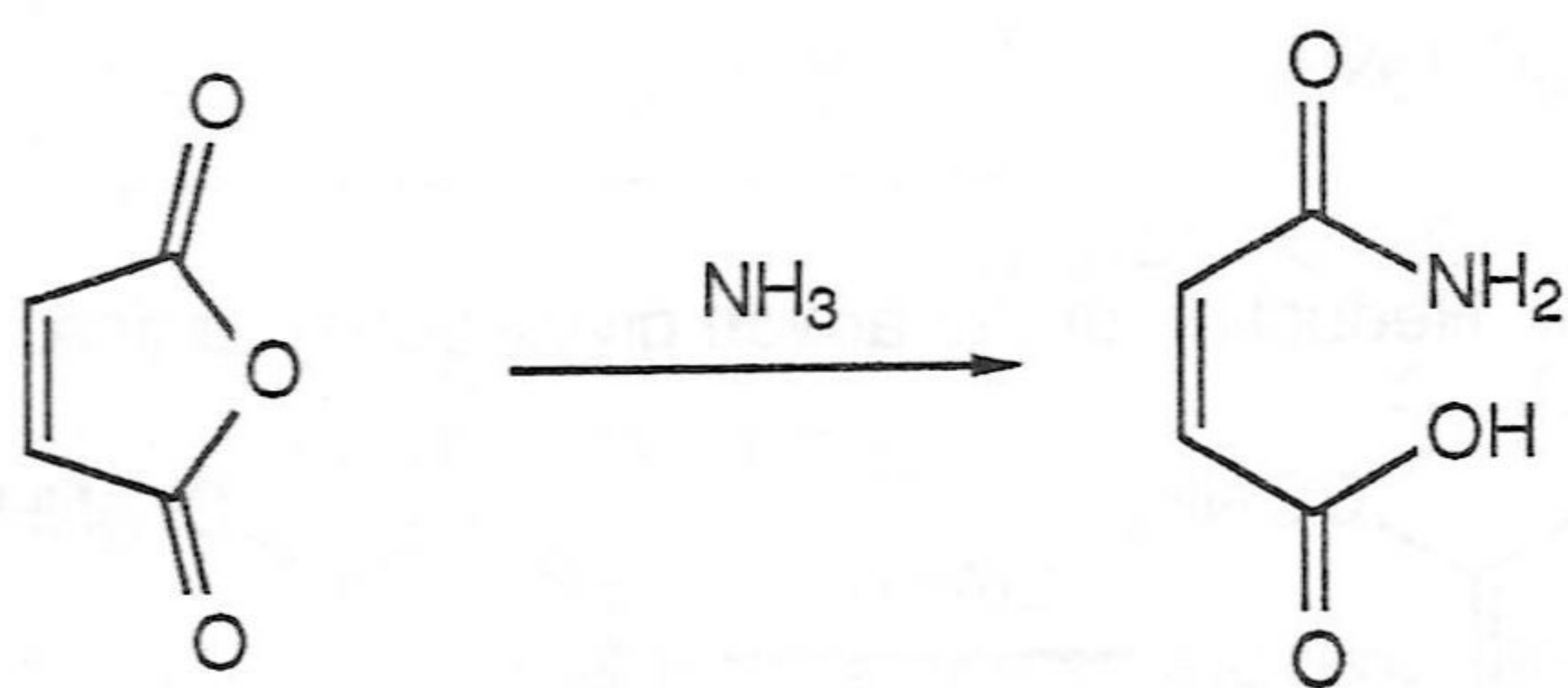
10.28 a. Use the top part of eq. 10.37 as a guide:



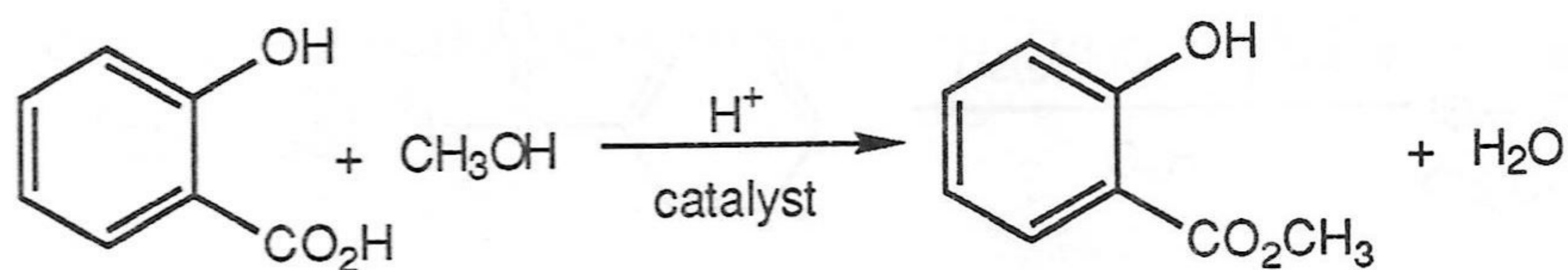
b. Use the middle of eq. 10.37 as a guide:



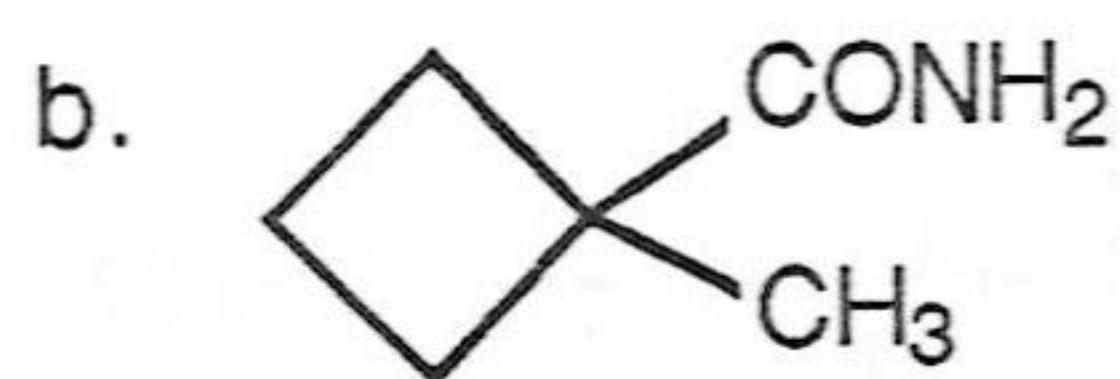
c. Use the bottom of eq. 10.37 as a guide:



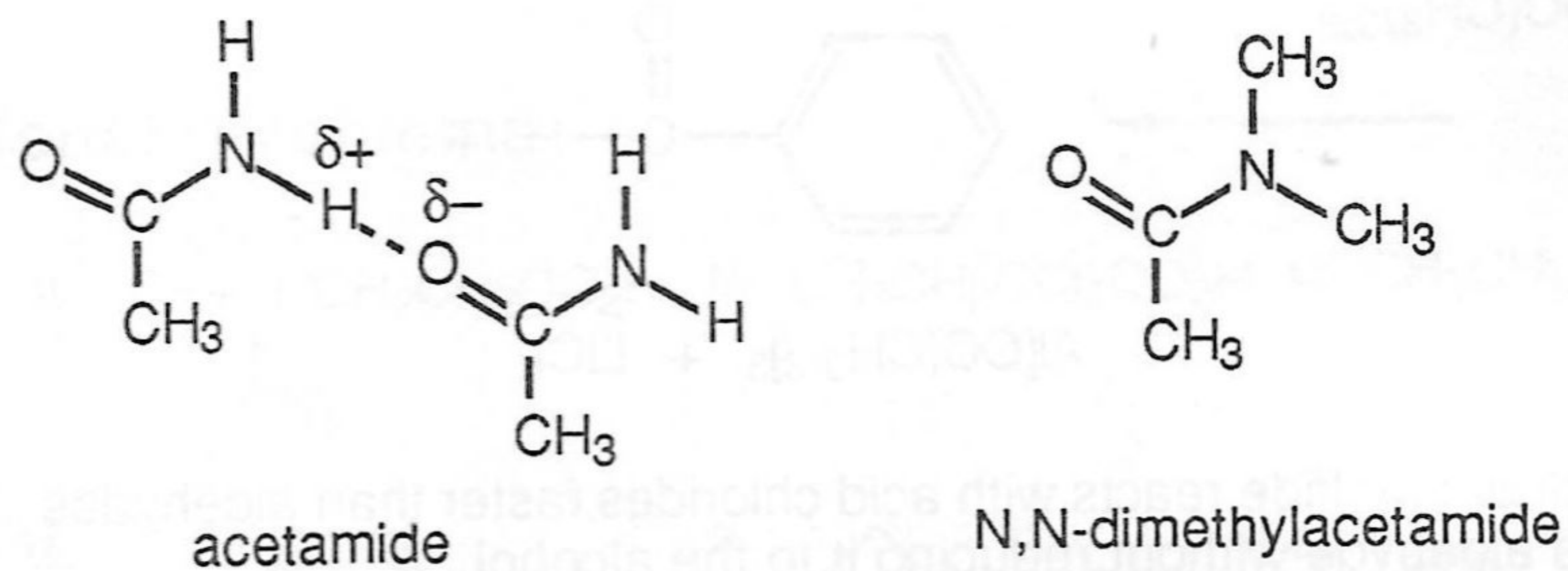
10.29 Follow eq. 10.16.



10.30 a. 2-methylpropanamide

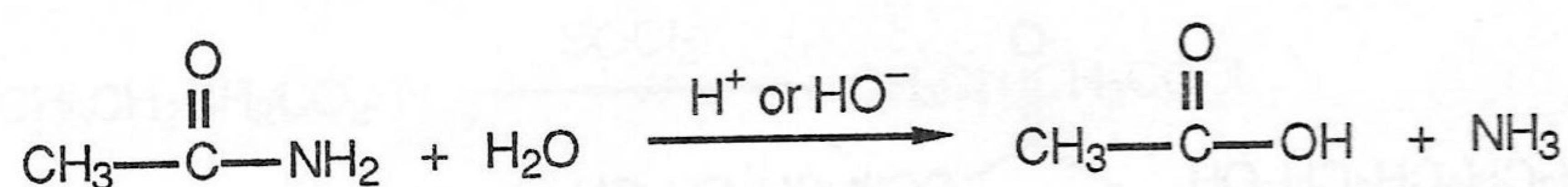


10.31 See Sec. 10.20:



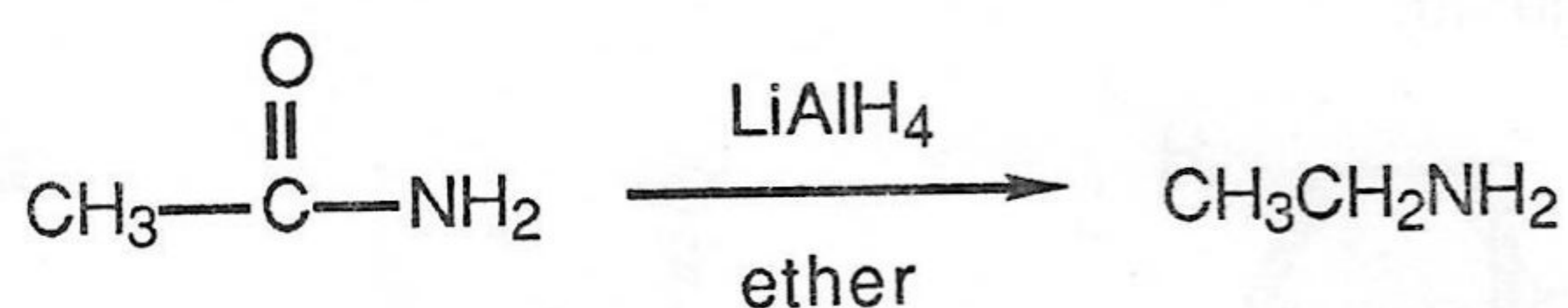
The oxygen behaves as a Lewis base and the hydrogen behaves as a Lewis acid. N,N-dimethylacetamide has no acidic hydrogen, and hydrogen bonding cannot occur.

10.32 Follow eq. 10.40, with R = CH<sub>3</sub>.

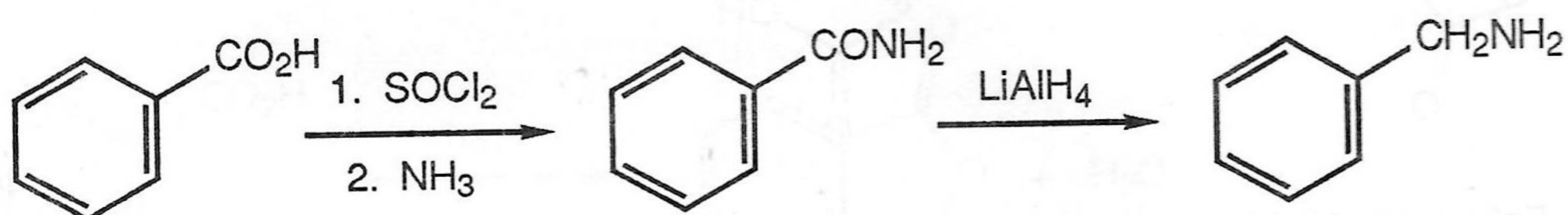


With acid catalysis, the products are CH<sub>3</sub>CO<sub>2</sub>H + NH<sub>4</sub><sup>+</sup>.  
With base catalysis, the products are CH<sub>3</sub>CO<sub>2</sub><sup>-</sup> + NH<sub>3</sub>.

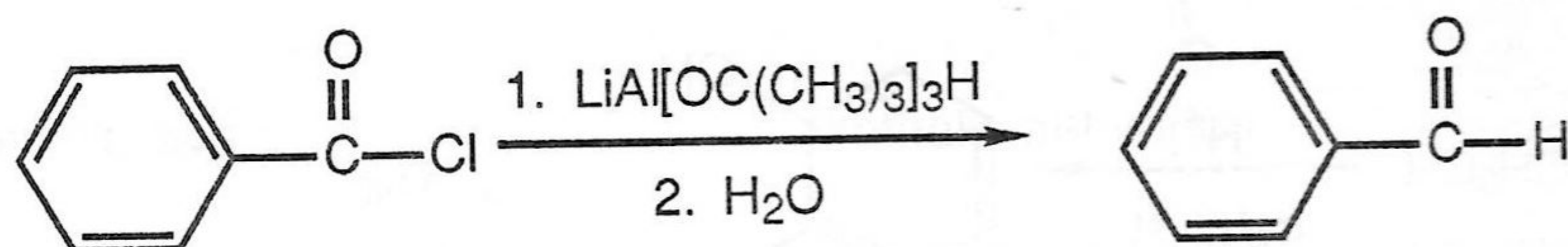
10.33 Follow eq. 10.41, with R = CH<sub>3</sub>.



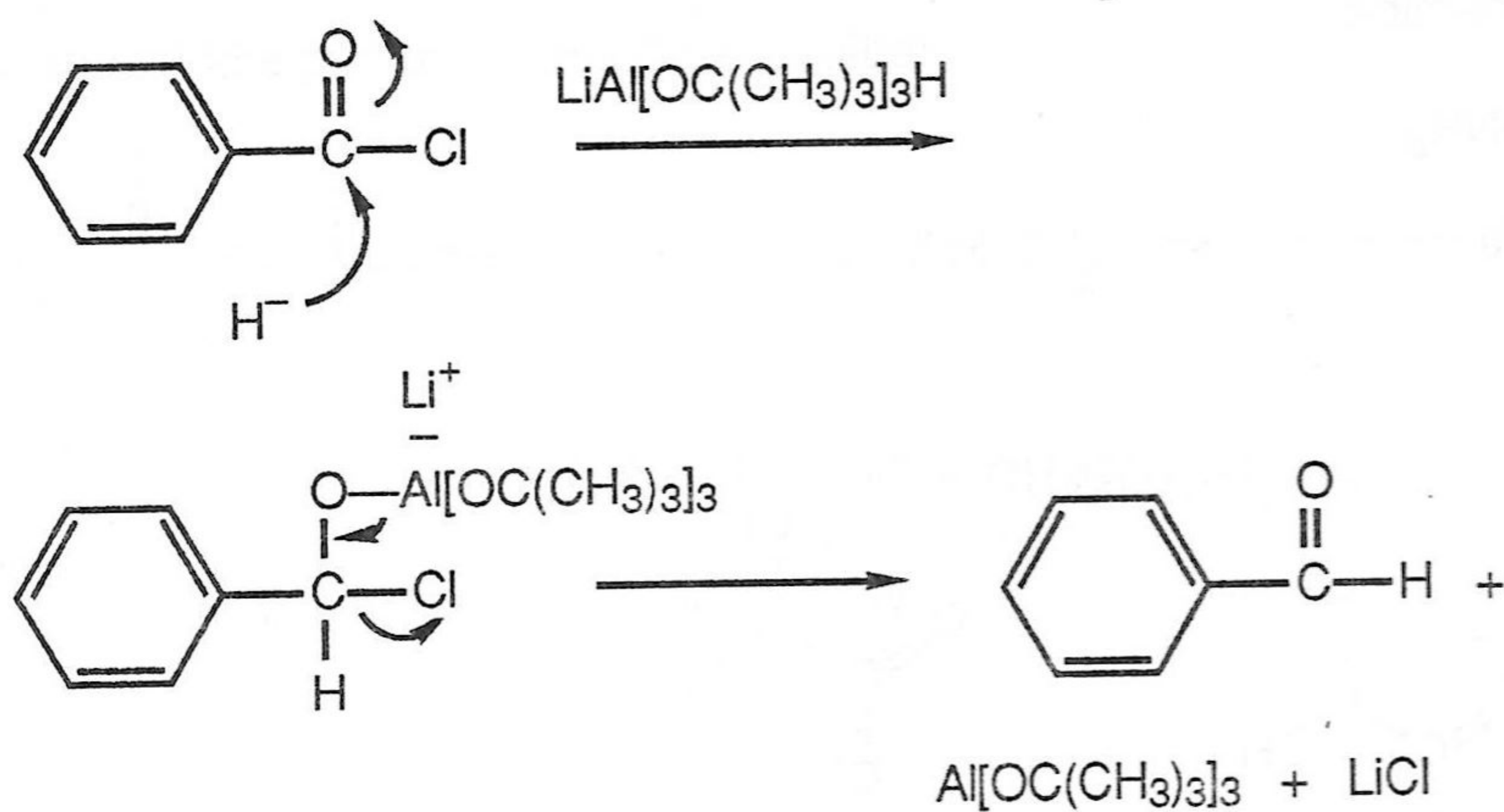
10.34 First convert benzoic acid to benzamide. Reduction of the amide gives benzylamine.



