

Chapter 7

Alcohols, Phenols, and Thiols

Chapter Summary

The functional group of alcohols and phenols is the **hydroxyl group**. In alcohols, this group is connected to an aliphatic carbon, whereas in phenols, it is attached to an aromatic ring.

In the IUPAC system of nomenclature, the suffix for alcohols is *-ol*. Alcohols are classified as **primary**, **secondary**, or **tertiary** depending on whether one, two, or three organic groups are attached to the hydroxyl-bearing carbon. The nomenclature of alcohols and phenols is summarized in Sec. 7.1.

Alcohols and phenols form **hydrogen bonds**. These bonds account for the relatively high boiling points of these substances and the water solubility of lower members of the series.

Brønsted-Lowry and Lewis definitions of acids and bases are reviewed in Sec. 7.6. Alcohols are comparable in acidity to water, but phenols are much more acidic. This increased acidity is due to charge delocalization (resonance) in phenoxide ions. Electron-withdrawing groups, such as —F and —NO_2 , increase acidity, through either an **inductive** or a **resonance** effect, or both.

Alkoxides, the conjugate bases of alcohols, are prepared from alcohols by reaction with reactive metals or metal hydrides. They are used as organic bases. Because of the greater acidity of phenols, phenoxides can be obtained from phenols and aqueous base.

Alcohols and phenols are also weak bases. They can be protonated on the oxygen by strong acids. This reaction is the first step in the acid-catalyzed dehydration of alcohols to alkenes and in the conversion of alcohols to alkyl halides by reaction with hydrogen halides. Alkyl halides can also be prepared from alcohols by reaction with **thionyl chloride** or **phosphorus halides**.

Primary alcohols can be oxidized to **carboxylic acids** using **Jones' reagent**, whereas secondary alcohols give **ketones**. Primary alcohols can be oxidized to aldehydes using **pyridinium chlorochromate (PCC)**.

Glycols have two or more hydroxyl groups on adjacent carbons. **Ethylene glycol**, **glycerol**, and **sorbitol** are examples of glycols that are commercially important. Three important industrial alcohols are **methanol**, **ethanol**, and **2-propanol**.

Phenols readily undergo aromatic substitution since the hydroxyl group is ring-activating and *ortho,para*-directing. Phenols are easily oxidized to **quinones**. Phenols with bulky *ortho* substituents are commercial antioxidants.

Examples of biologically important alcohols are **geraniol**, **farnesol**, and **cholesterol**.

The functional group of **thiols** is the **sulfhydryl group**, —SH . Thiols are also called **mercaptans** because of their reaction with mercury salts to form **mercaptides**. Thiols have intense, disagreeable odors. They are more acidic than alcohols and are easily oxidized to **disulfides**.

Reaction Summary

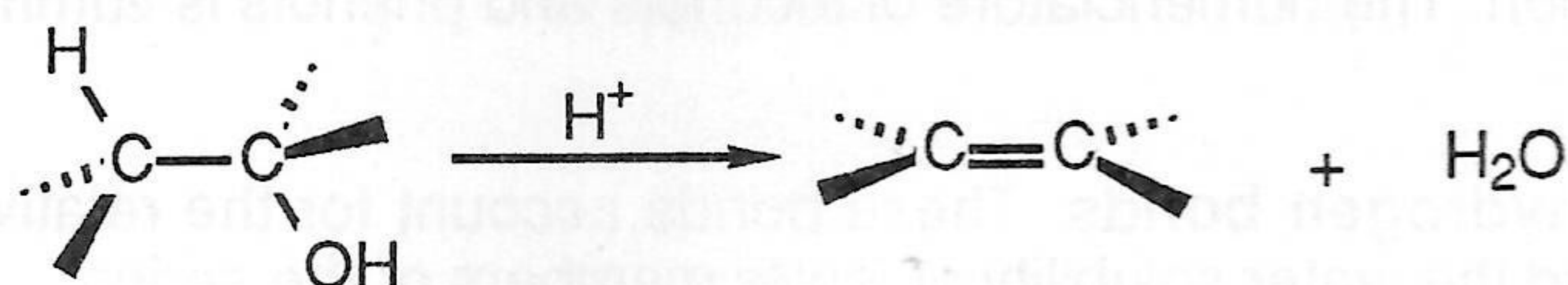
Alkoxides from Alcohols



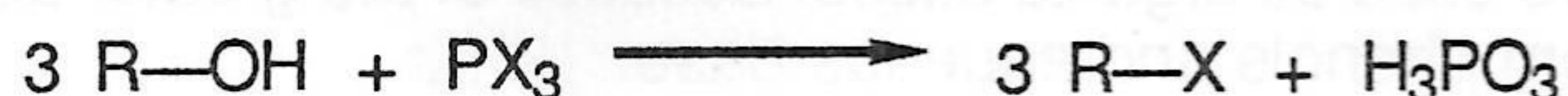
Phenoxides from Phenols



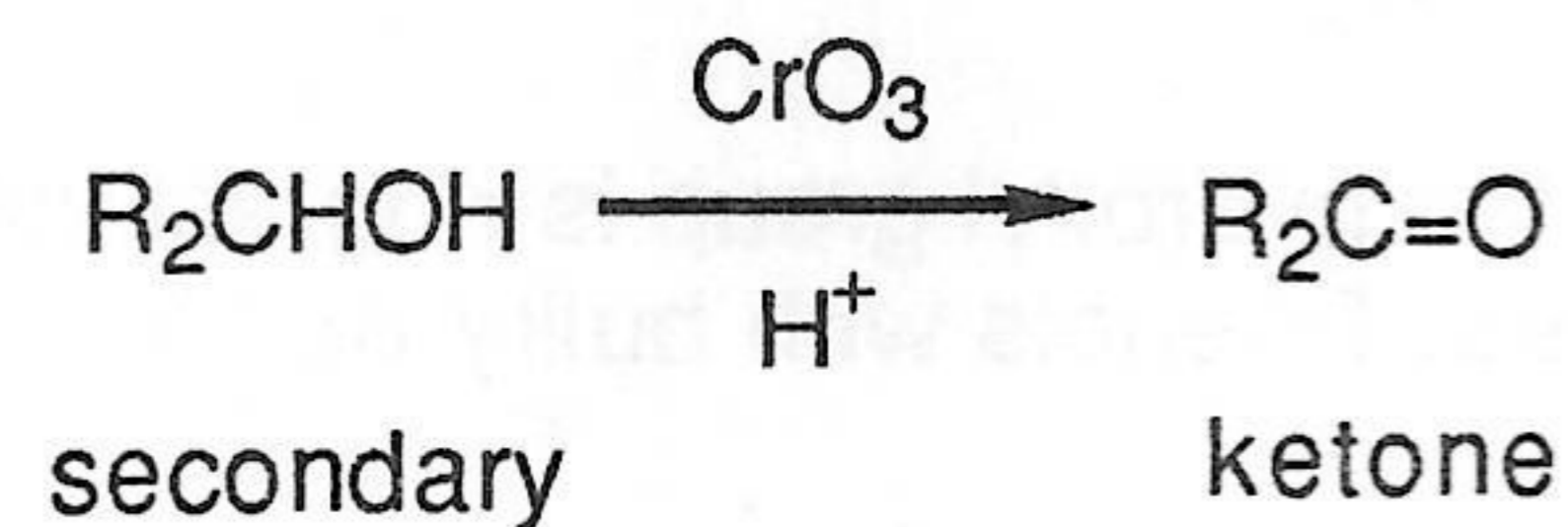
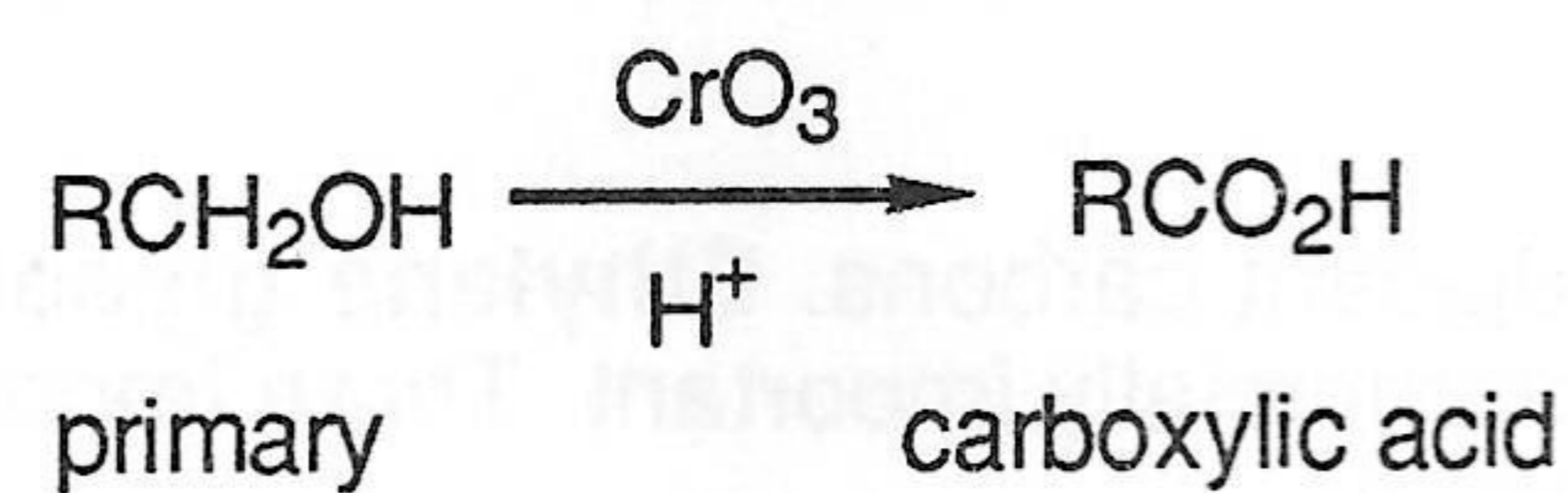
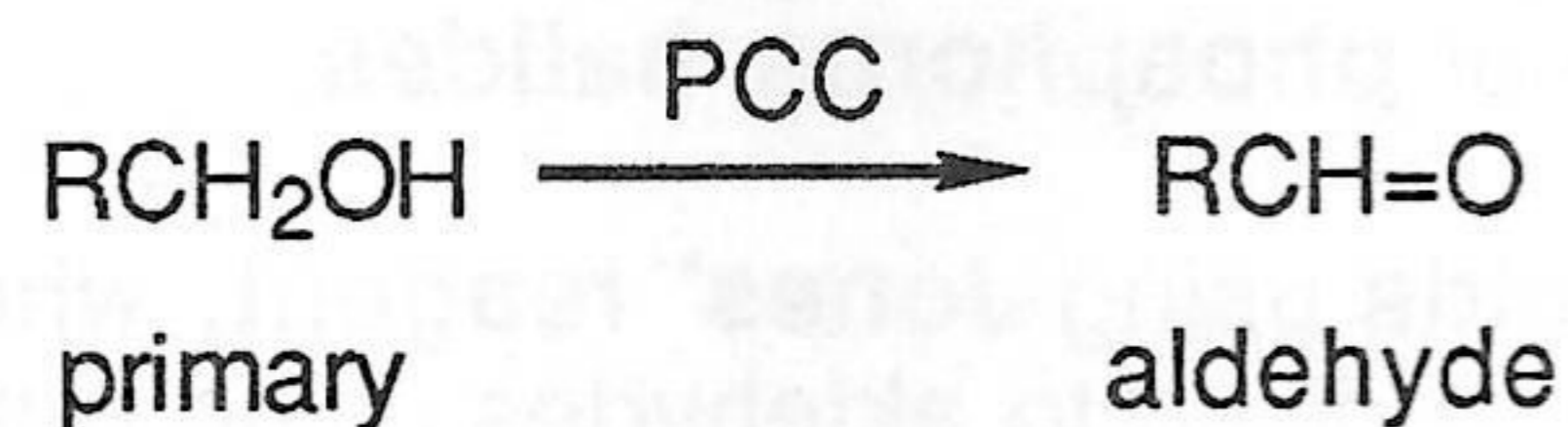
Dehydration of Alcohols