10.35

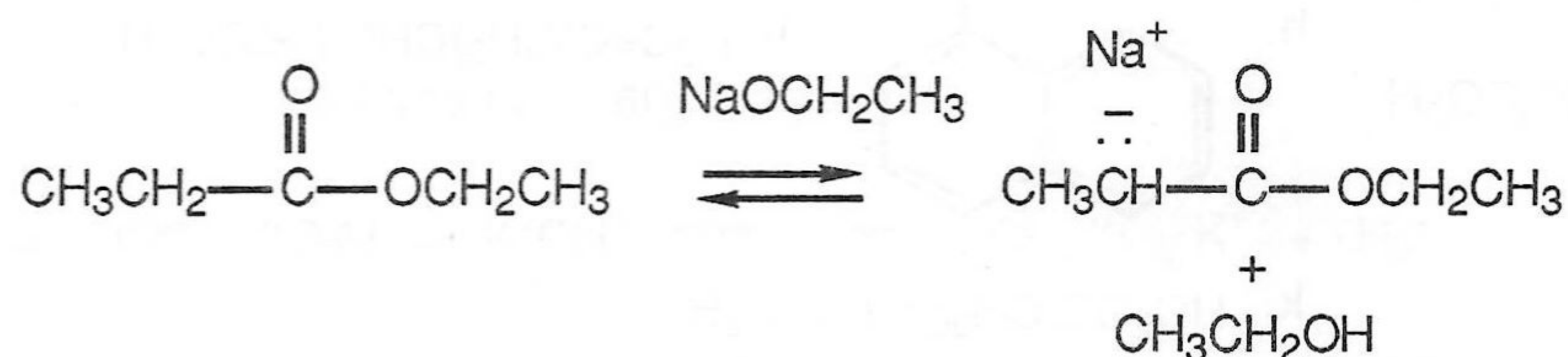


Mechanism:

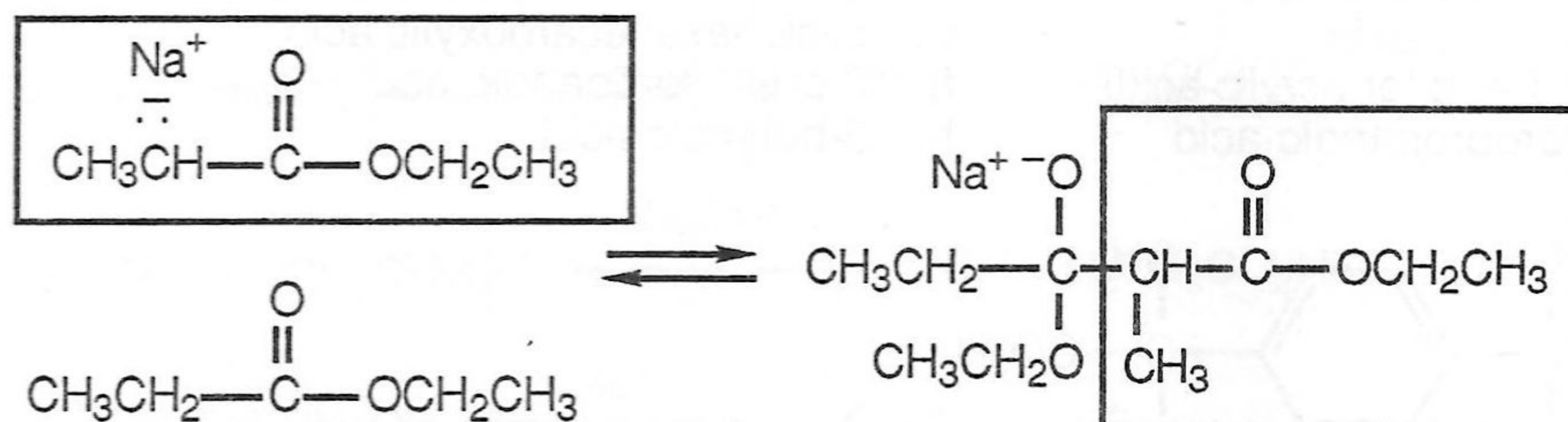


Lithium tri-*t*-butoxyaluminum hydride reacts with acid chlorides faster than aldehydes. Thus it is possible to obtain the aldehyde without reducing it to the alcohol.

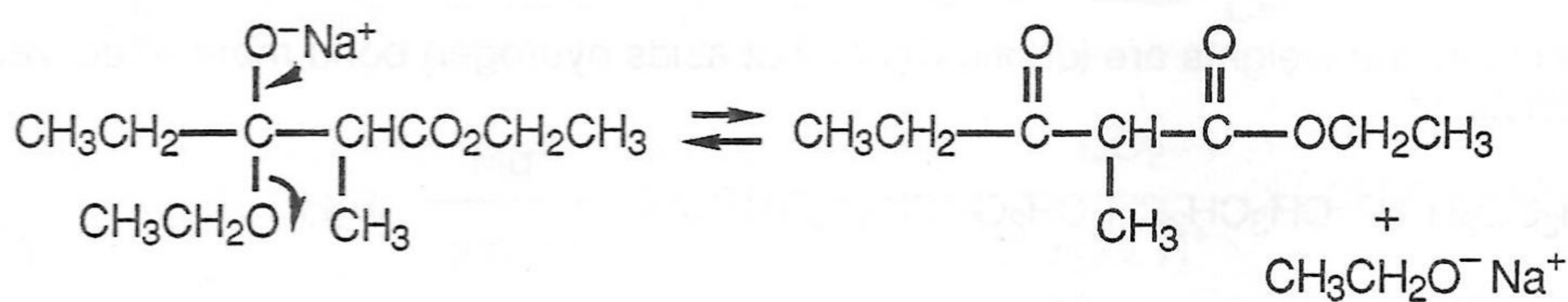
10.36 Step 1: Deprotonation gives an ester enolate.



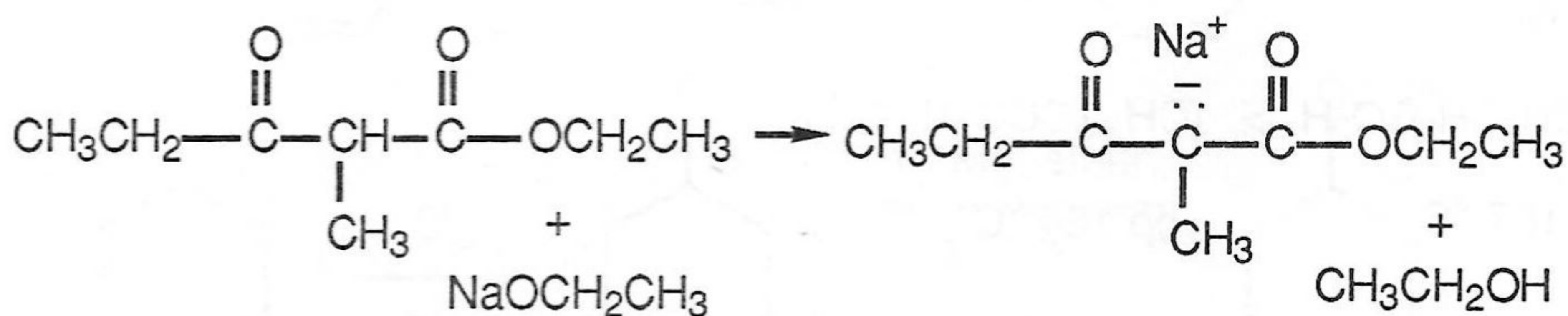
Step 2: Carbonyl addition gives a tetrahedral intermediate.



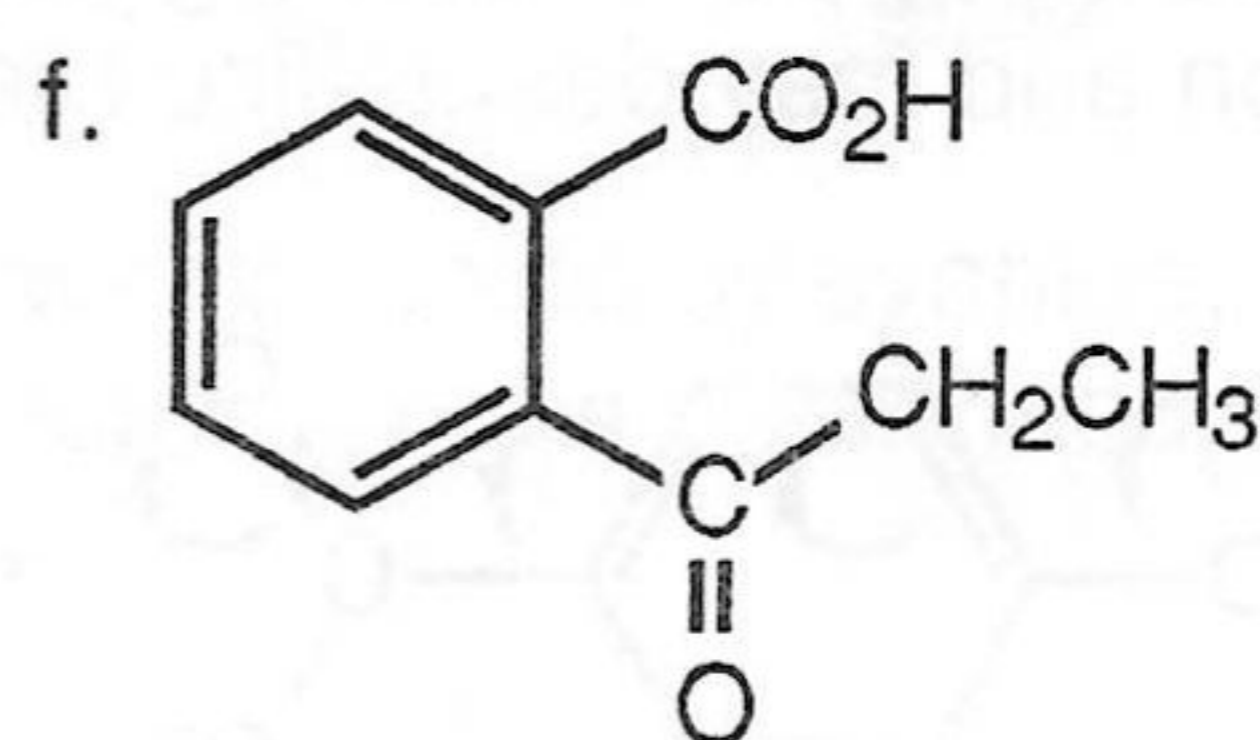
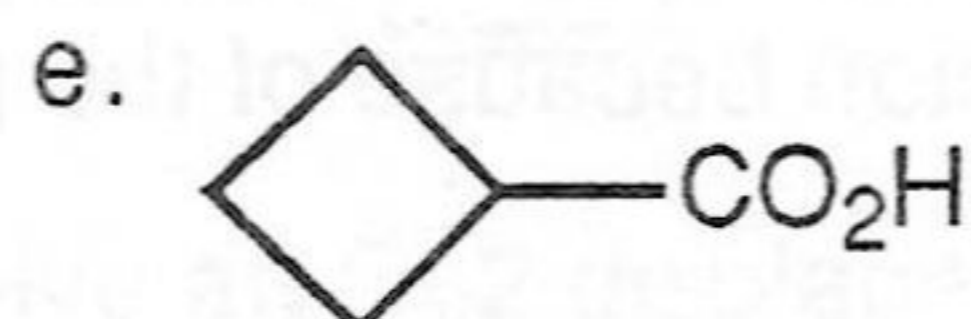
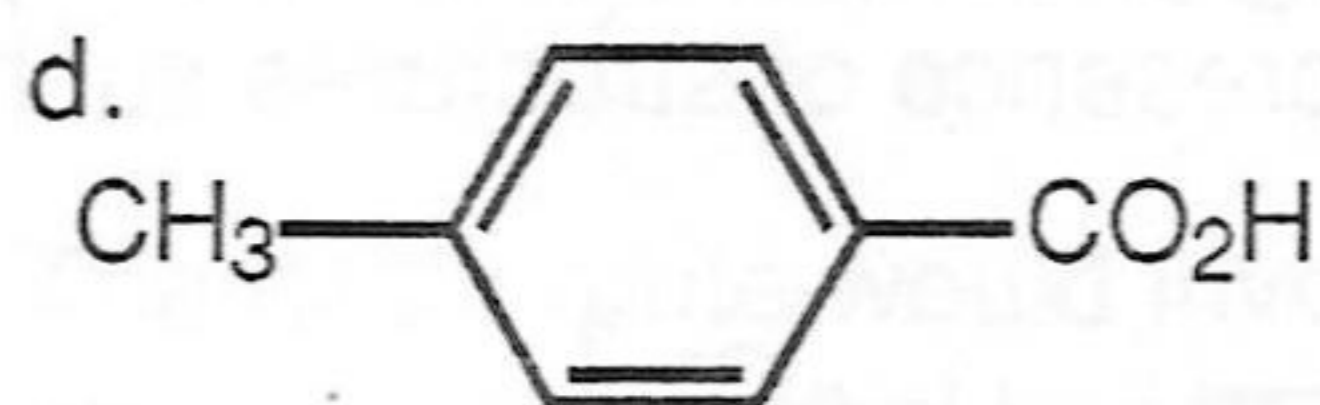
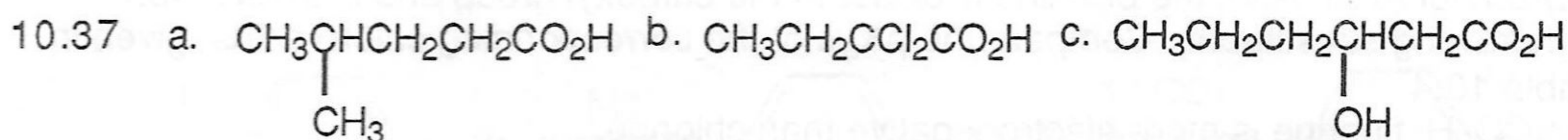
Step 3: The tetrahedral intermediate gives an ester plus ethoxide.

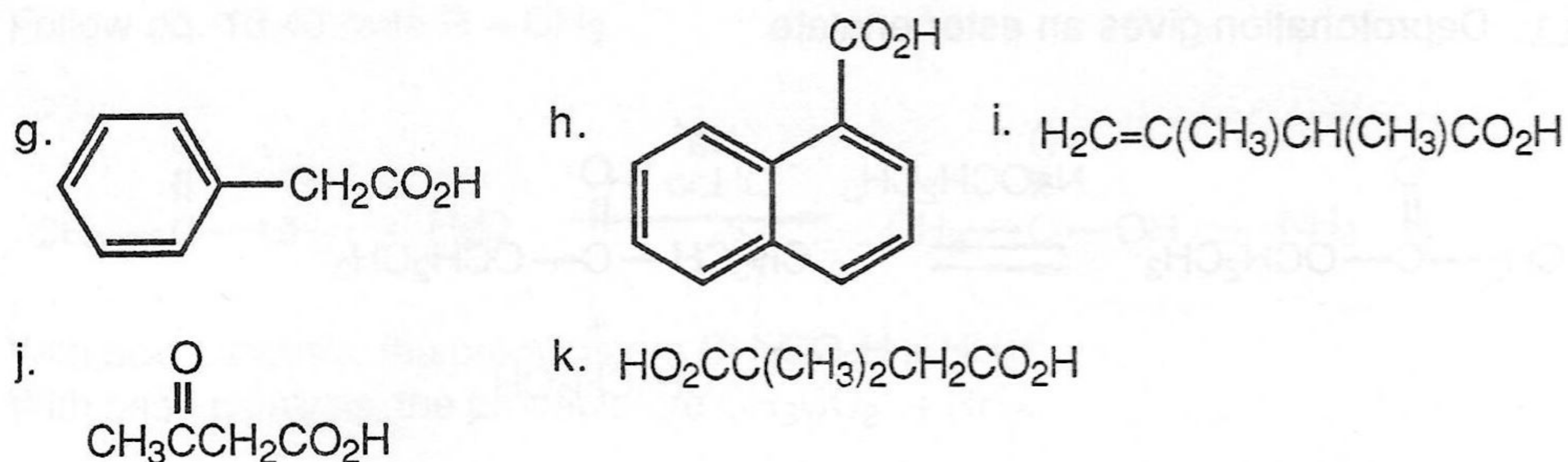


Step 4: An acid-base reaction drives the equilibria to the right.