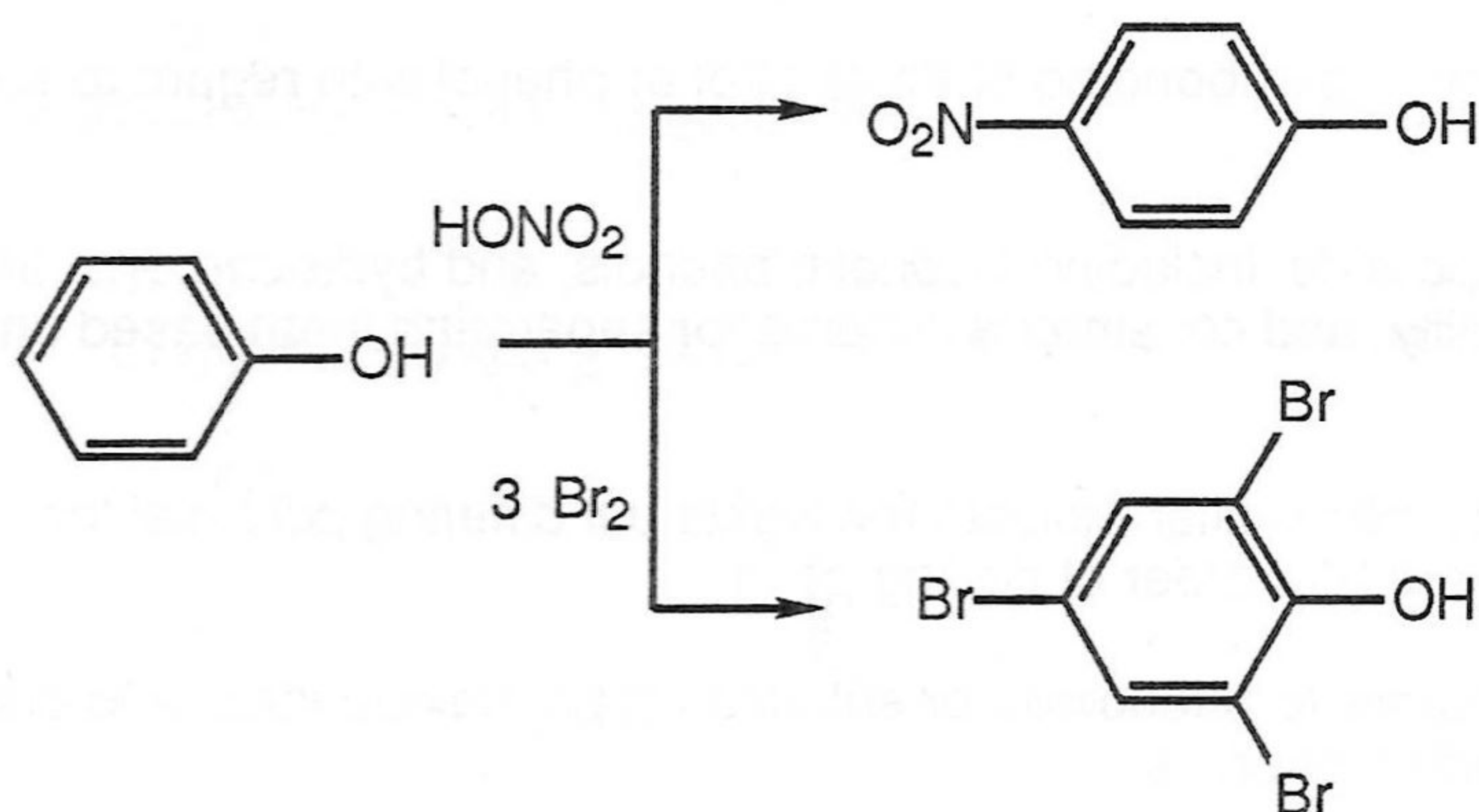
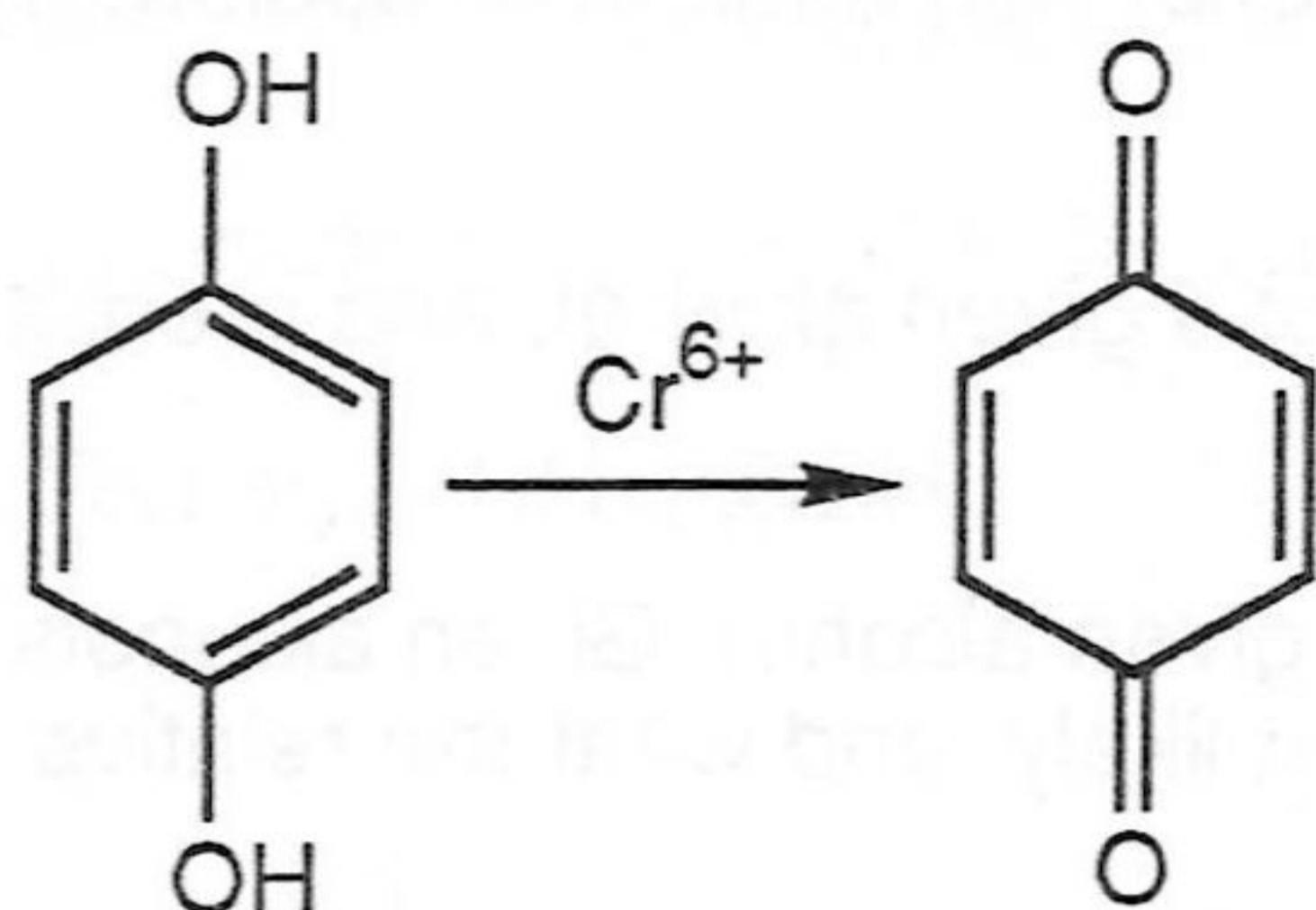
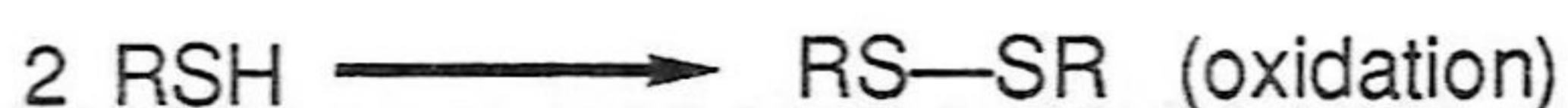