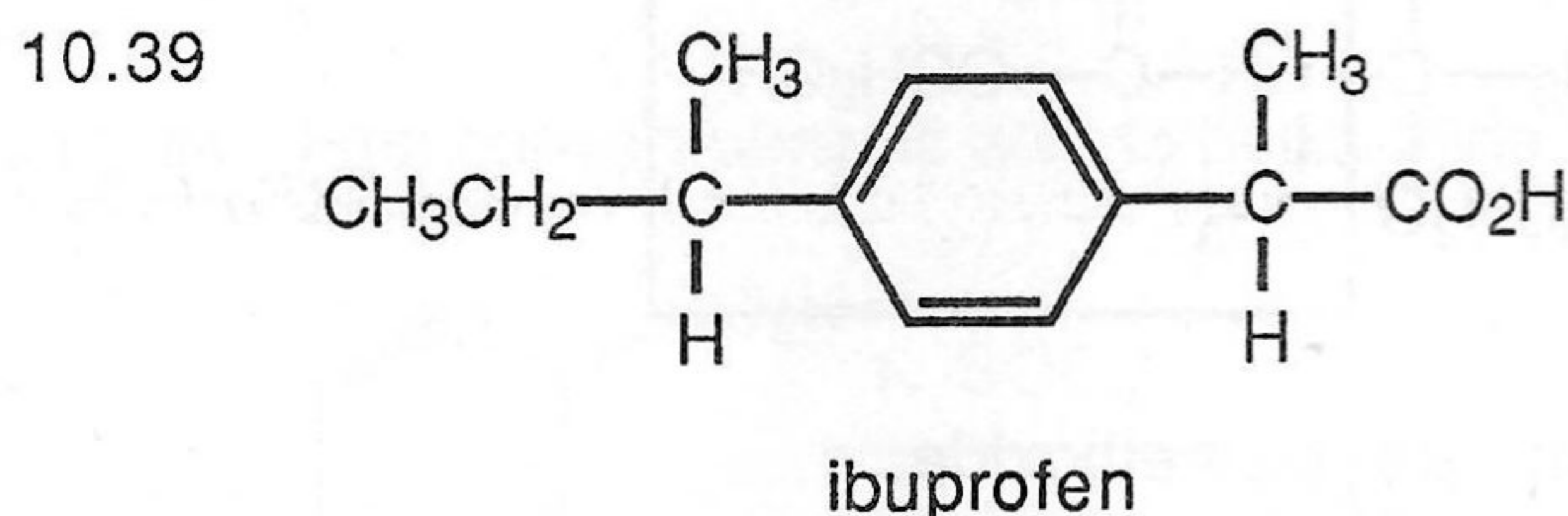


### Additional Problems

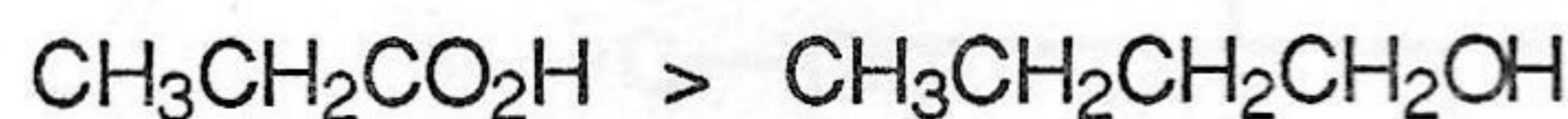




- 10.38 a. 4-methylpentanoic acid      b. 3-chloro-2-methylbutanoic acid  
 c. *p*-nitrobenzoic acid      d. cyclohexanecarboxylic acid  
 e. propenoic acid (or acrylic acid)      f. 2-phenylpropanoic acid  
 g. 2,2-difluoropropanoic acid      h. 3-butyric acid

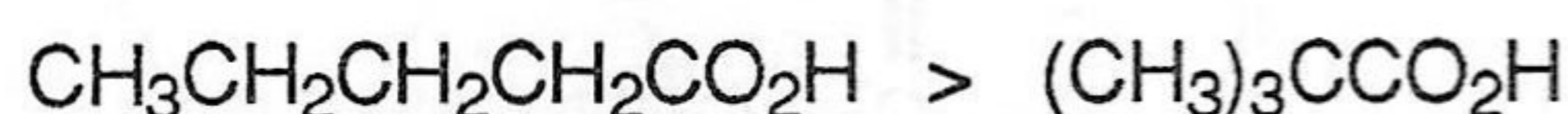


- 10.40 a. The molecular weights are identical (74), but acids hydrogen-bond more effectively than alcohols do.



bp 141 °C      bp 118 °C

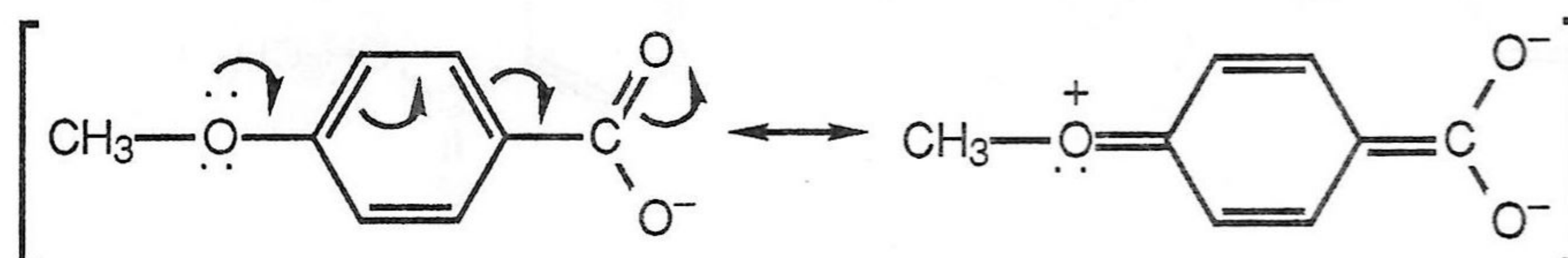
- b. Chain branching generally lowers the boiling point. Thus for these isomeric acids the order is:



bp 187 °C      bp 164 °C

- 10.41 The factors that affect acidity of carboxylic acids are discussed in Sec. 10.5.

- a.  $\text{ClCH}_2\text{CO}_2\text{H}$ ; both substituents, chlorine and bromine, are approximately the same distance from the carboxyl group, but chlorine is more electronegative than bromine.  
 b. *o*-Bromobenzoic acid; the bromine is closer to the carboxyl group and is an electron-withdrawing substituent. Compare the  $\text{p}K_a$ 's of the corresponding chloro acids, given in Table 10.4.  
 c.  $\text{CF}_3\text{CO}_2\text{H}$ ; fluorine is more electronegative than chlorine.  
 d. Benzoic acid; the methoxy group is an electron-releasing substituent when in the *para* position and may destabilize the anion because of the presence of structures such as



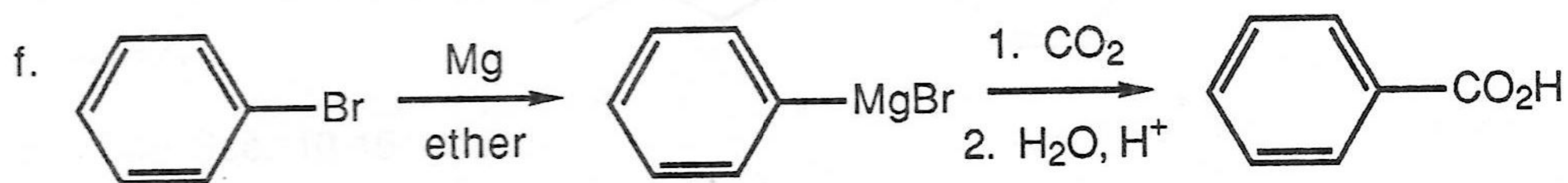
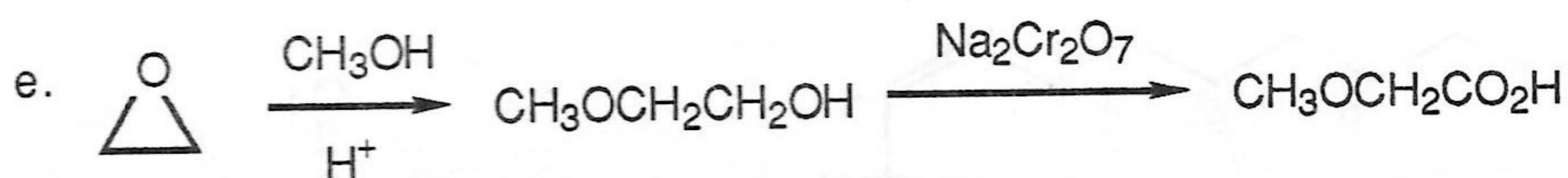
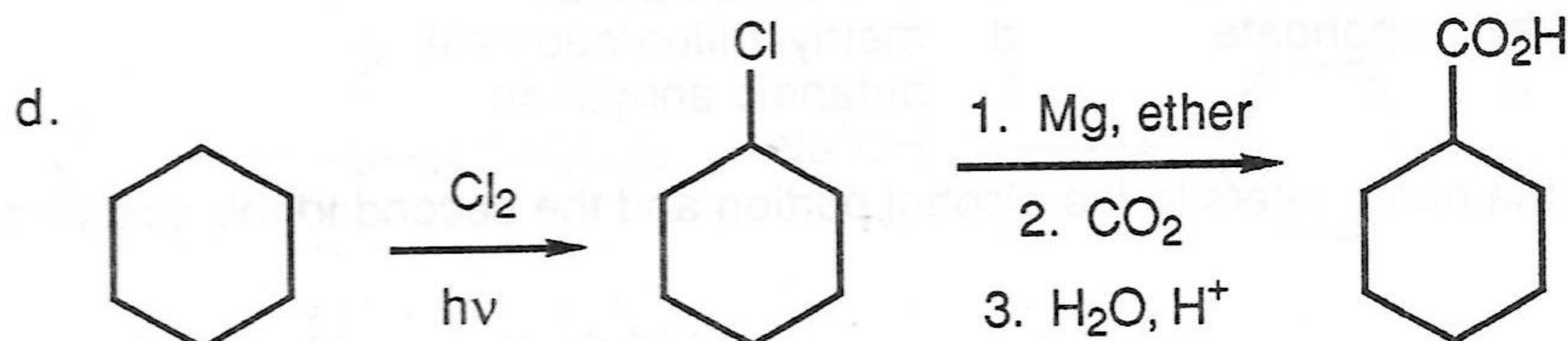
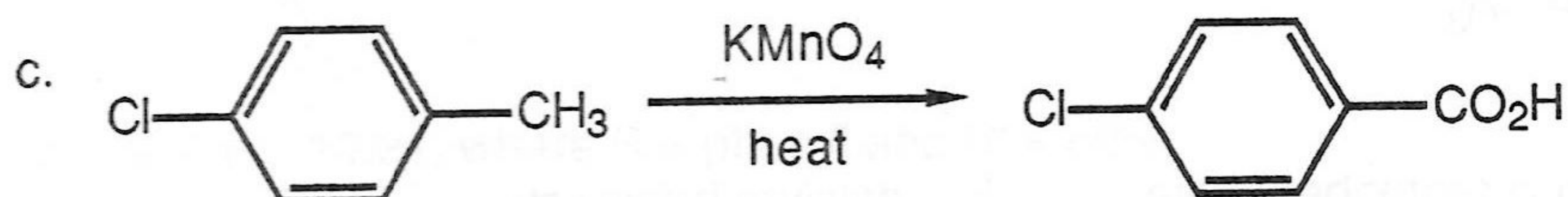
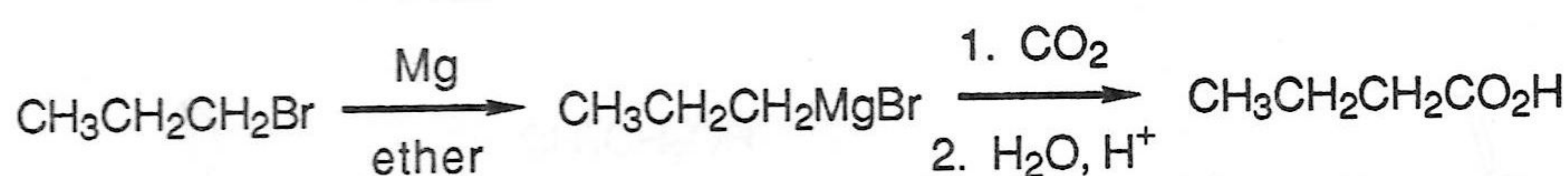
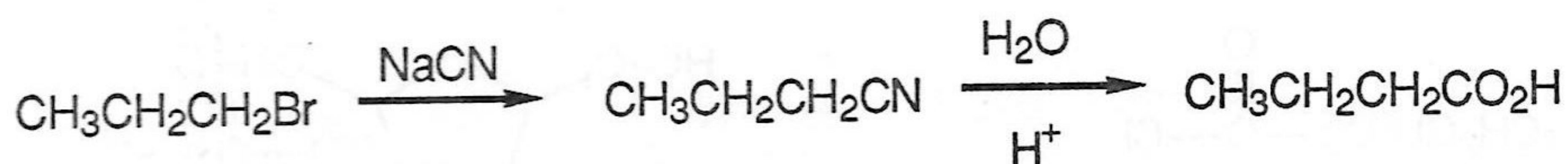
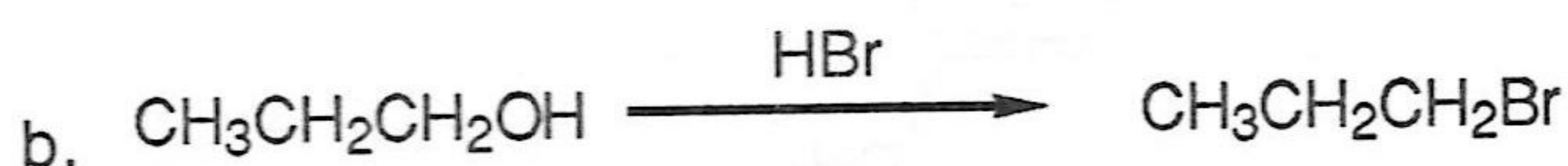
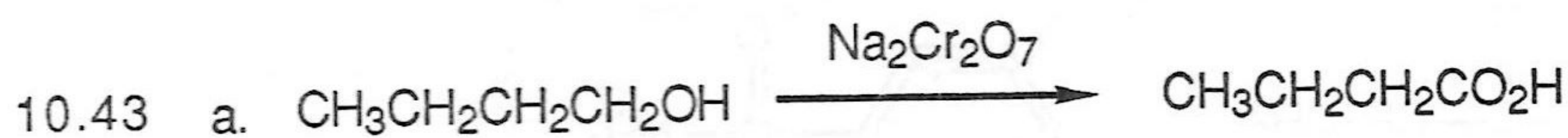
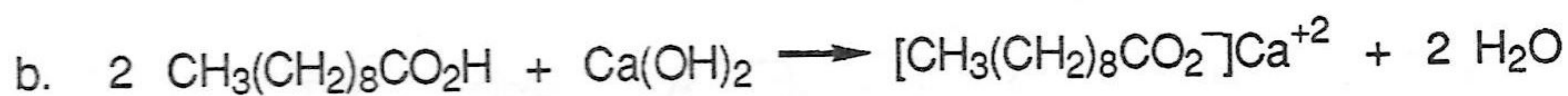
which bring two negative charges near one another.

- e.  $\text{CH}_3\text{CHClCO}_2\text{H}$ ; the chlorine, which is electron-withdrawing, is closer to the carboxyl group.

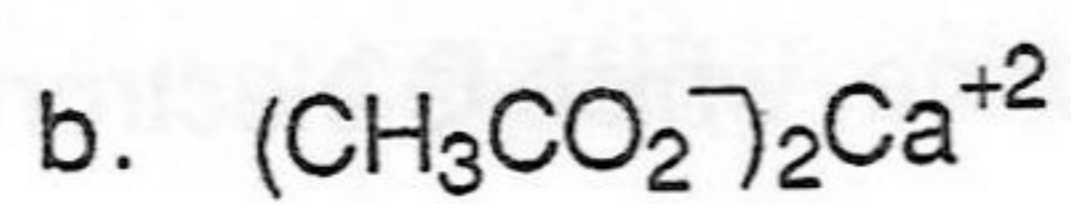
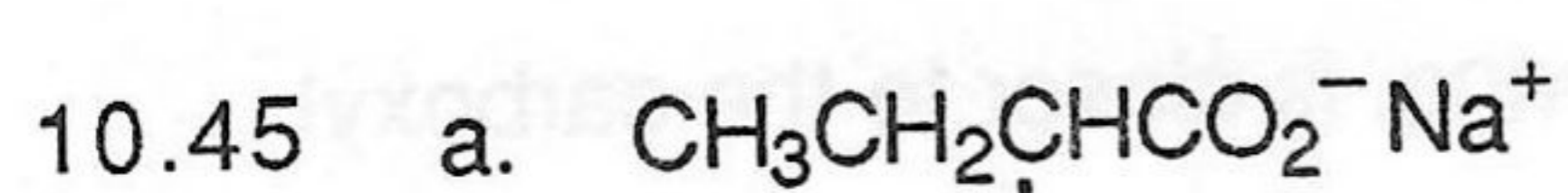
10.42 See Sec. 10.6 if you have any difficulty.