Alkyl Halides from Alcohols



Oxidation of Alcohols



Aromatic Substitution in PhenolsOxidation of Phenols to QuinonesThiols**Learning Objectives**

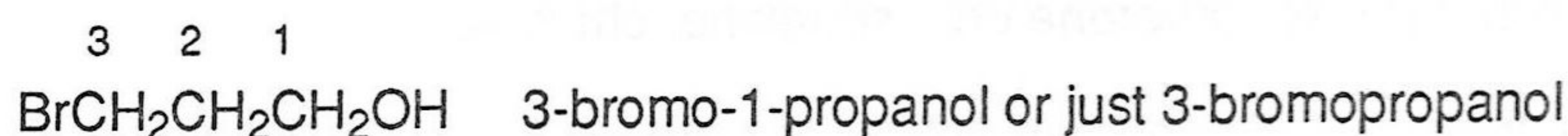
1. Know the meaning of: alcohol, phenol, thiol, hydroxyl group, primary, secondary, and tertiary alcohol.
2. Know the meaning of: alkoxide, phenoxide, oxonium ion, alkyloxonium ion.
3. Know the meaning of: dehydration, thionyl chloride, phosphorus trichloride, phosphorus tribromide.
4. Know the meaning of: chromic anhydride, PCC, aldehyde, ketone, carboxylic acid, glycol, glycerol, sorbitol, glyceryl trinitrate (nitroglycerine), quinone, antioxidant.
5. Be familiar with: geraniol, farnesol, isoprene unit, squalene, cholesterol.
6. Know the meaning of: thiol, mercaptan, mercaptide, sulfhydryl group, disulfide.
7. Given the structure of an alcohol, tell whether it is a primary, secondary, or tertiary.
8. Given the IUPAC name of an alcohol or phenol, draw its structure.

9. Given the structure of an alcohol or phenol, assign it a correct name.
10. Explain the significance of hydrogen bonding of an alcohol or phenol with regard to solubility in water and boiling point.
11. Given a small group of compounds, including alcohols, phenols, and hydrocarbons, arrange them in order of water solubility, and construct a scheme for separating them based on acidity differences.
12. Given a group of compounds with similar molecular weights but differing potential for hydrogen bonding, arrange them in order of boiling point.
13. Draw the resonance contributors to phenoxide or substituted phenoxide ions, and discuss the acidity of the corresponding phenols.
14. Account for the acidity difference between alcohols and phenols.
15. Write equations for the reaction of a specific alcohol or phenol with sodium or sodium hydride or with an aqueous base (NaOH, KOH).
16. Write the structures for all possible dehydration products of a given alcohol, and predict which product should predominate.
17. Write the steps in the mechanism for the dehydration of a given alcohol. Given alcohols of different classes, tell which dehydration mechanism is most likely, and what the relative dehydration rates will be.
18. Write equations for the reaction of a given alcohol with HCl, HBr, or HI, with cold, concentrated H_2SO_4 or HNO_3 , with PCl_3 or PBr_3 , with thionyl chloride (SOCl_2), or with an oxidant such as chromic anhydride or PCC.
19. Write the steps in the mechanism for conversion of an alcohol to an alkyl halide upon reaction with a hydrogen halide.
20. Write equations for the reaction of phenol with dilute aqueous nitric acid and with bromine water.
21. Contrast the acidity of alcohols and thiols. Also contrast their reactivity toward oxidizing agents.
22. Write equations for the reaction of a given thiol with Hg^{2+} , base, or an oxidizing agent such as H_2O_2 .

Answers to Problems

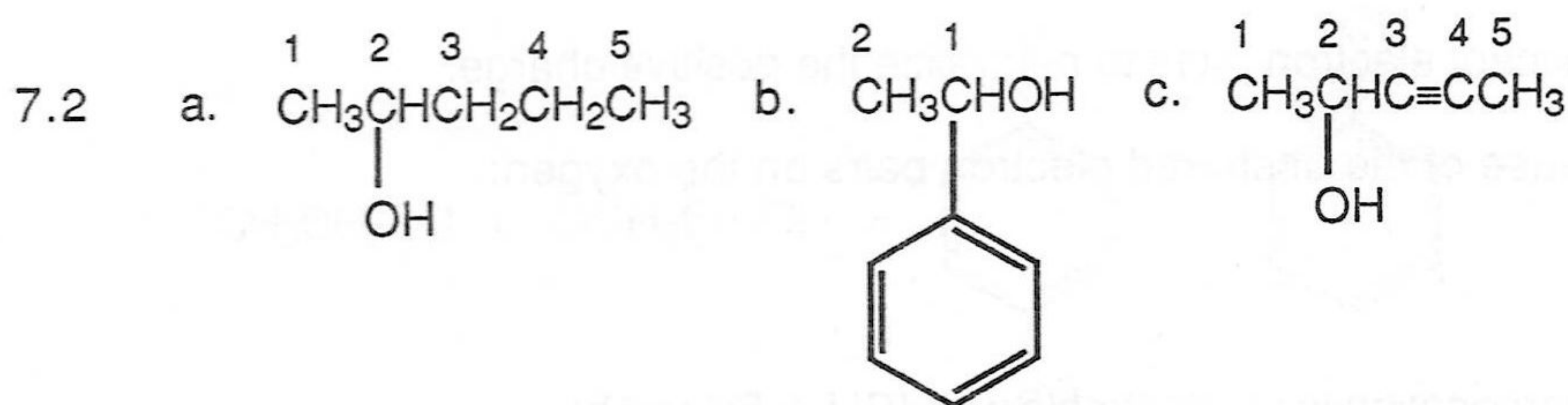
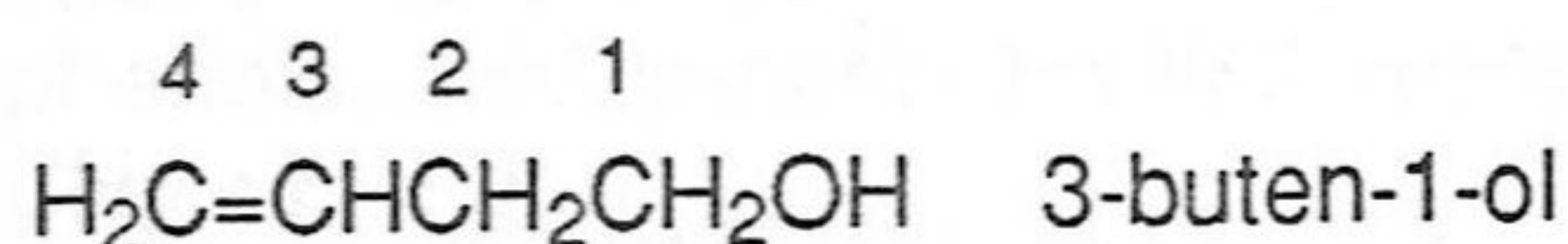
Problems Within the Chapter

- 7.1 a. Number from the hydroxyl-bearing carbon:



- b. cyclopentanol

c. The alcohol takes precedence over the double bond.

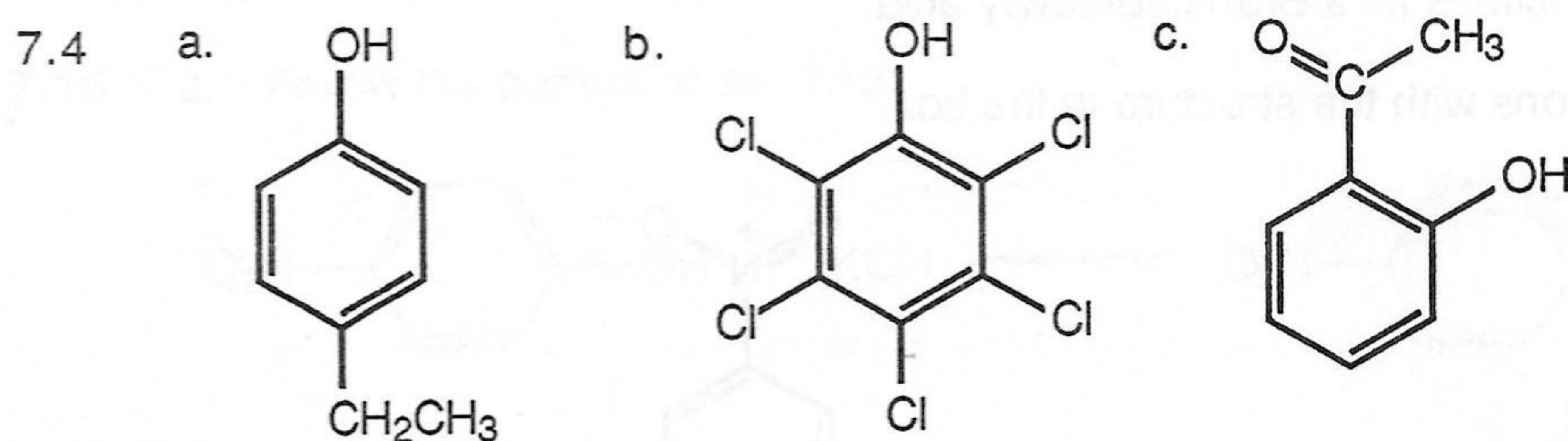


7.3 Methanol is usually grouped with the primary alcohols:

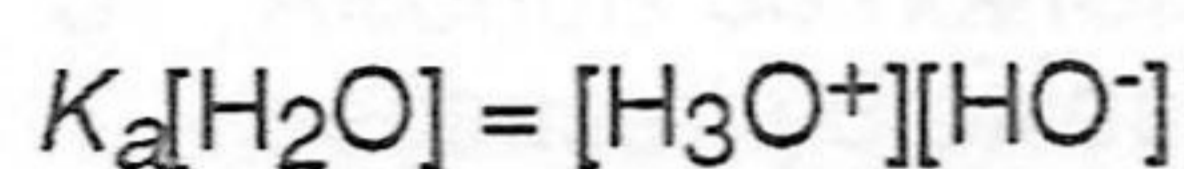
Primary: CH_3OH , $\text{CH}_3\text{CH}_2\text{OH}$, $\text{CH}_3\text{CH}_2\text{CH}_2\text{OH}$, $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{OH}$, $(\text{CH}_3)_2\text{CHCH}_2\text{OH}$, $\text{CH}_2=\text{CHCH}_2\text{OH}$, $\text{C}_6\text{H}_5\text{CH}_2\text{OH}$ (all have a $-\text{CH}_2\text{OH}$ group)

Secondary: $(\text{CH}_3)_2\text{CHOH}$, $\text{CH}_3\text{CH}(\text{OH})\text{CH}_2\text{CH}_3$, cyclohexanol (all have a CHOH group)

Tertiary: $(\text{CH}_3)_3\text{COH}$



7.5 Another way to write eq. 7.6 is:



For the ionization of water (eq. 7.5), $[\text{H}_3\text{O}^+] = [\text{HO}^-]$.

Therefore $K_a[\text{H}_2\text{O}] = [\text{H}_3\text{O}^+]^2$ (or $[\text{HO}^-]^2$).

Substituting, $(1.8 \times 10^{-16})(55.5) = 10^{-14} = [\text{H}_3\text{O}^+]^2$ or $[\text{H}_3\text{O}^+] = 10^{-7}$.

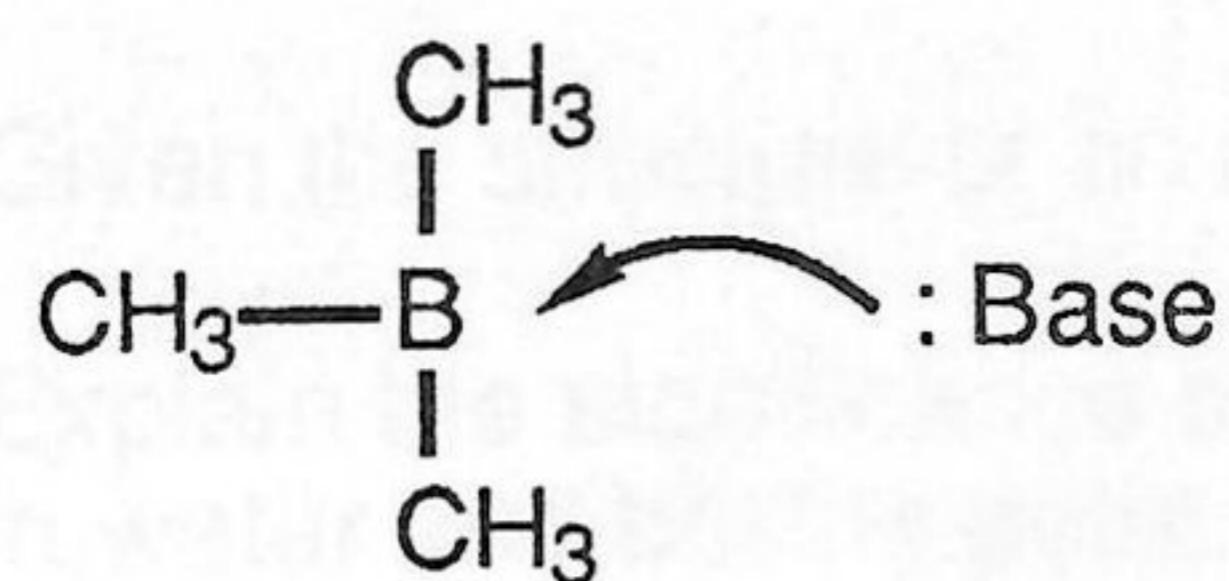
7.6 Use eq. 7.7.

$$\text{p}K_a = -\log(1.0 \times 10^{-16}) = 16.0$$

7.7 Acetic acid has the lower $\text{p}K_a$, and hence is the stronger acid.

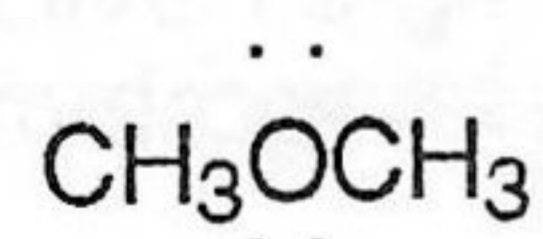
7.8 a. Lewis base; can donate its electron pair to an acid; this carbanion is isoelectronic with $(\text{CH}_3)_3\text{N}$: (part g).

b. Lewis acid; the boron has only six valence electrons around it and can accept two more:



c. Lewis acid; can accept electron pairs to neutralize the positive charge.

d. Lewis base, because of the unshared electron pairs on the oxygen:



e. Lewis acid; this carbocation is isoelectronic with $(\text{CH}_3)_3\text{B}$ (part b).

f. Lewis base, because of the unshared electron pair on the nitrogen.