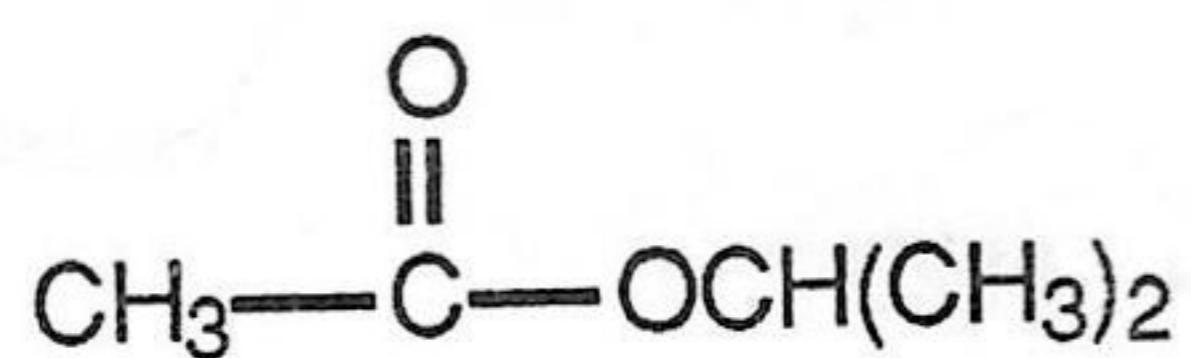
Salt formation occurs at room temperature. If the reagents are heated for some time, an  $\text{S}_{\text{N}}2$  displacement on the primary chloride may also occur, giving the salt of hydroxyacetic acid,  $\text{HOCH}_2\text{CO}_2^-\text{K}^+$ .



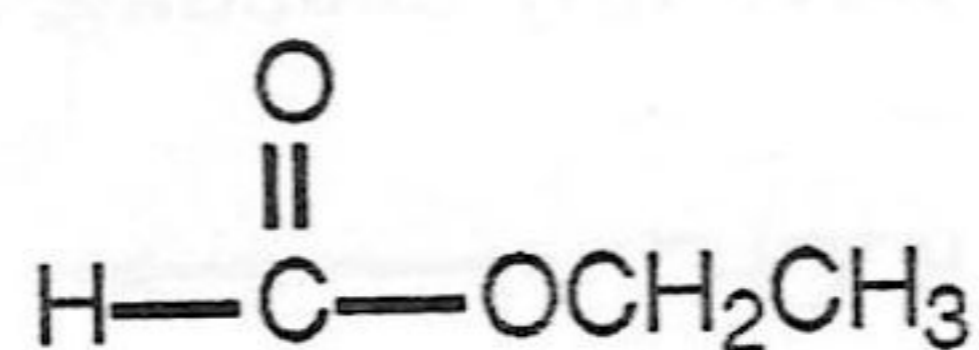
- 10.44 The nitrile route would involve an  $\text{S}_{\text{N}}2$  displacement of bromide by cyanide, a highly unlikely step when the alkyl halide is tertiary. The Grignard route, on the other hand, works well for all alkyl halides—primary, secondary, and tertiary.



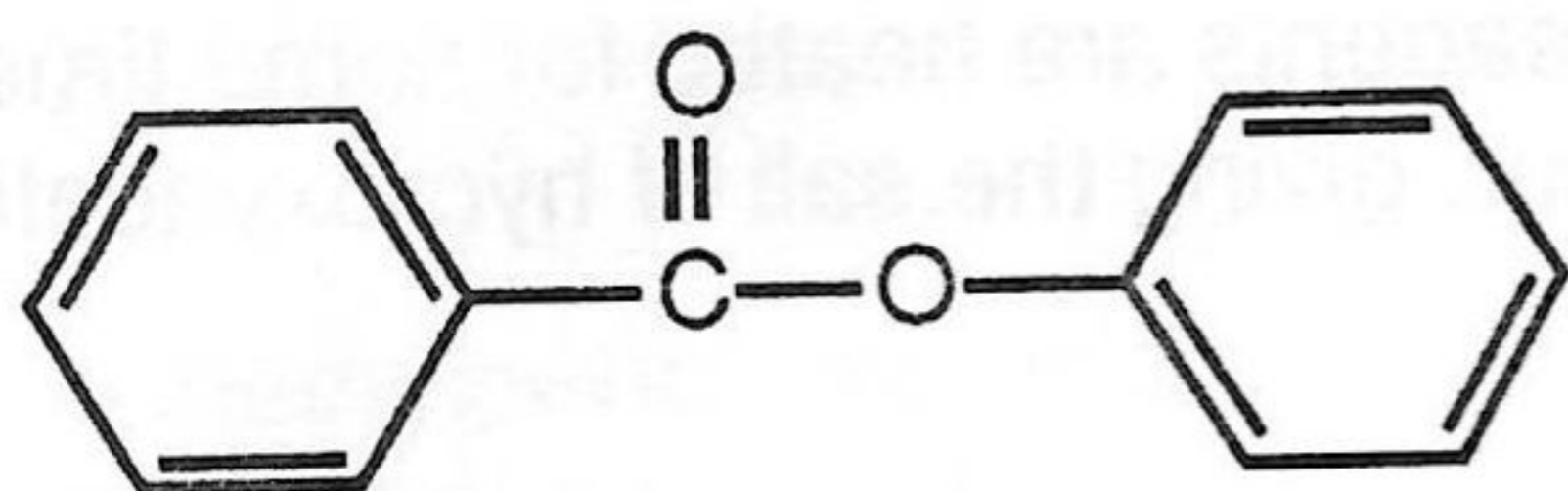
c.



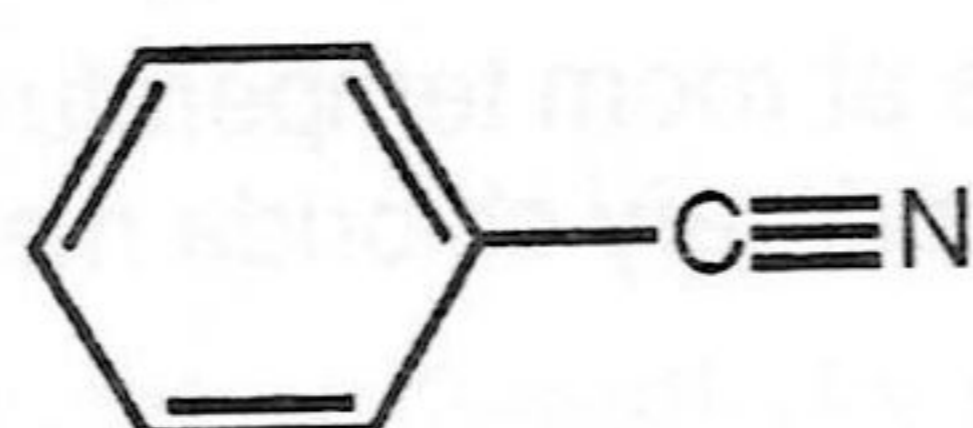
d.



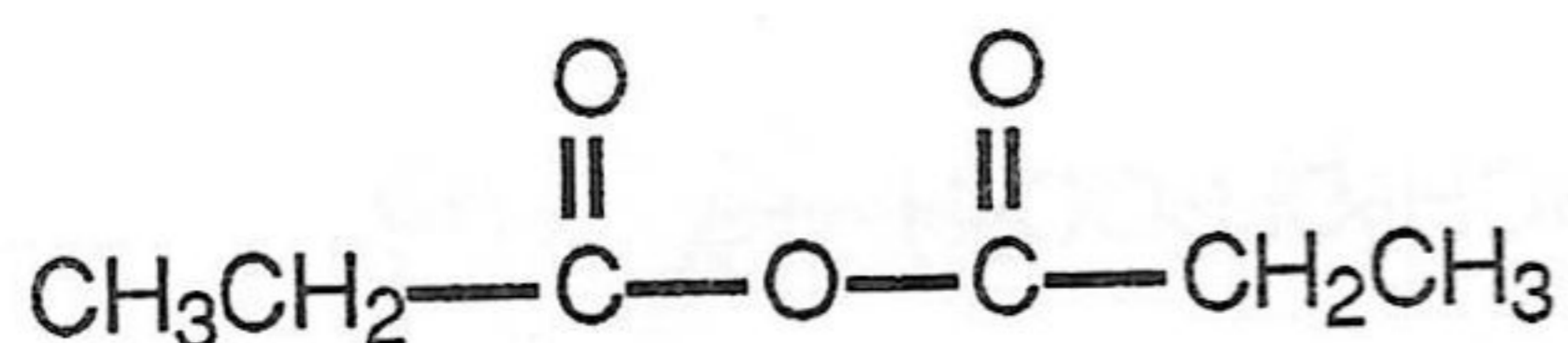
e.



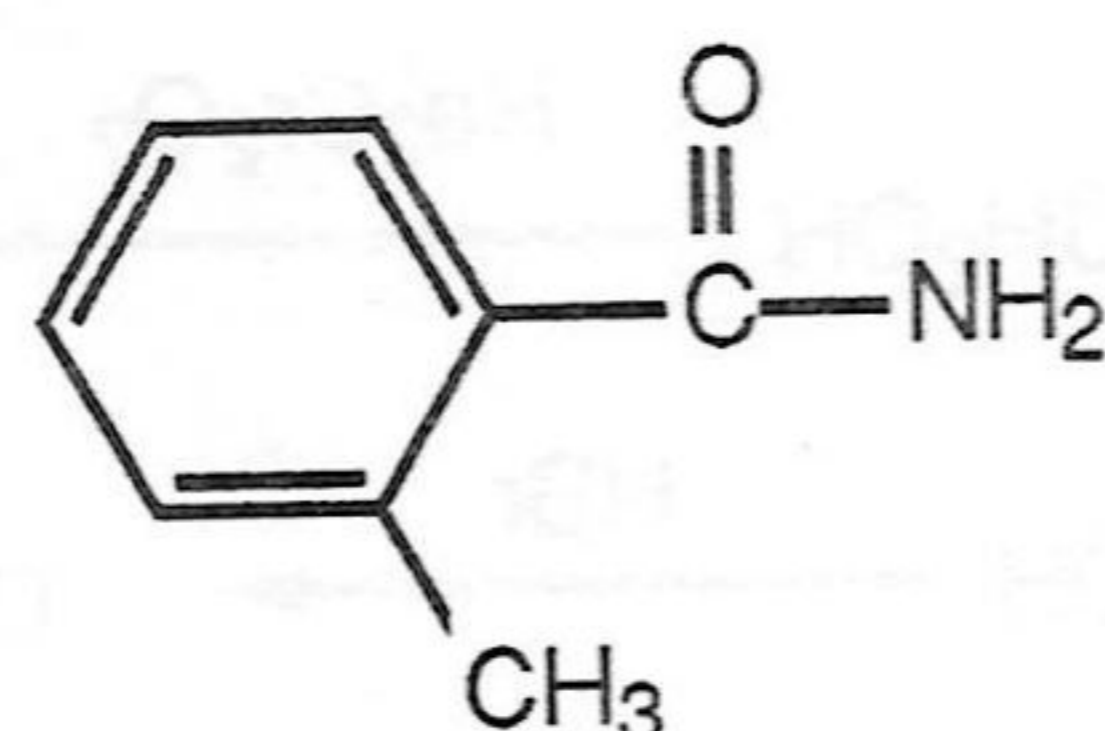
f.



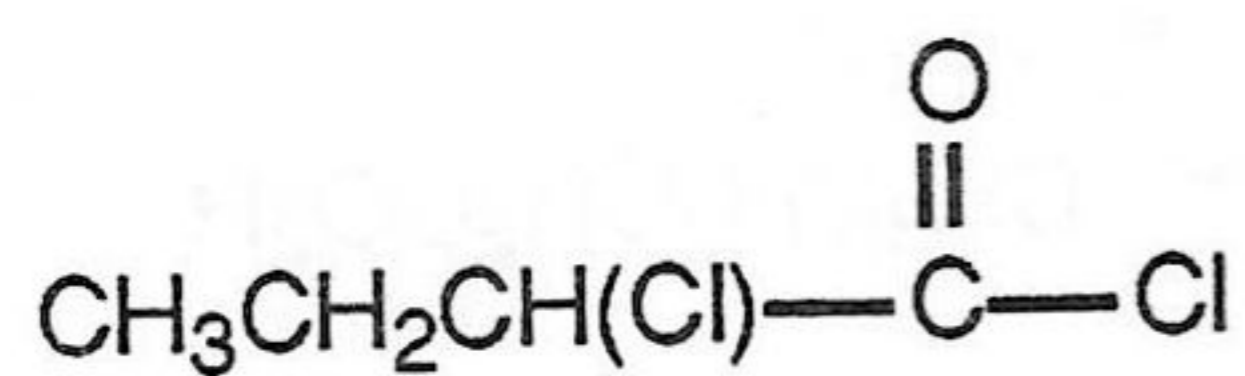
g.



h.



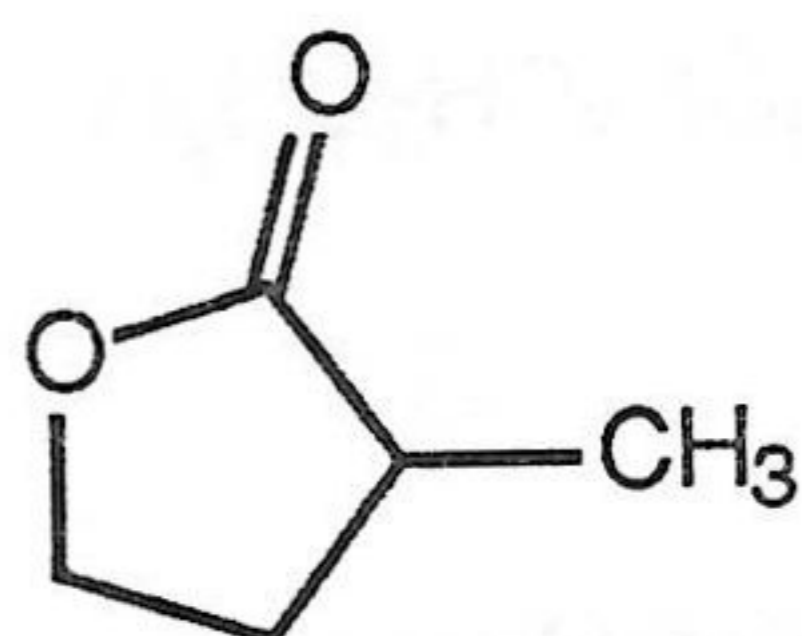
i.



j.



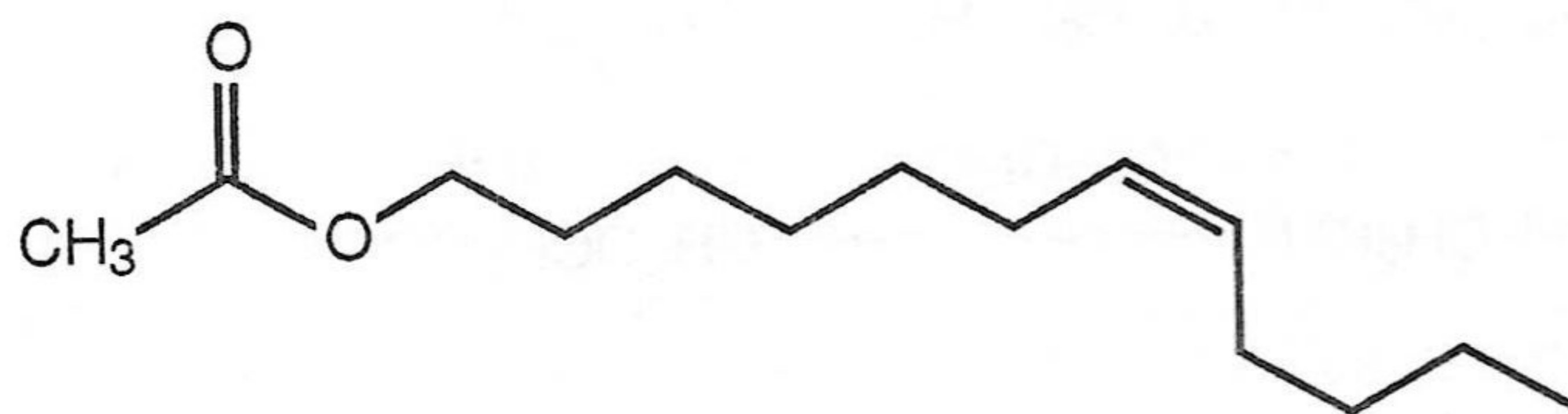
k.