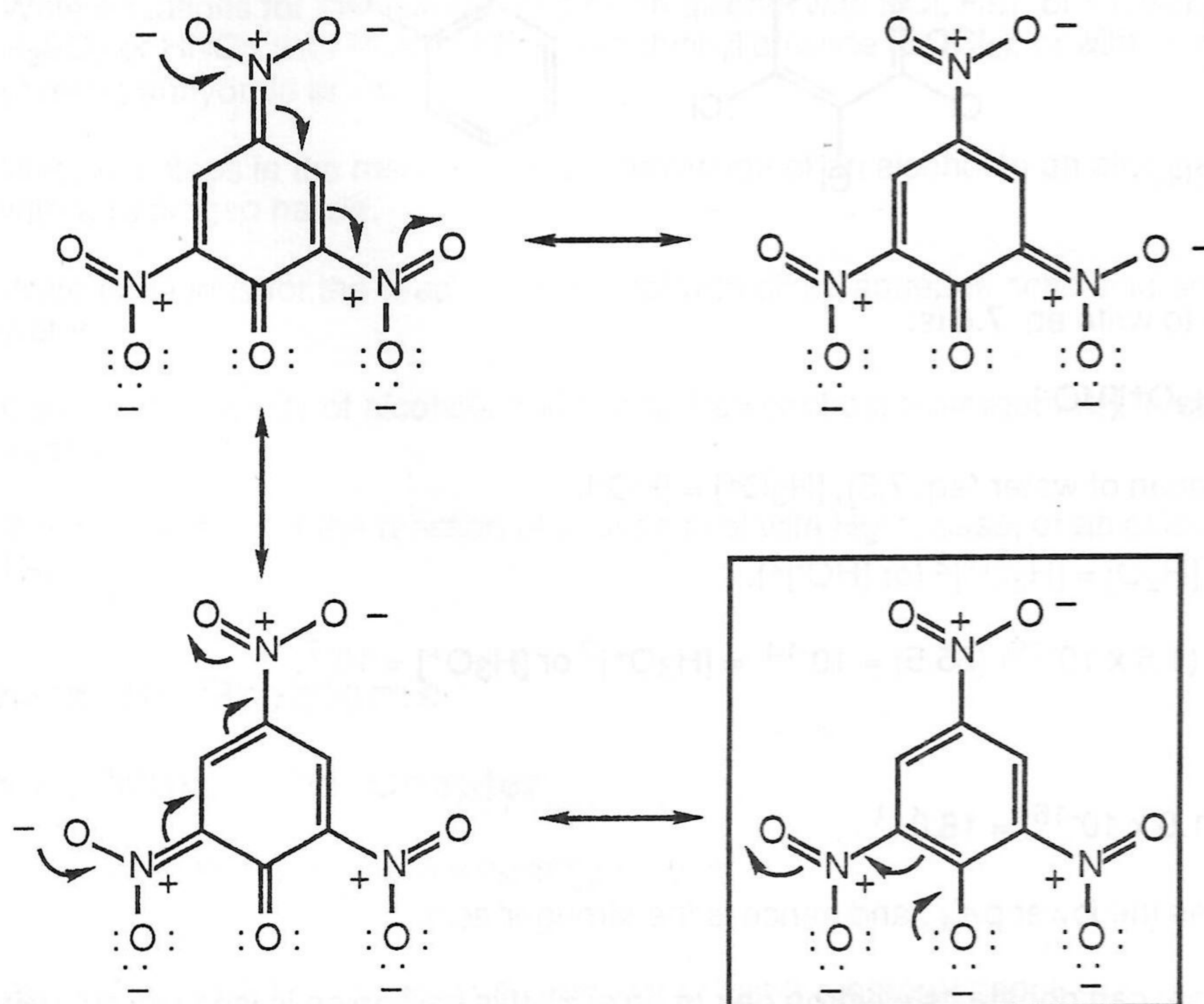
g. Lewis base, again because of the unshared electron pair on the nitrogen.

h. Lewis base; hydride can donate its electron pair to an acid.

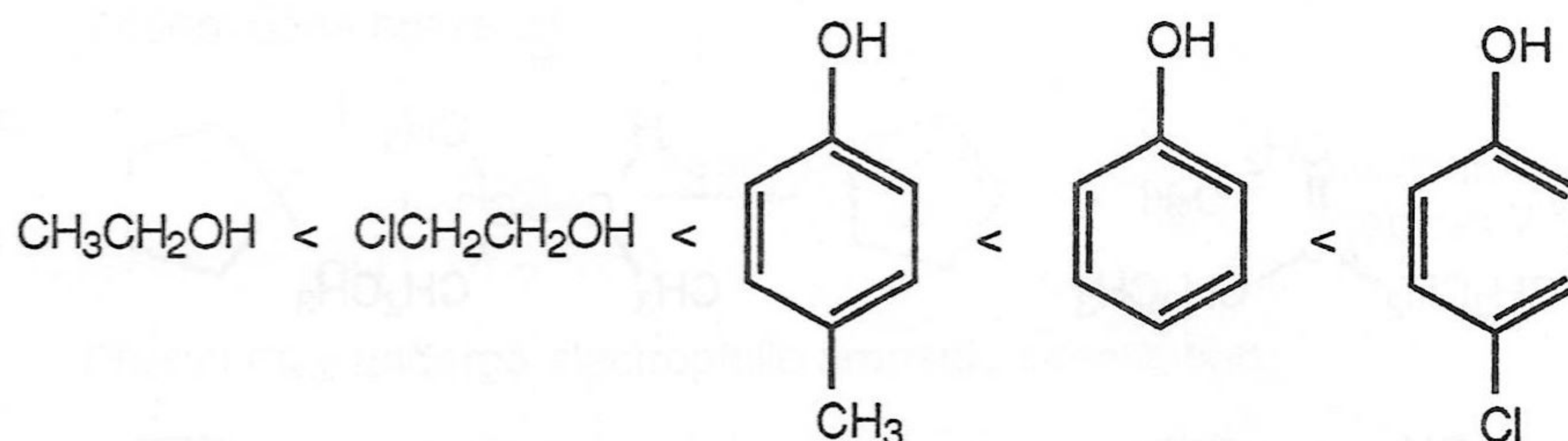
i. Lewis acid; can accept electron pairs to neutralize the positive charge.

7.9 The amide anion functions as a Brønsted-Lowry base. It accepts a proton from a terminal acetylene, which functions as a Brønsted-Lowry acid.

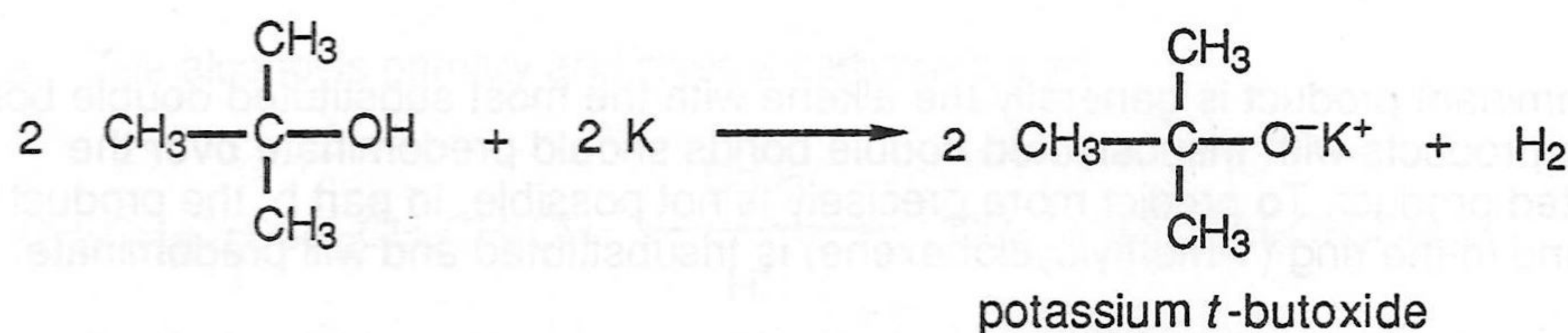
7.10 Start pushing electrons with the structure in the box.



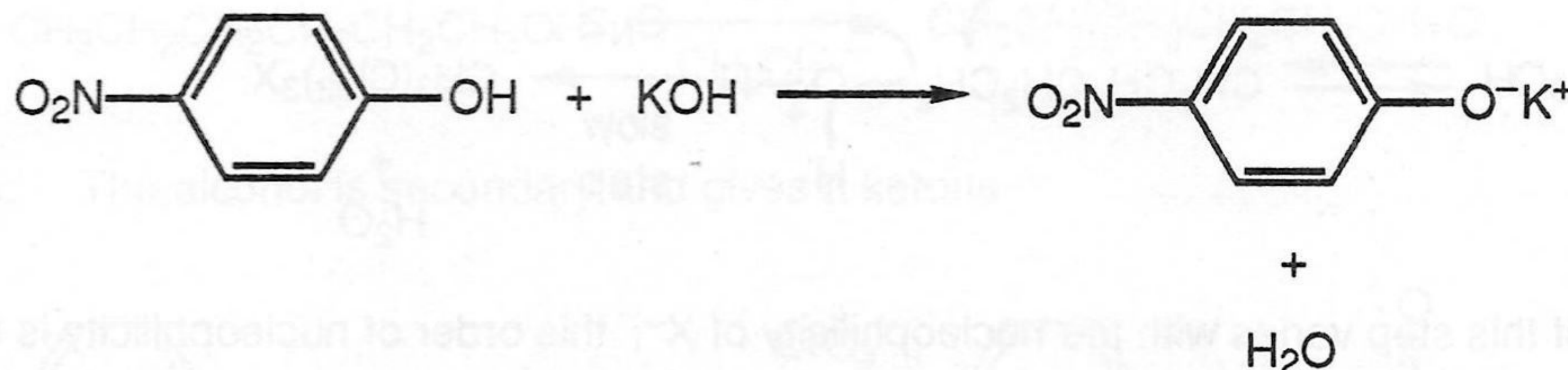
- 7.11 Both alcohols are weaker acids than the three phenols. Of the alcohols, 2-chloroethanol is the stronger acid because of the electronegativity of the chlorine substituent. Among the three phenols, acidity increases with increasing electronegativity of the *para* substituent: $\text{CH}_3 < \text{H} < \text{Cl}$.



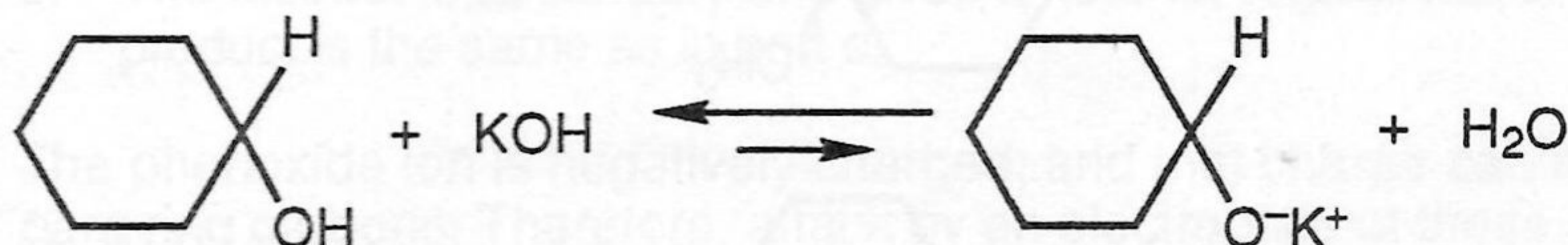
- 7.12 Follow the pattern of eq. 7.12:



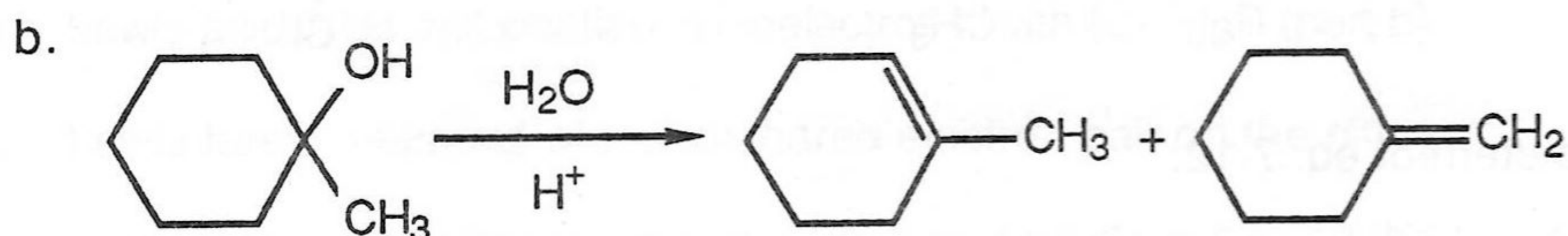
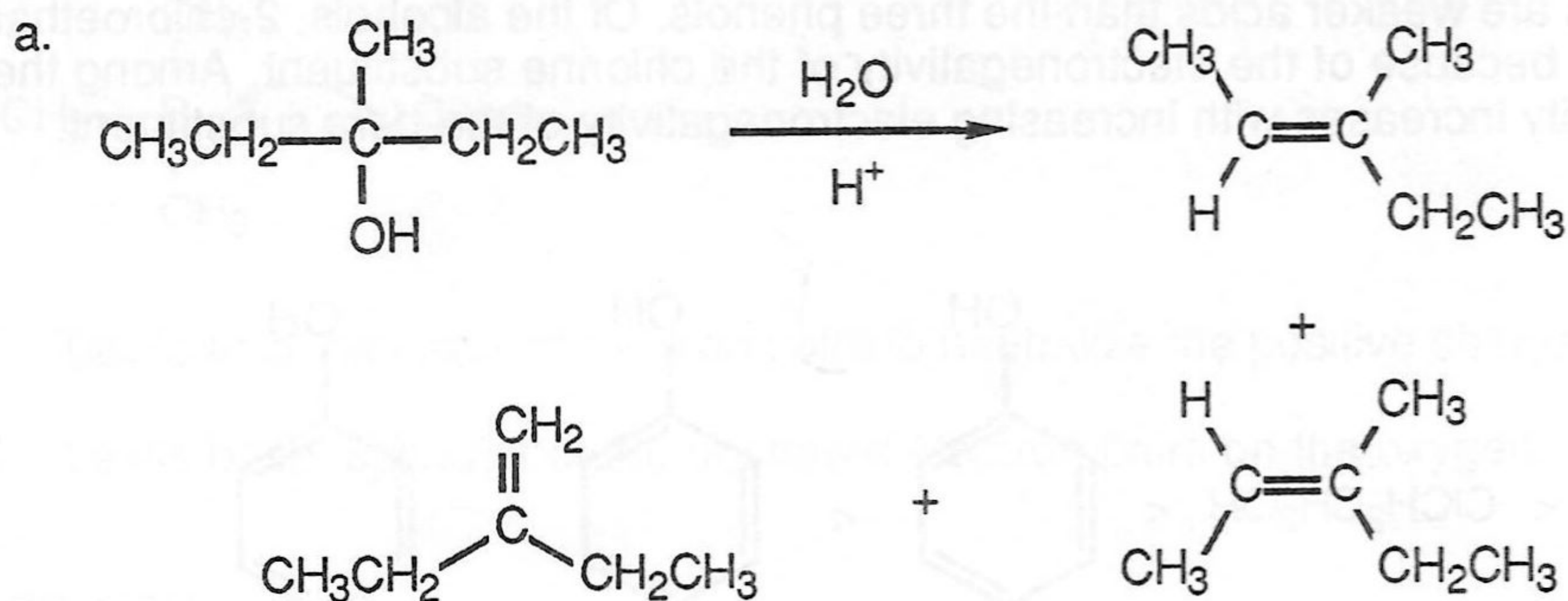
- 7.13 a. Follow the pattern of eq. 7.15:



- b. Alcohols do not react with aqueous base. The equilibrium favors the starting material because hydroxide ion is a weaker base than alkoxide ion:

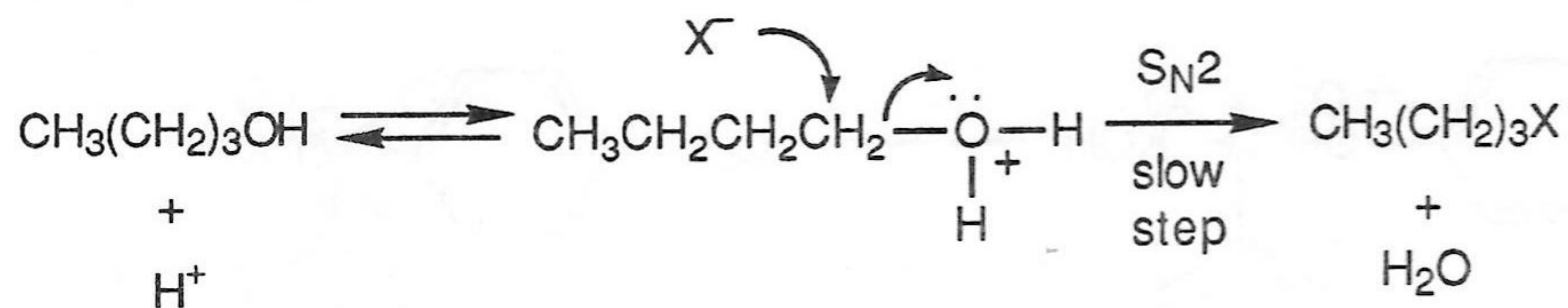


- 7.14 Write the structure of the alcohol, and consider products with a double bond between the hydroxyl-bearing carbon and each adjacent carbon that also has at least one hydrogen attached.

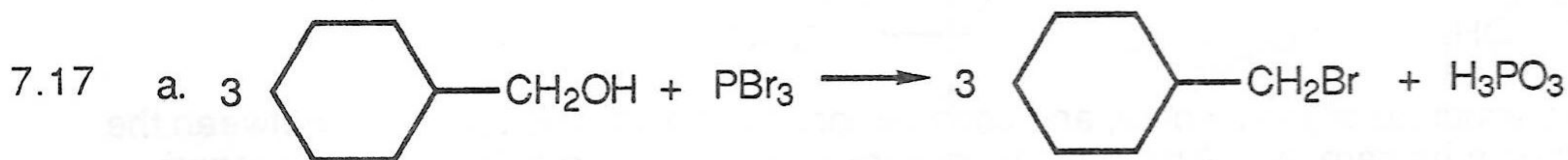
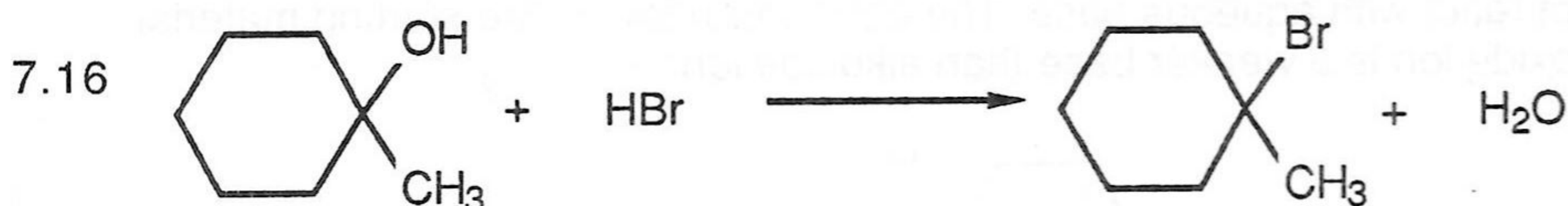


The predominant product is generally the alkene with the most substituted double bond. In part a, the products with trisubstituted double bonds should predominate over the disubstituted product. To predict more precisely is not possible. In part b, the product with the double bond in the ring (1-methylcyclohexene) is trisubstituted and will predominate.