- 10.46 a. ammonium *p*-bromobenzoate  
c. phenyl 2-methylpropanoate  
e. formamide

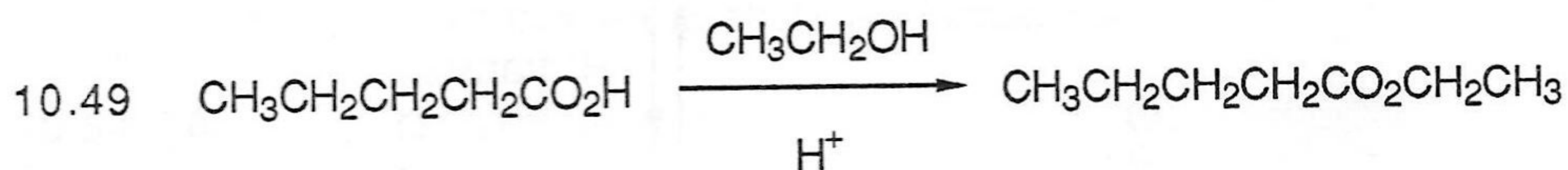
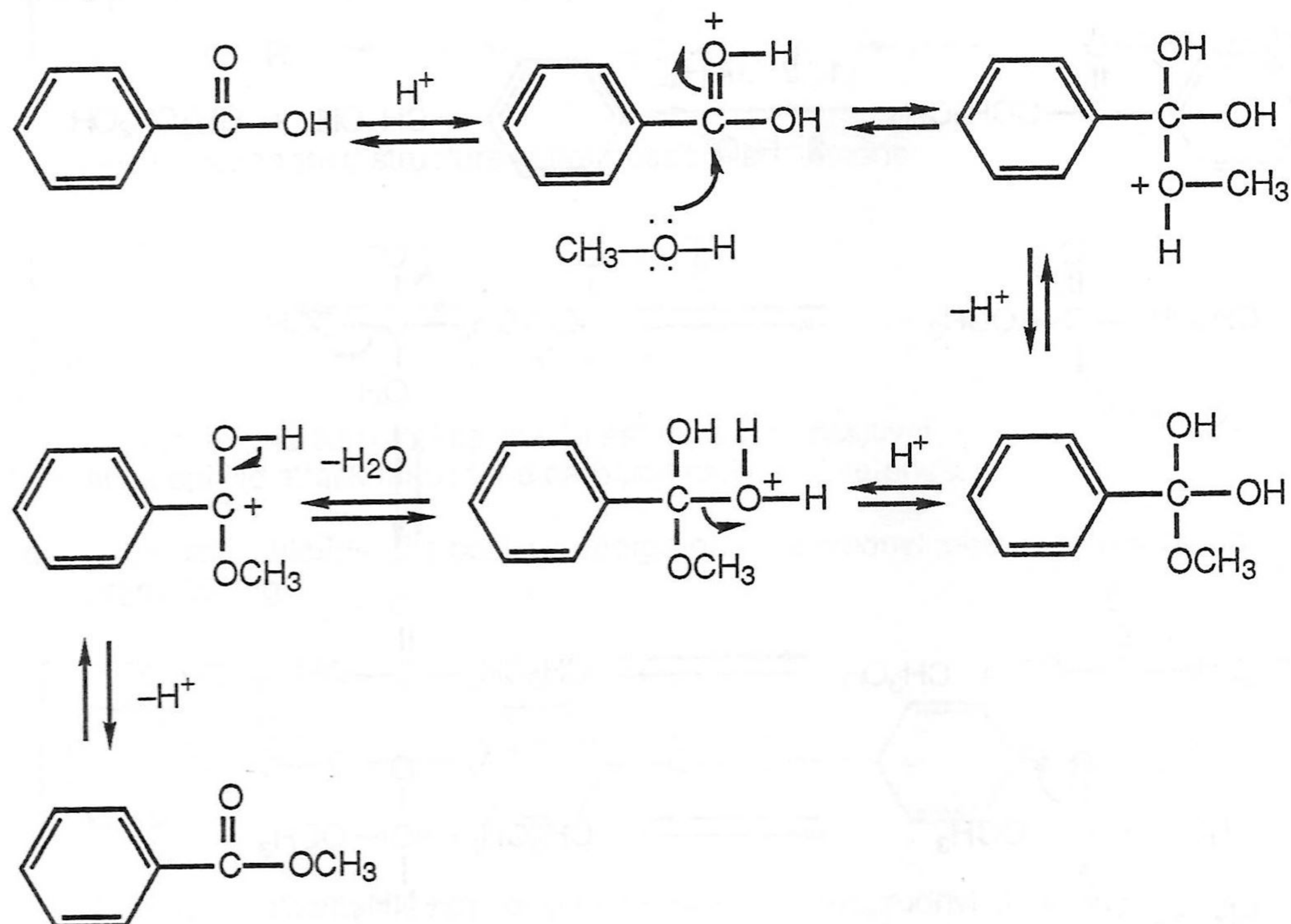
- b. calcium butanoate  
d. methyl trifluoroacetate  
f. butanoic anhydride

10.47 The first word of the name refers to the alcohol portion and the second to the acid portion:





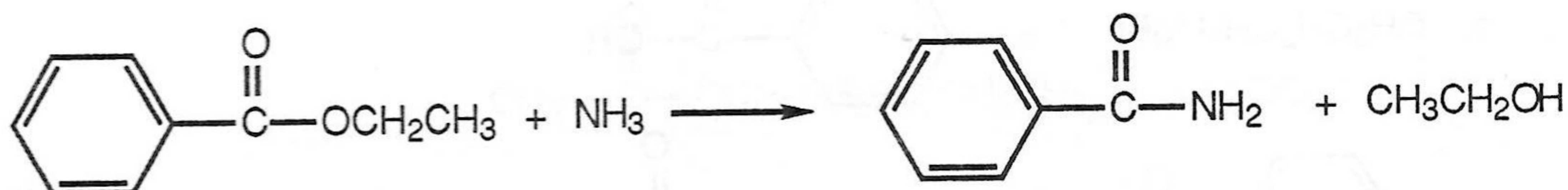
10.48 Compare with the answer to Problem 10.16.



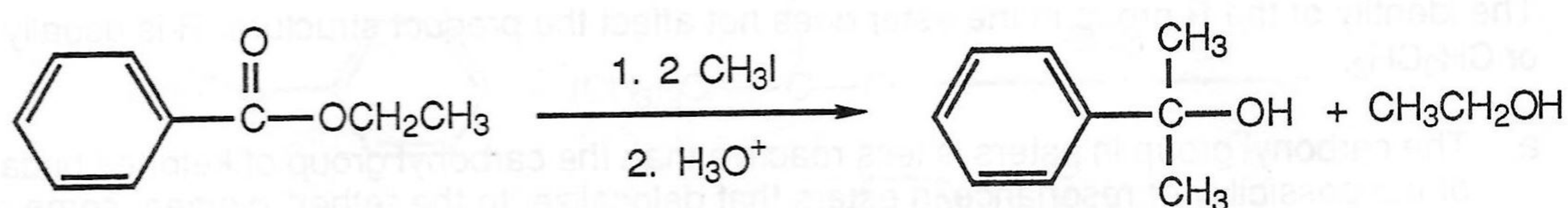
10.50 a. See eq. 10.21, where R = phenyl and R' = ethyl.



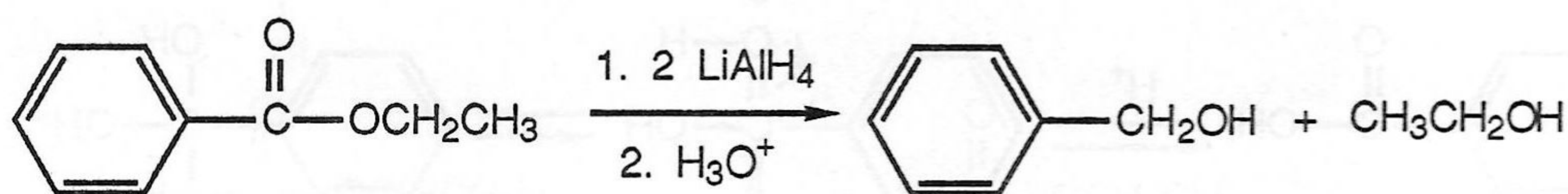
b. Compare with eq. 10.23.



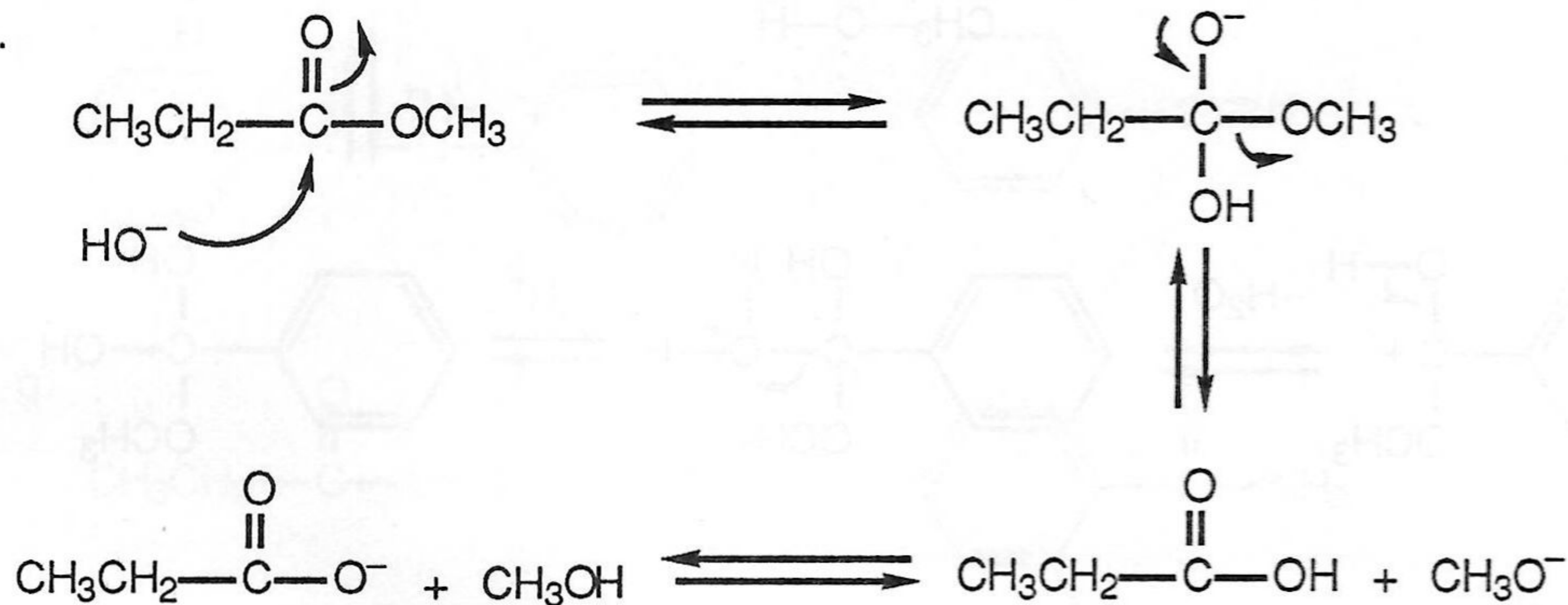
c. See Sec. 10.15.



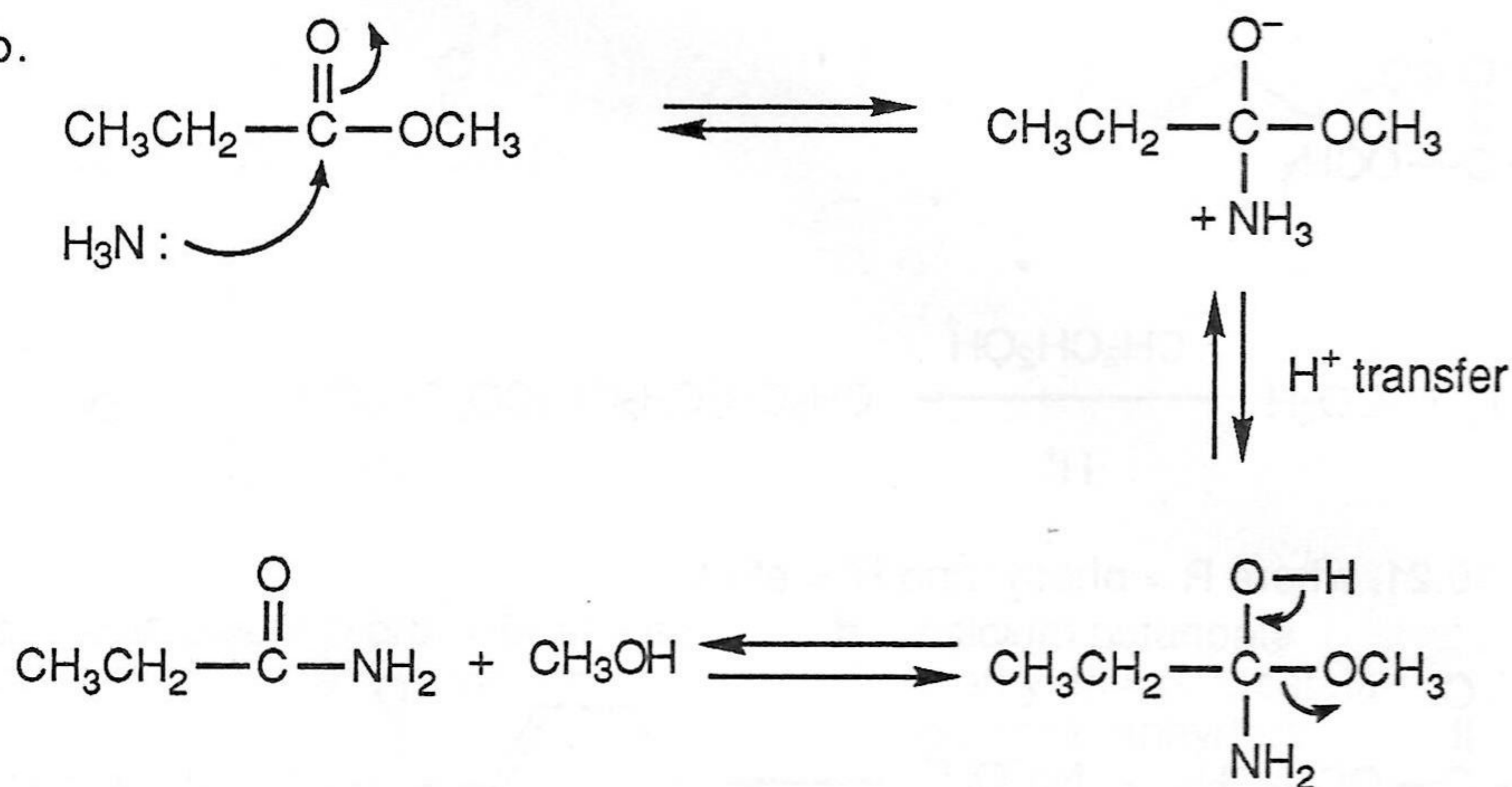
d. See Sec. 10.16.



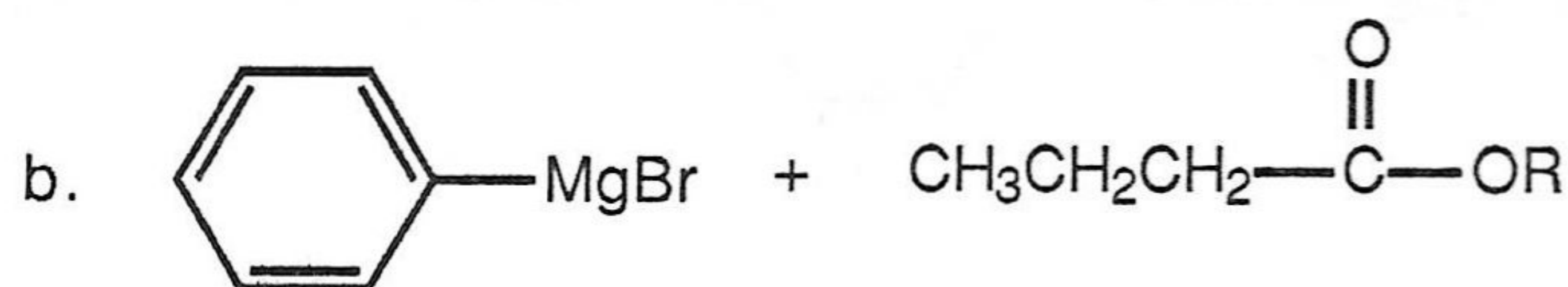
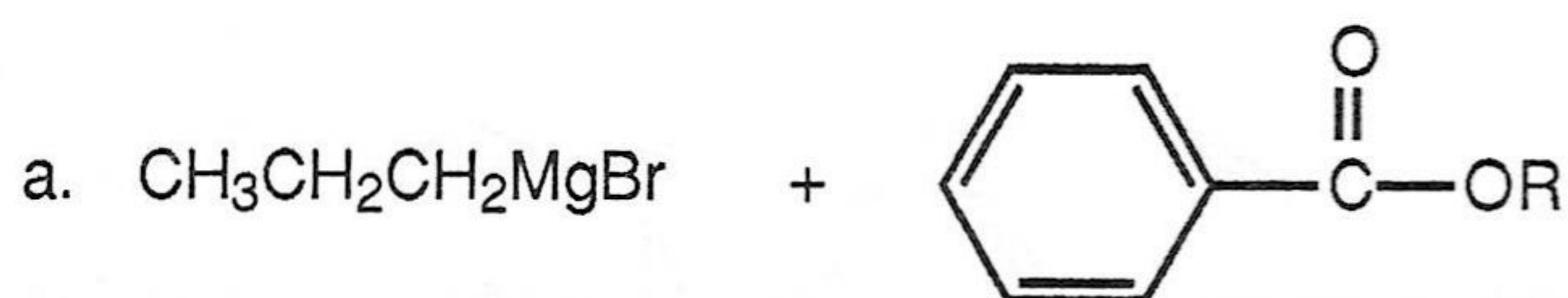
10.51 a.



b.

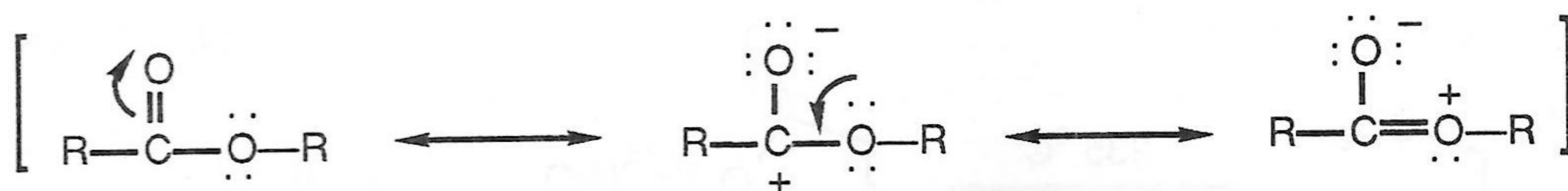


10.52 In each case, the two like organic groups attached to the hydroxyl-bearing carbon come from the Grignard reagent, and the third group comes from the acid part of the ester.



The identity of the R group in the ester does not affect the product structure. R is usually  $\text{CH}_3$  or  $\text{CH}_3\text{CH}_2$ .

10.53 a. The carbonyl group in esters is less reactive than the carbonyl group of ketones because of the possibility of resonance in esters that delocalize, to the "ether" oxygen, some of the positive charge associated with the carbonyl carbon atom.

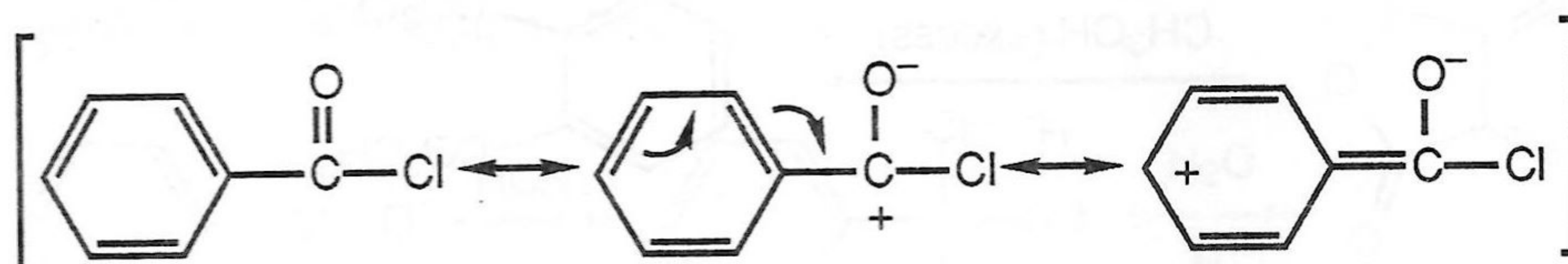


Such a resonance structure is not possible in a ketone.



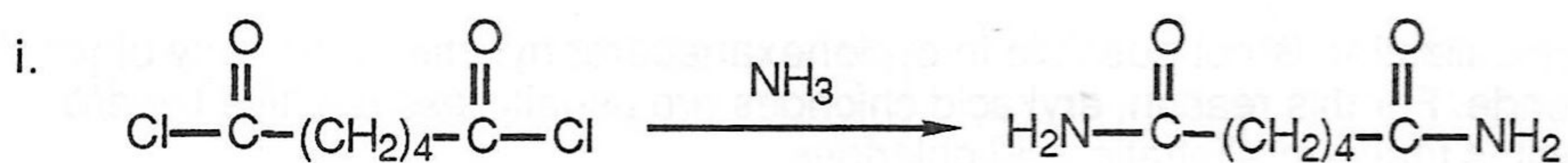
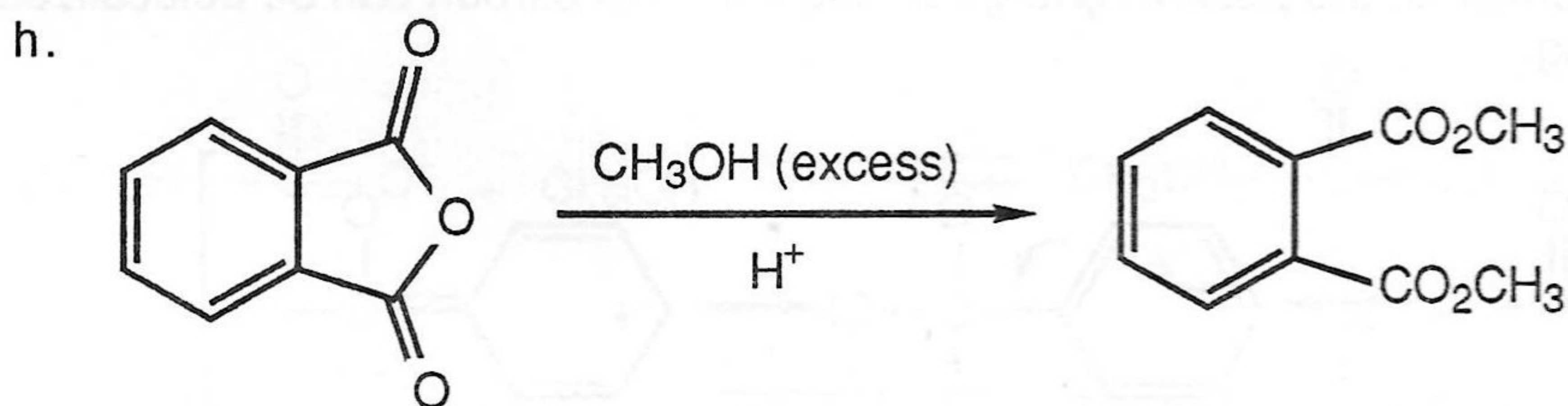
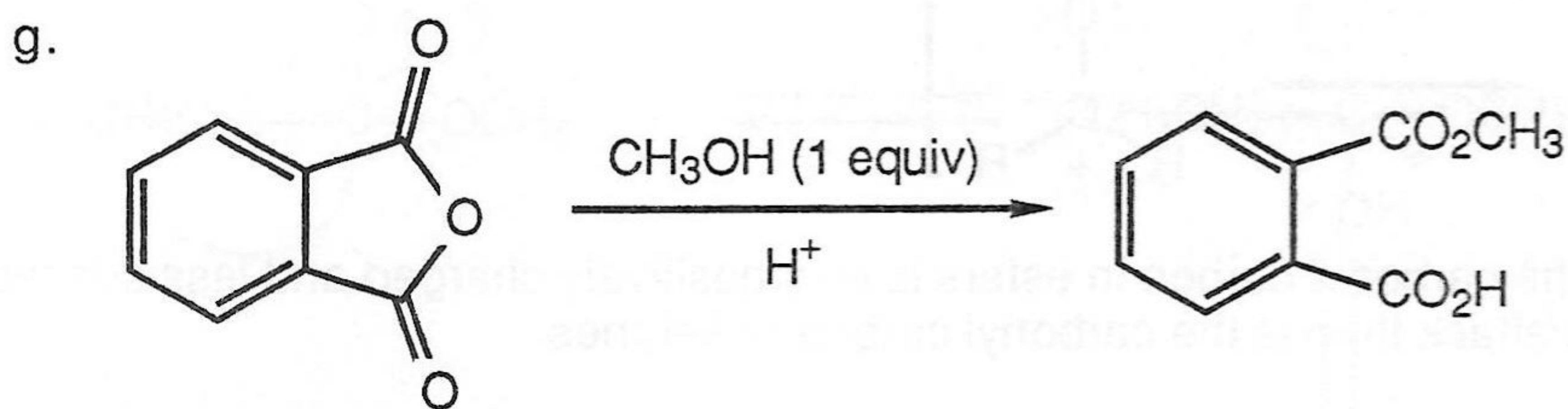
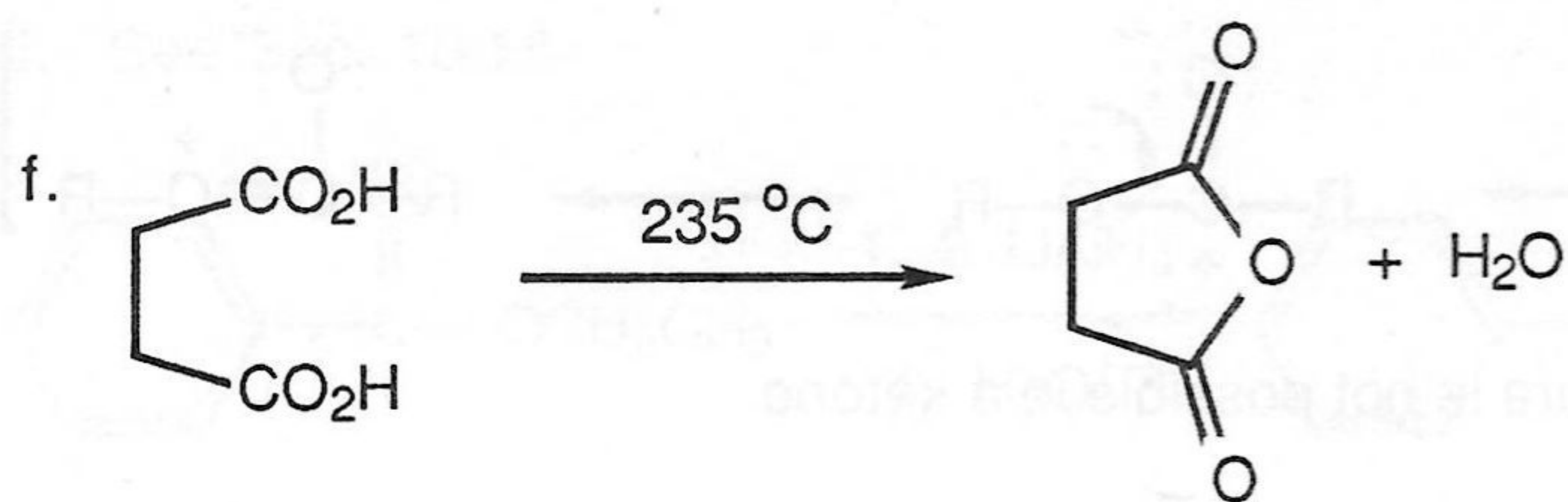
Therefore, the carbonyl carbon in esters is less positively charged and less susceptible to nucleophilic attack than is the carbonyl carbon of ketones.

- b. In benzoyl chloride, the positive charge on the carbonyl carbon can be delocalized in the aromatic ring.

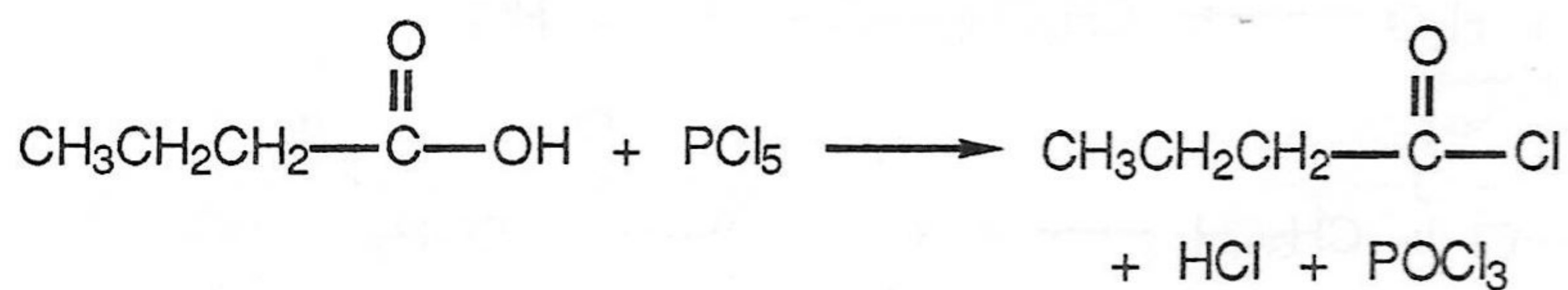


Such delocalization is not possible in cyclohexanecarbonyl chloride or any other aliphatic acid chloride. For this reason, aryl acid chlorides are usually less reactive toward nucleophiles than are aliphatic acid chlorides.

- 10.54 a.  $\text{CH}_3\text{CH}_2-\overset{\text{O}}{\parallel}{\text{C}}-\text{Cl} + \text{H}_2\text{O} \longrightarrow \text{CH}_3\text{CH}_2-\overset{\text{O}}{\parallel}{\text{C}}-\text{OH} + \text{HCl}$
- b.  $\text{C}_6\text{H}_5-\overset{\text{O}}{\parallel}{\text{C}}-\text{Cl} + \text{CH}_3\text{OH} \longrightarrow \text{C}_6\text{H}_5-\overset{\text{O}}{\parallel}{\text{C}}-\text{OCH}_3 + \text{HCl}$
- c.  $\text{CH}_3-\overset{\text{O}}{\parallel}{\text{C}}-\text{O}-\overset{\text{O}}{\parallel}{\text{C}}-\text{CH}_3 + \text{HOCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 \longrightarrow \text{CH}_3-\overset{\text{O}}{\parallel}{\text{C}}-\text{OCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 + \text{CH}_3\text{CO}_2\text{H}$
- d.  $\text{CH}_3\text{CH}_2\text{CH}_2-\overset{\text{O}}{\parallel}{\text{C}}-\text{Br} + 2 \text{NH}_3 \longrightarrow \text{CH}_3\text{CH}_2\text{CH}_2-\overset{\text{O}}{\parallel}{\text{C}}-\text{NH}_2 + \text{NH}_4^+ \text{Br}^-$
- e.  $\text{CH}_3\text{CH}_2-\text{C}_6\text{H}_4 + (\text{CH}_3)_2\text{CH}-\overset{\text{O}}{\parallel}{\text{C}}-\text{Cl} \xrightarrow{\text{AlCl}_3} \text{CH}_3\text{CH}_2-\text{C}_6\text{H}_4-\overset{\text{O}}{\parallel}{\text{C}}-\text{CH}(\text{CH}_3)_2$



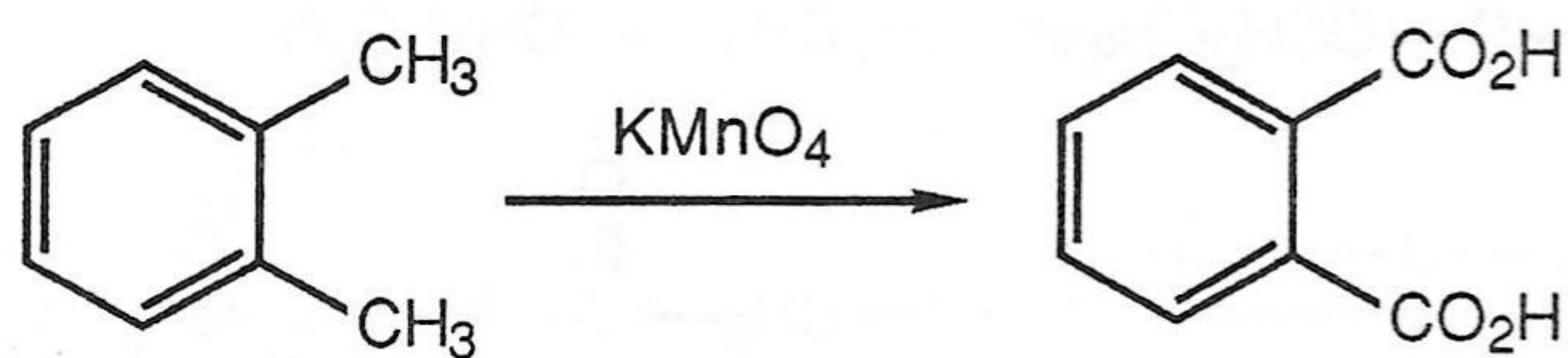
10.55 a. See eq. 10.31.



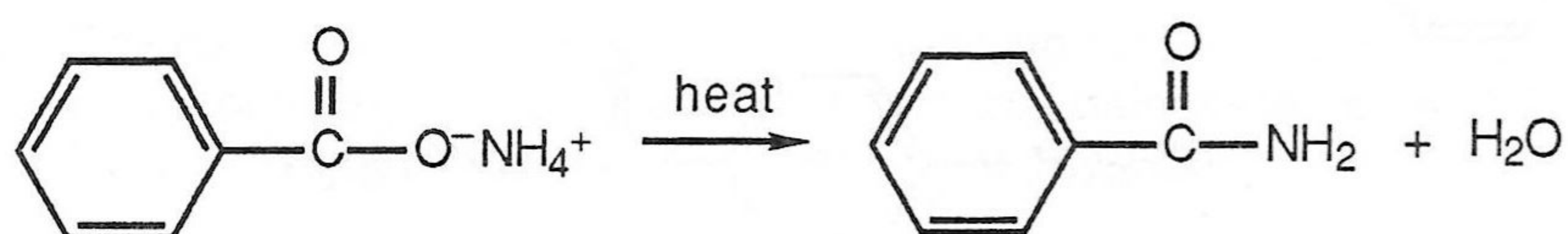
b. See eq. 10.30.