7.15 Unlike the alcohol in Example 7.2, the alcohol in this case is primary instead of tertiary. The rate-determining step is the $\text{S}_{\text{N}}2$ reaction:

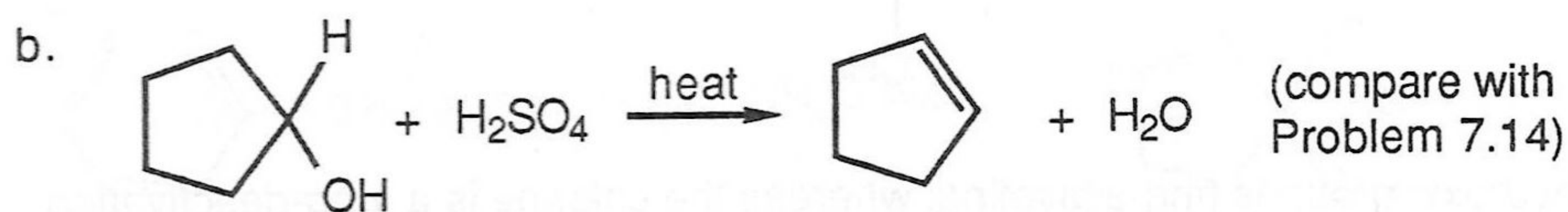


The rate of this step varies with the nucleophilicity of X^- ; this order of nucleophilicity is $\text{I}^- > \text{Br}^- > \text{Cl}^-$.

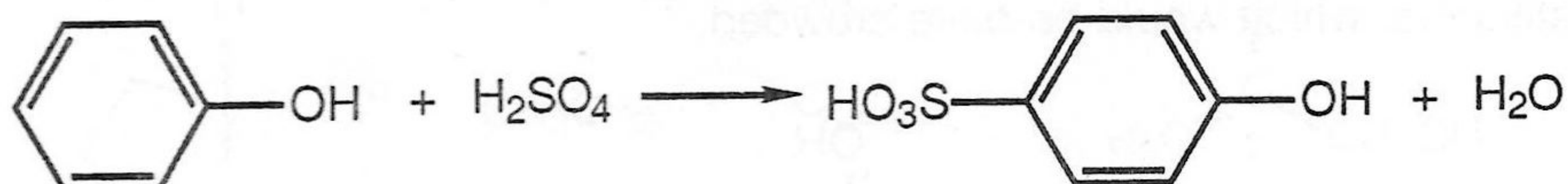




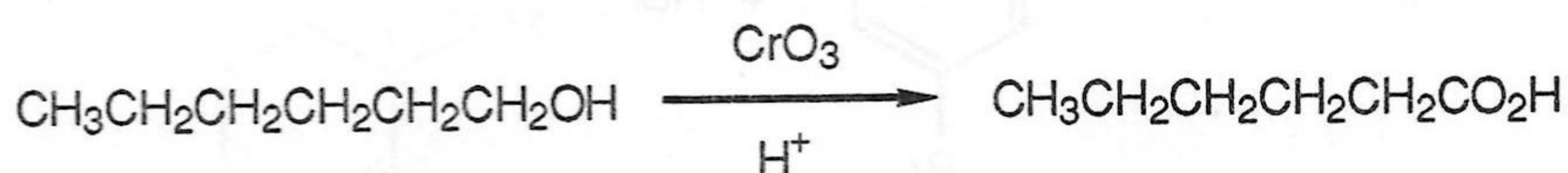
Phenol does not react.



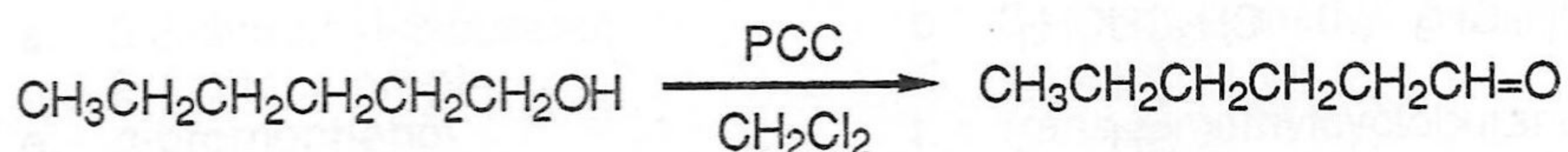
Phenol may undergo electrophilic aromatic substitution:



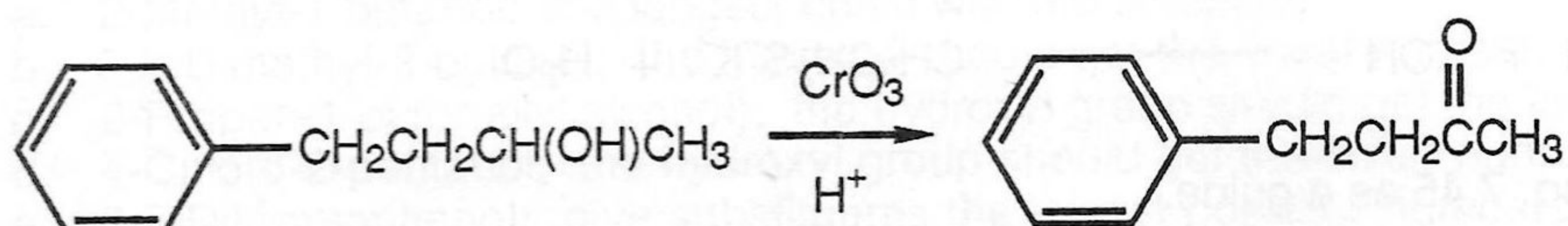
7.19 a. The alcohol is primary and gives a carboxylic acid.



b. The alcohol is primary and gives an aldehyde.

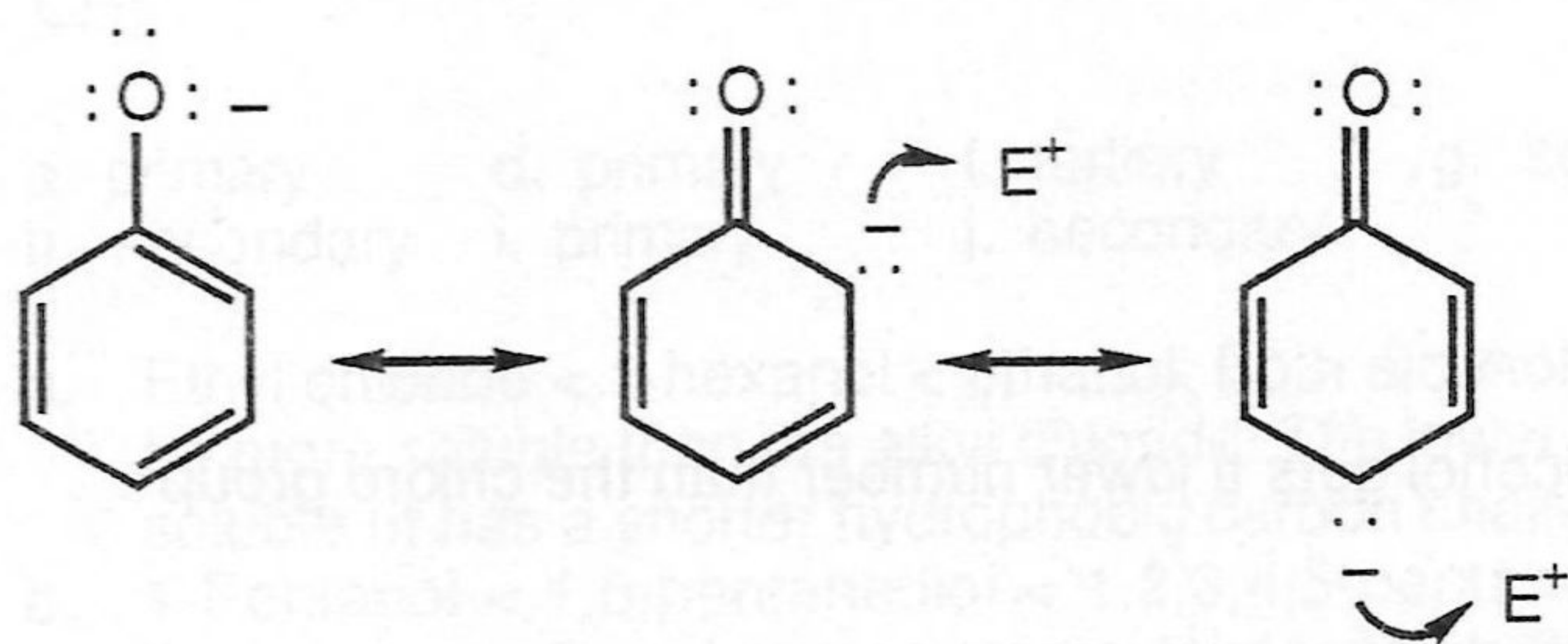


c. The alcohol is secondary and gives a ketone.

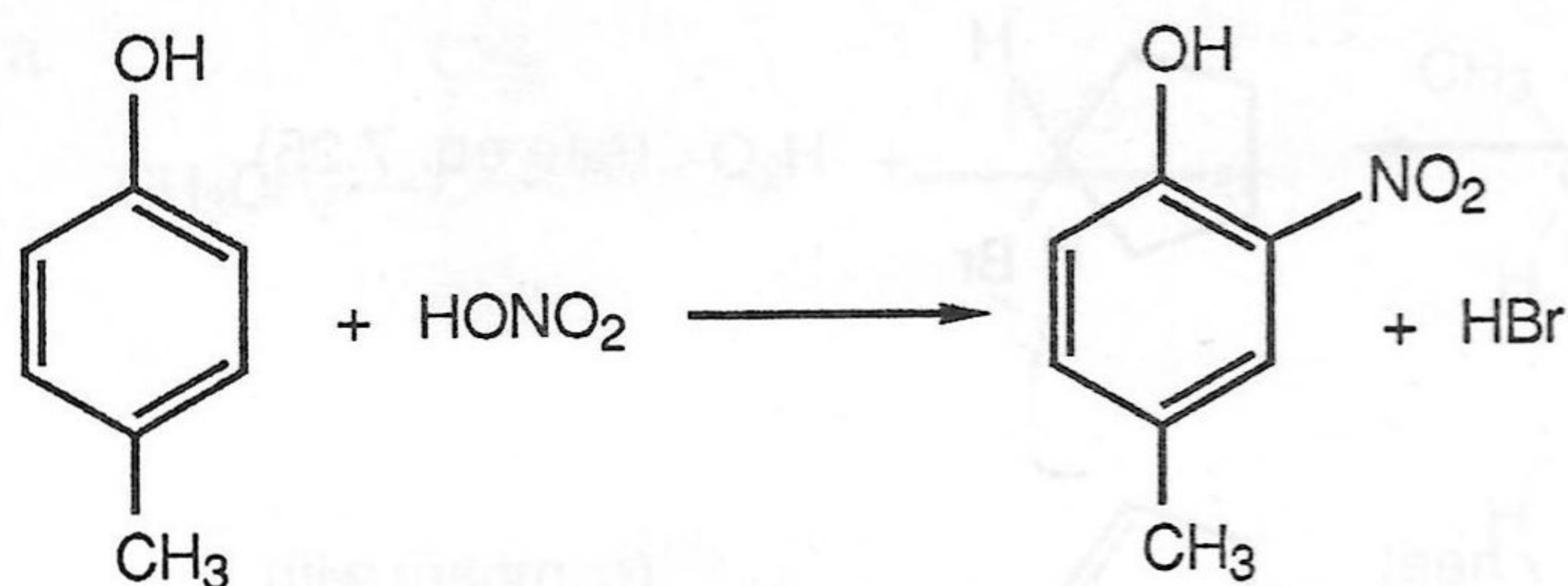


d. The alcohol is secondary and gives a ketone, regardless of the oxidizing agent. The product is the same as in part c.

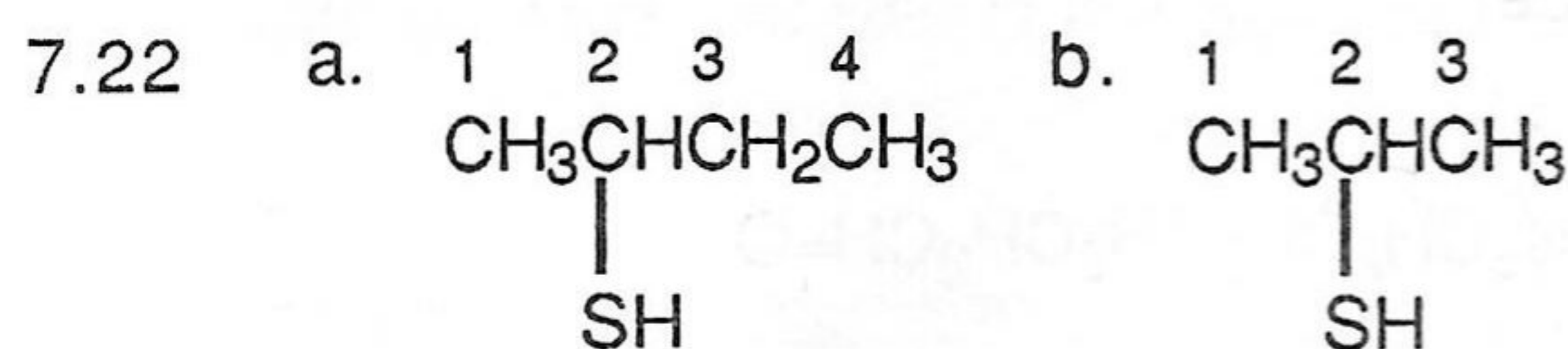
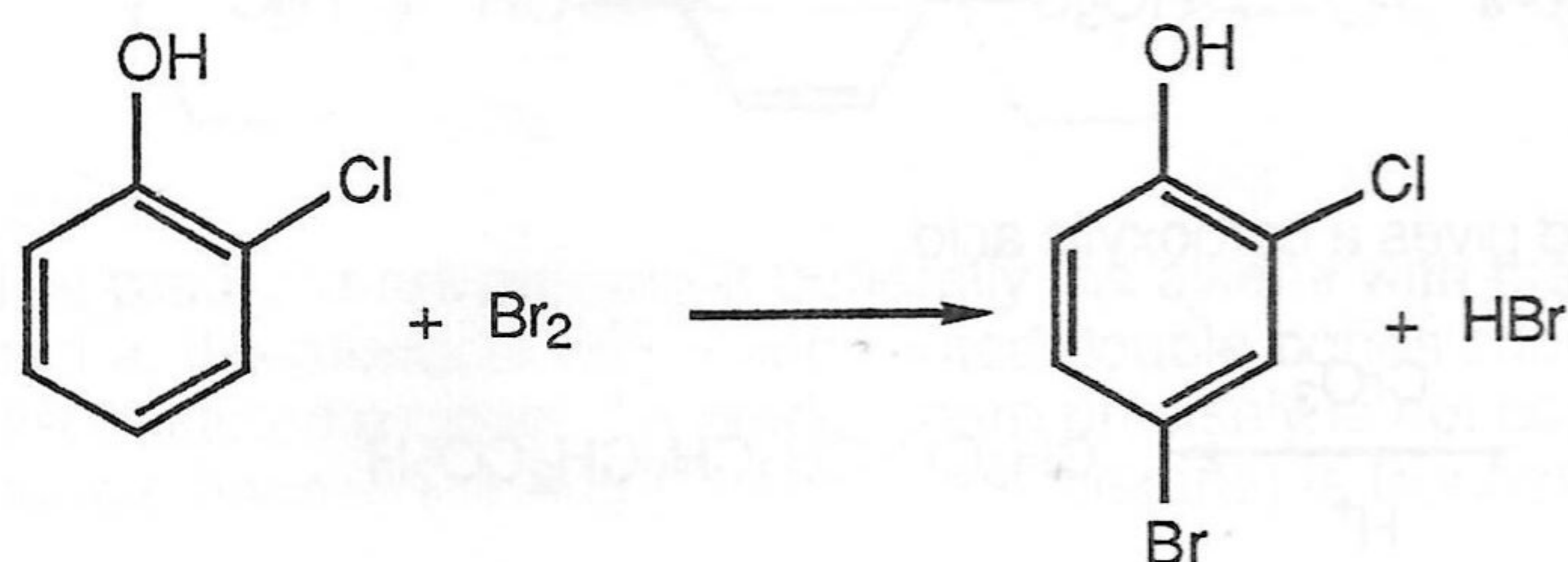
7.20 The phenoxide ion is negatively charged, and that charge can be delocalized to the *ortho* and *para* ring carbons. Therefore, attack by an electrophile at these positions is facilitated.



7.21 a. The hydroxyl group is more ring-activating than the methyl group. Thus substitution *ortho* to the hydroxyl group is preferred.



- b. The hydroxyl group is ring-activating, whereas the chlorine is a ring-deactivating substituent. Therefore, substitution occurs *para* to the hydroxyl group. Substitution *ortho* to the hydroxyl group is less likely since the product would have three adjacent substituents, which would be quite crowded.



- 7.23 a. Follow eq. 7.47 as a guide.



- b. Follow eq. 7.45 as a guide.