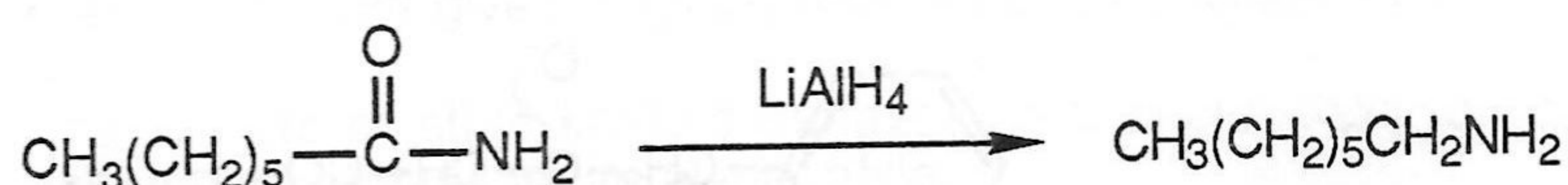
c. See eq. 10.8.



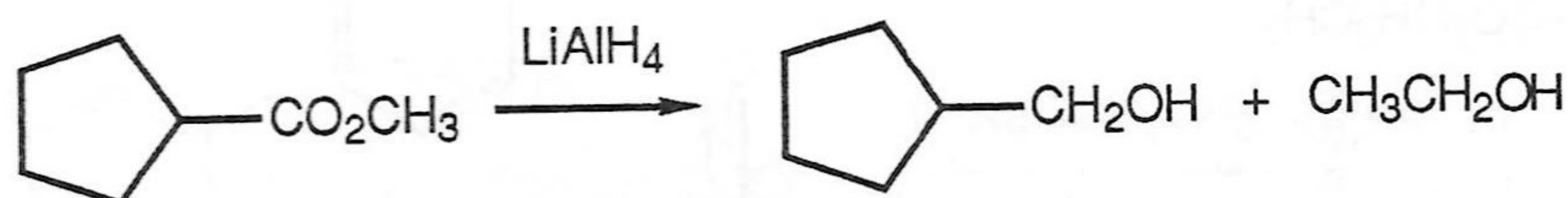
d. See eq. 10.39.



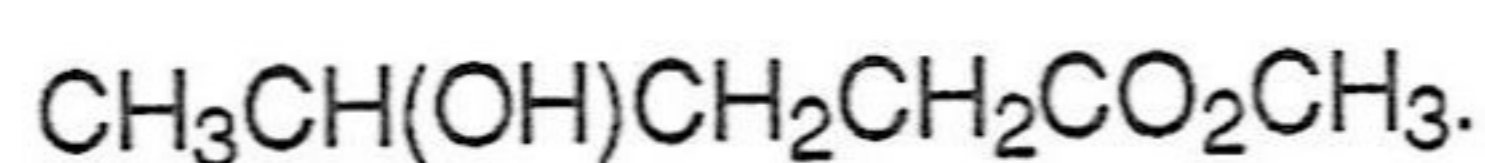
e. See eq. 10.41.



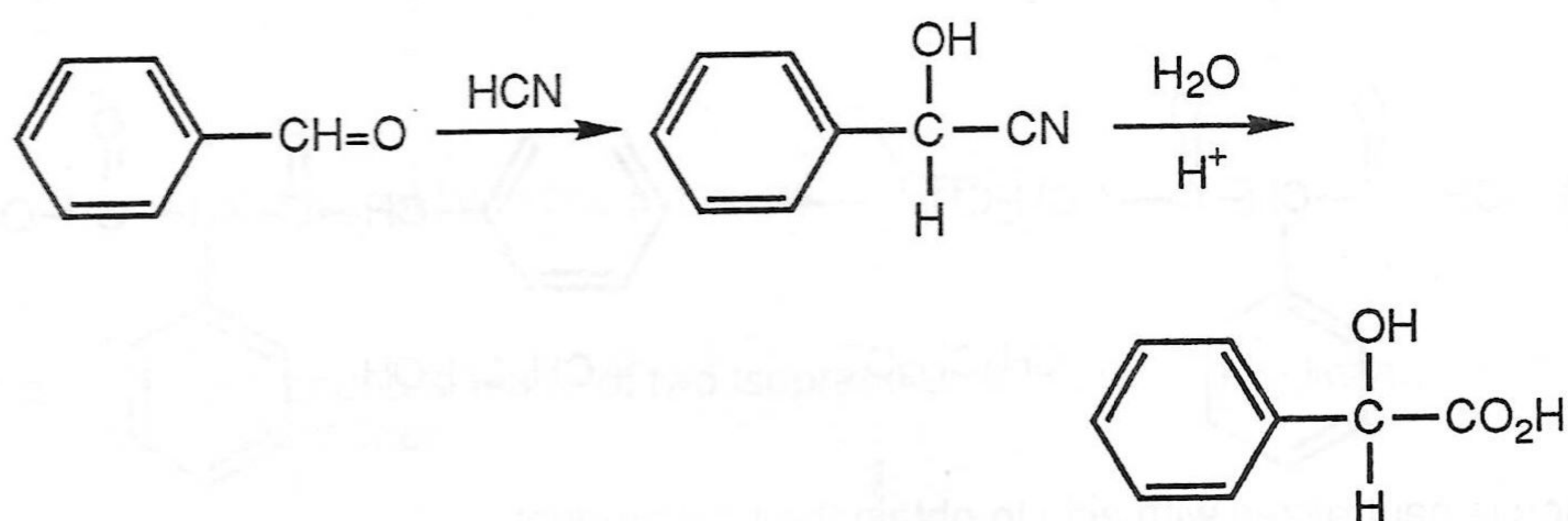
f. See eq. 10.26.



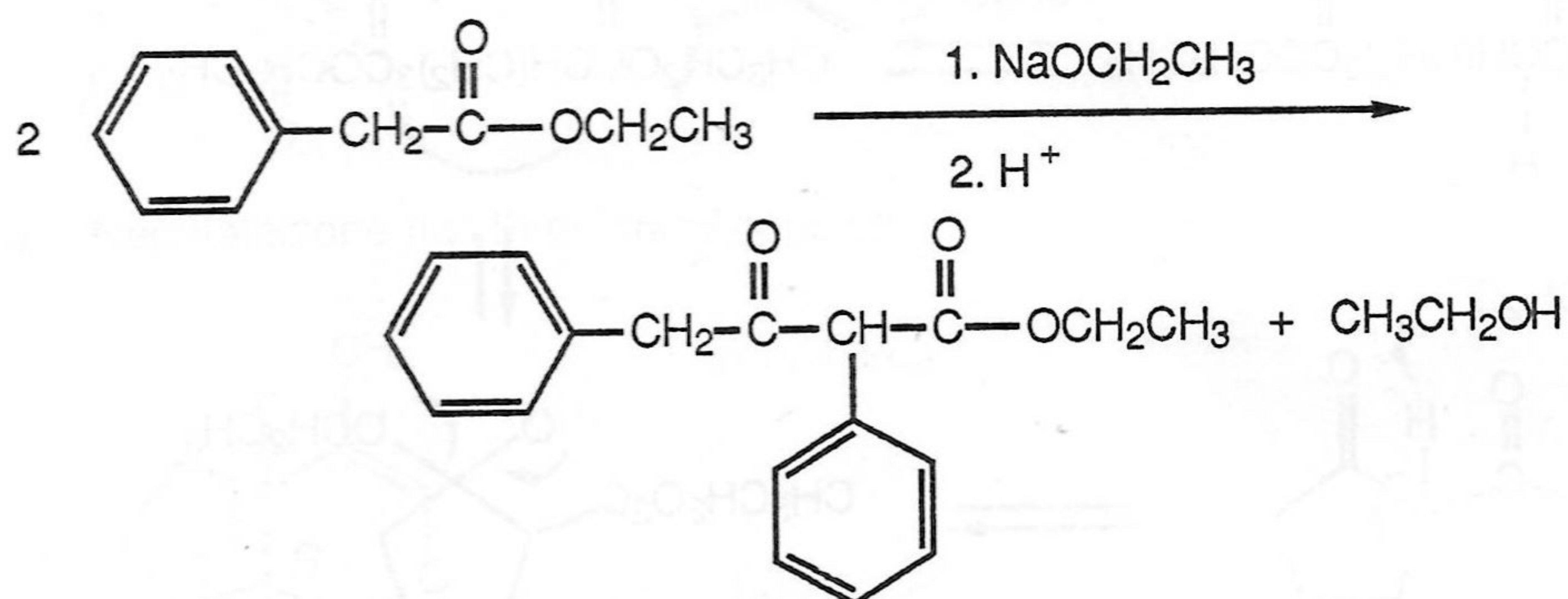
10.56 Ketones are more reactive toward nucleophiles than esters are. Reduction therefore occurs at the ketone carbonyl group, to give



10.57 The method combines the formation of a cyanohydrin (Sec. 9.10) with the hydrolysis of a cyanide to an acid (Sec. 10.7d).



10.58 Use eqs. 10.46–10.48 as a guide. The overall equation is

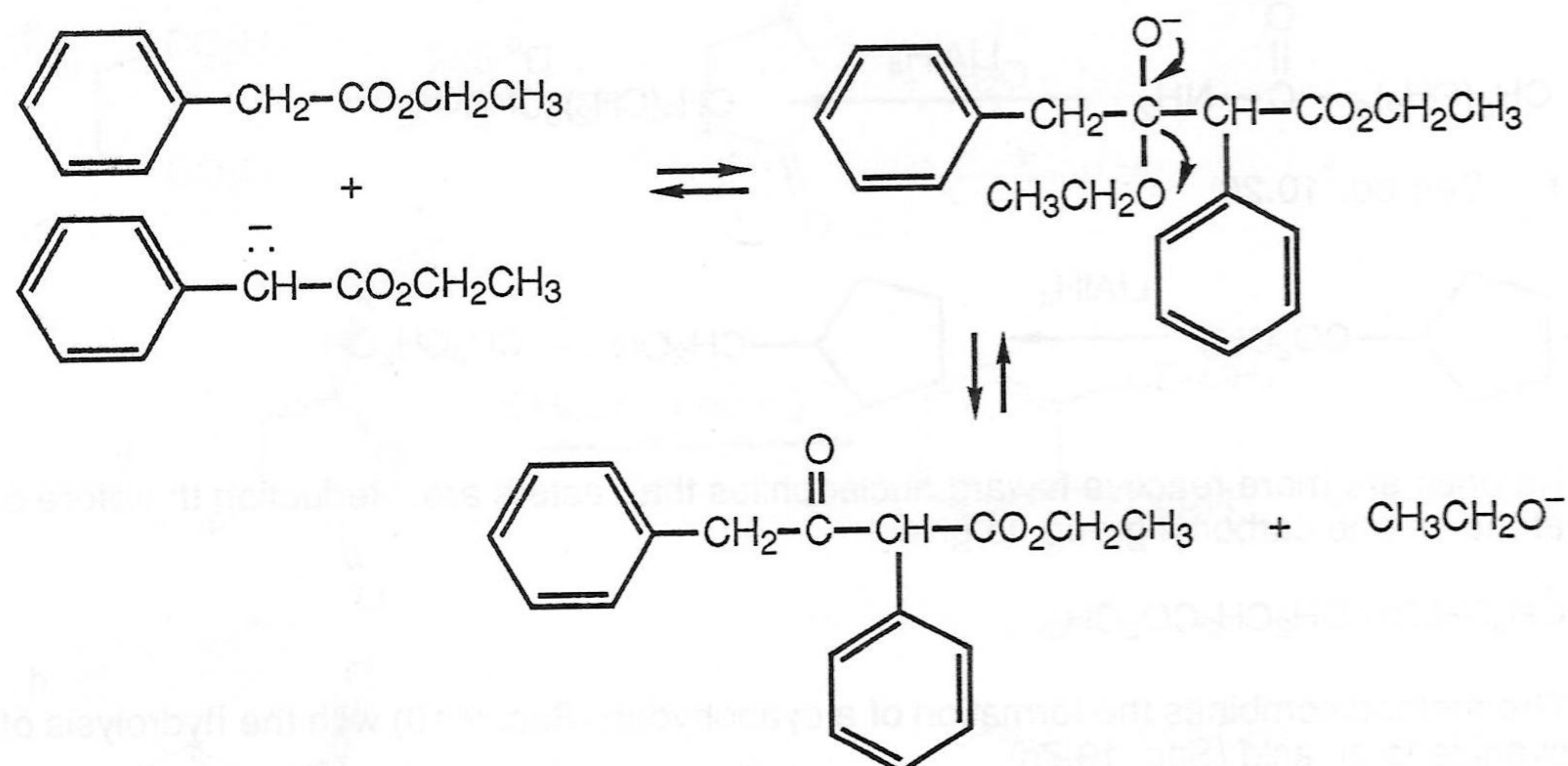


The steps are as follows:

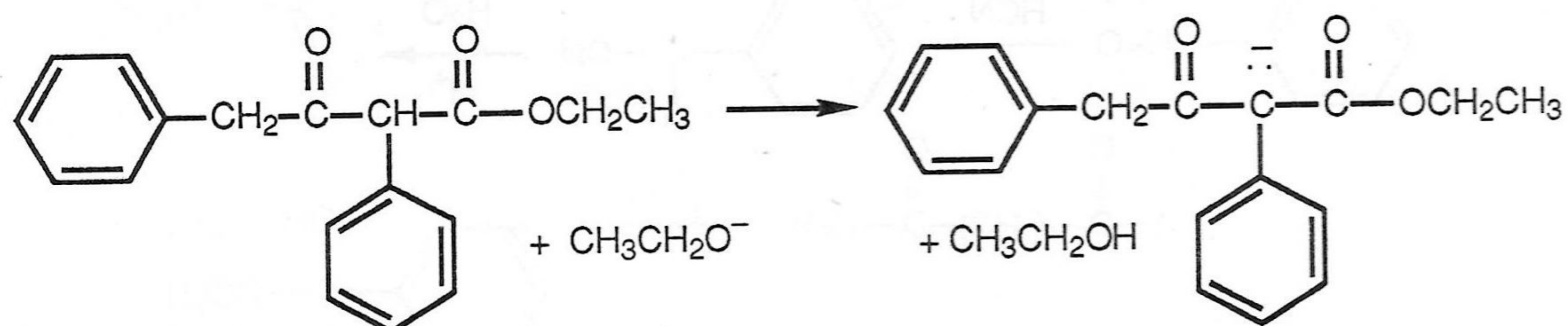
Step 1:



Step 2:

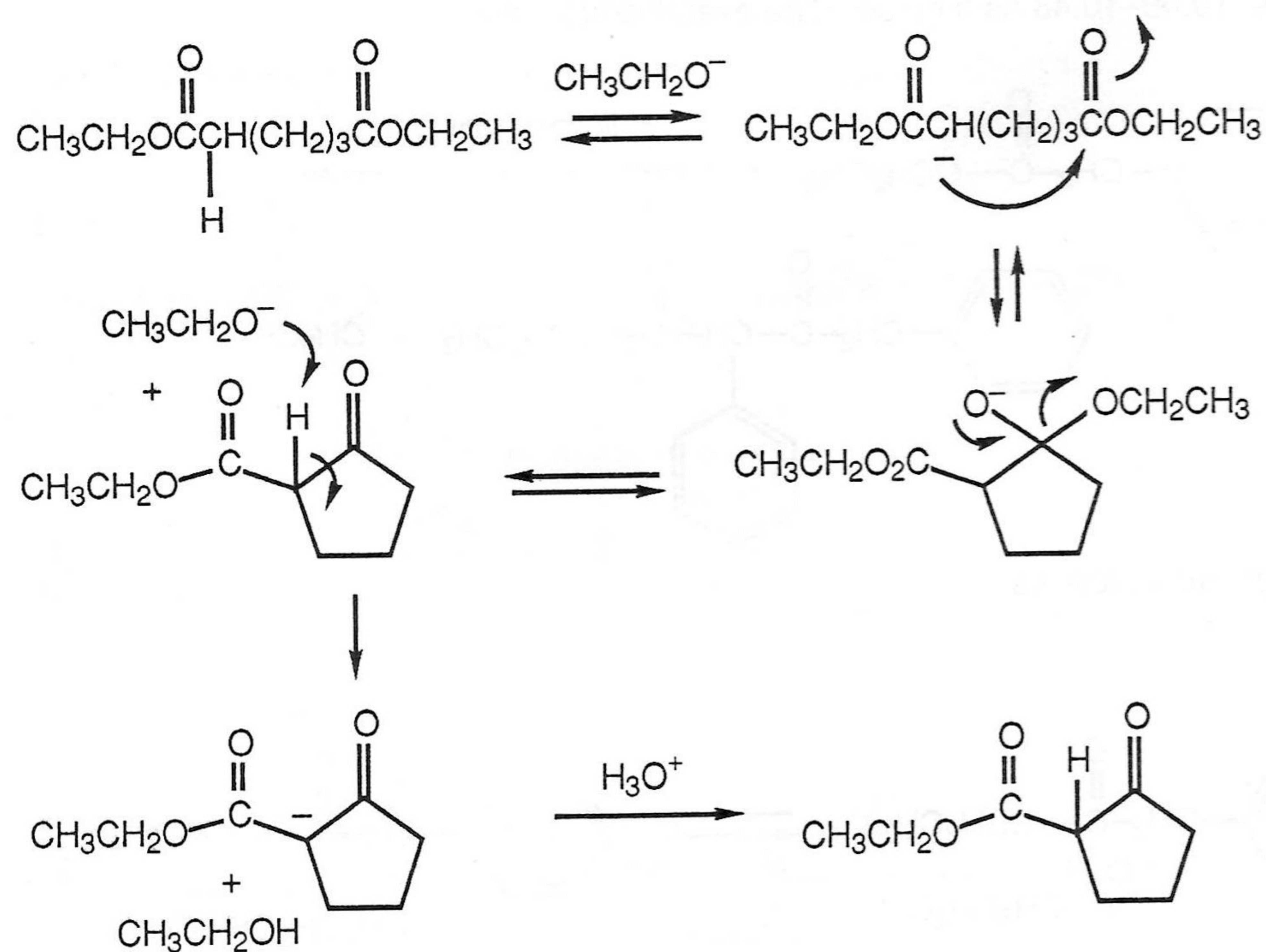


Step 3:



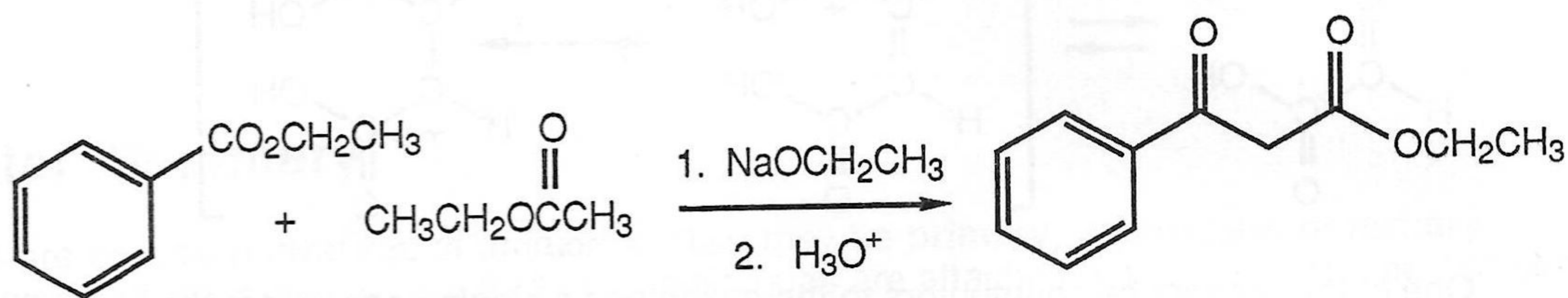
The reaction is neutralized with acid to obtain the final product.

10.59

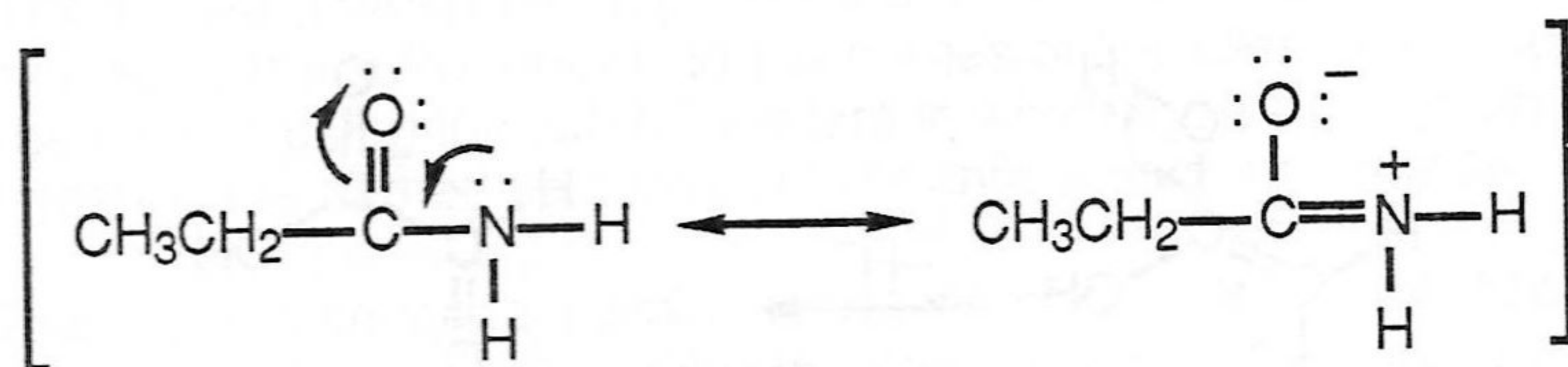


Deprotonation of the  $\beta$ -ketoester drives the equilibrium to the right. Neutralization of the reaction mixture gives ethyl 2-oxocyclopentanecarboxylate.

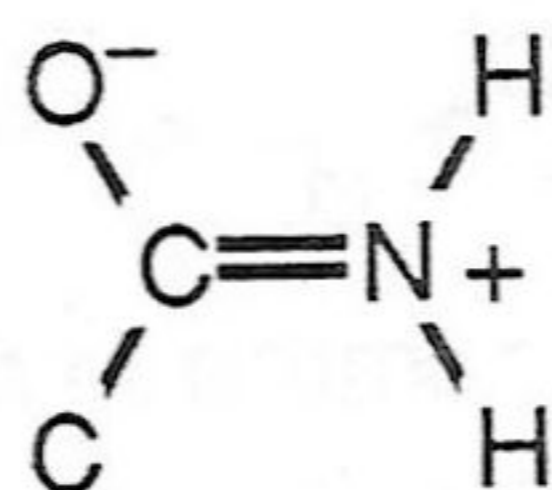
- 10.60 The enolate of ethyl acetate behaves as a nucleophile and the nonenolizable ester, ethyl benzoate, behaves as an electrophile.



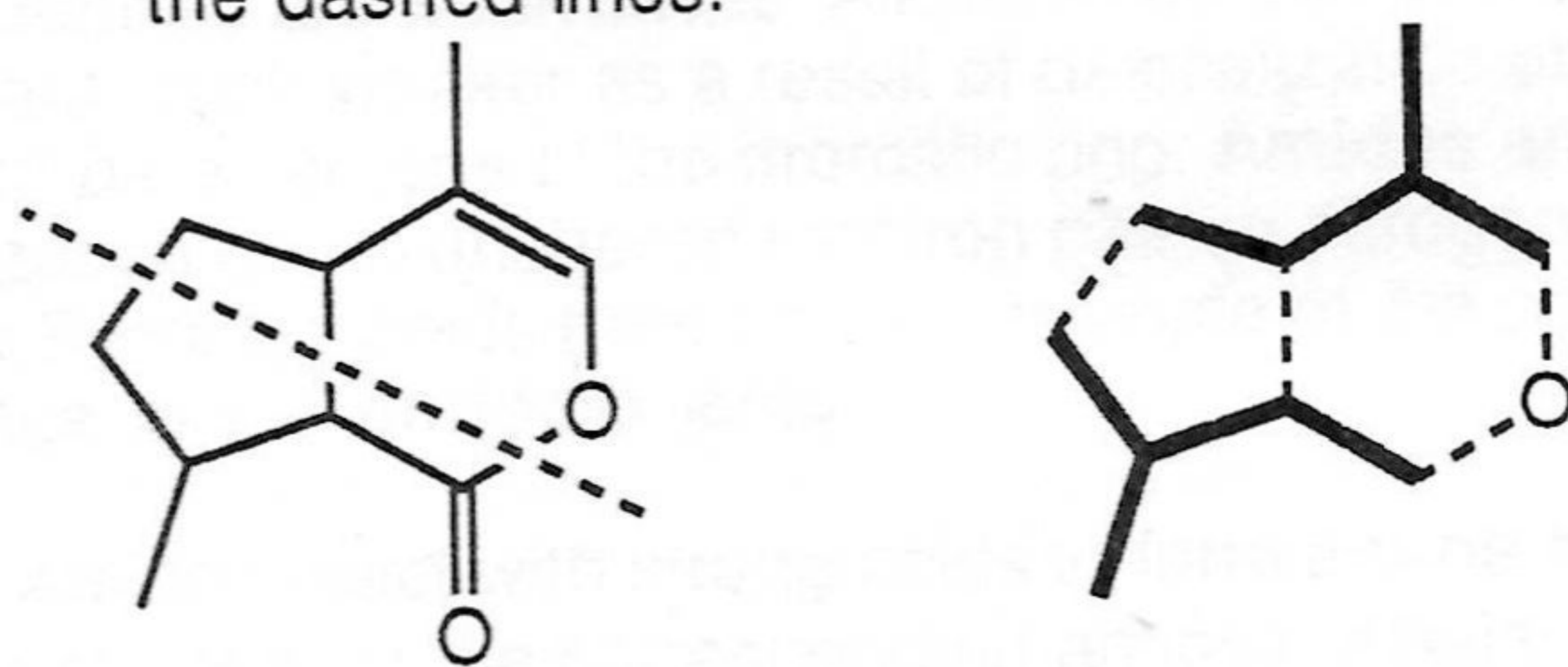
- 10.61 Review Sec. 10.20.



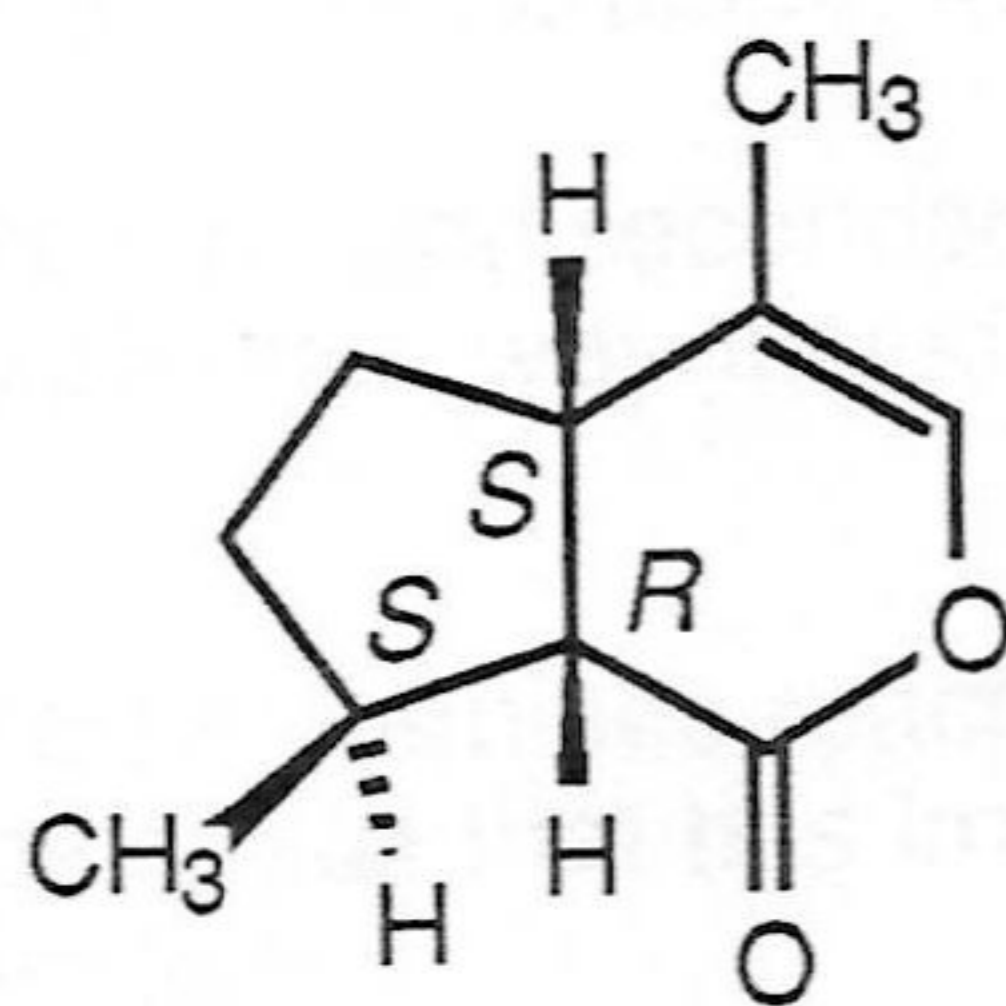
The six atoms that lie in one plane are



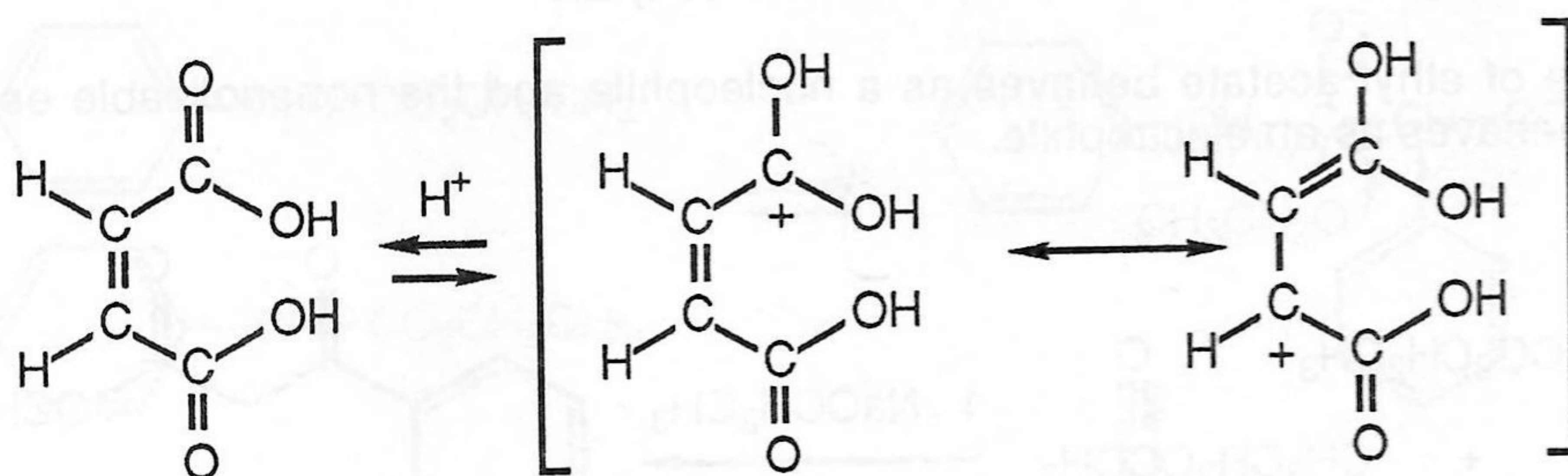
- 10.62 a. The compound is made of two isoprene units (heavy lines) linked together as shown by the dashed lines.



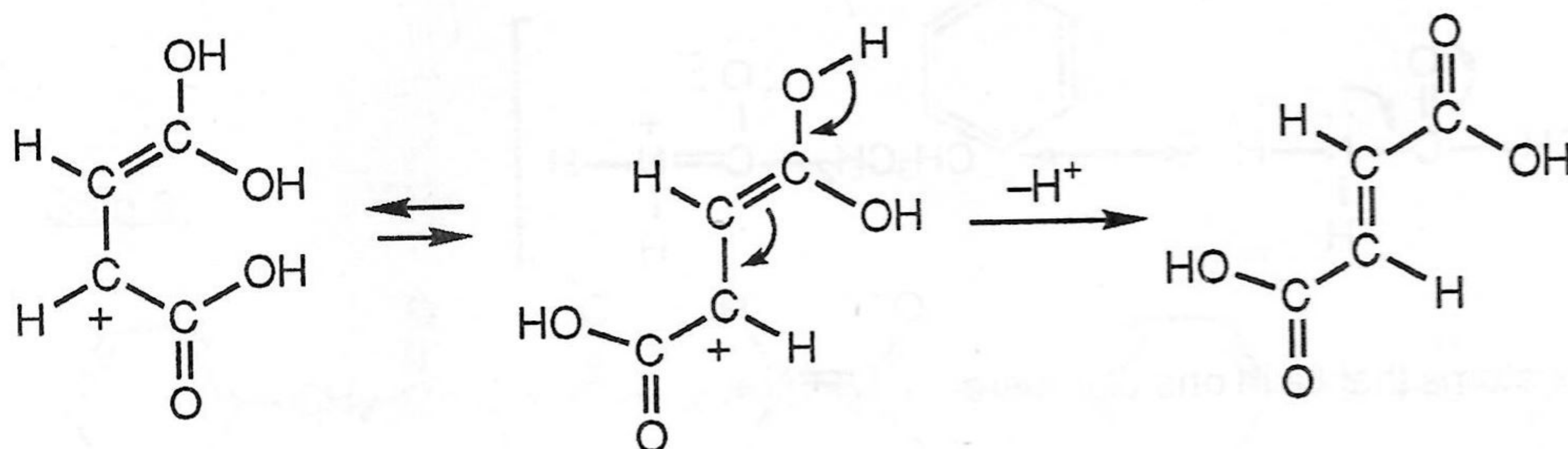
- b. Nepatalactone has three chiral centers:



10.63 Protonation of the carboxyl oxygen gives the allylic cation shown:



One of the resonance contributors to the cation has a single bond where the carbon-carbon double bond was. If rotation occurs around that single bond before proton loss, the product will be fumaric acid:



10.64 There are three stereogenic centers with the following absolute configurations:

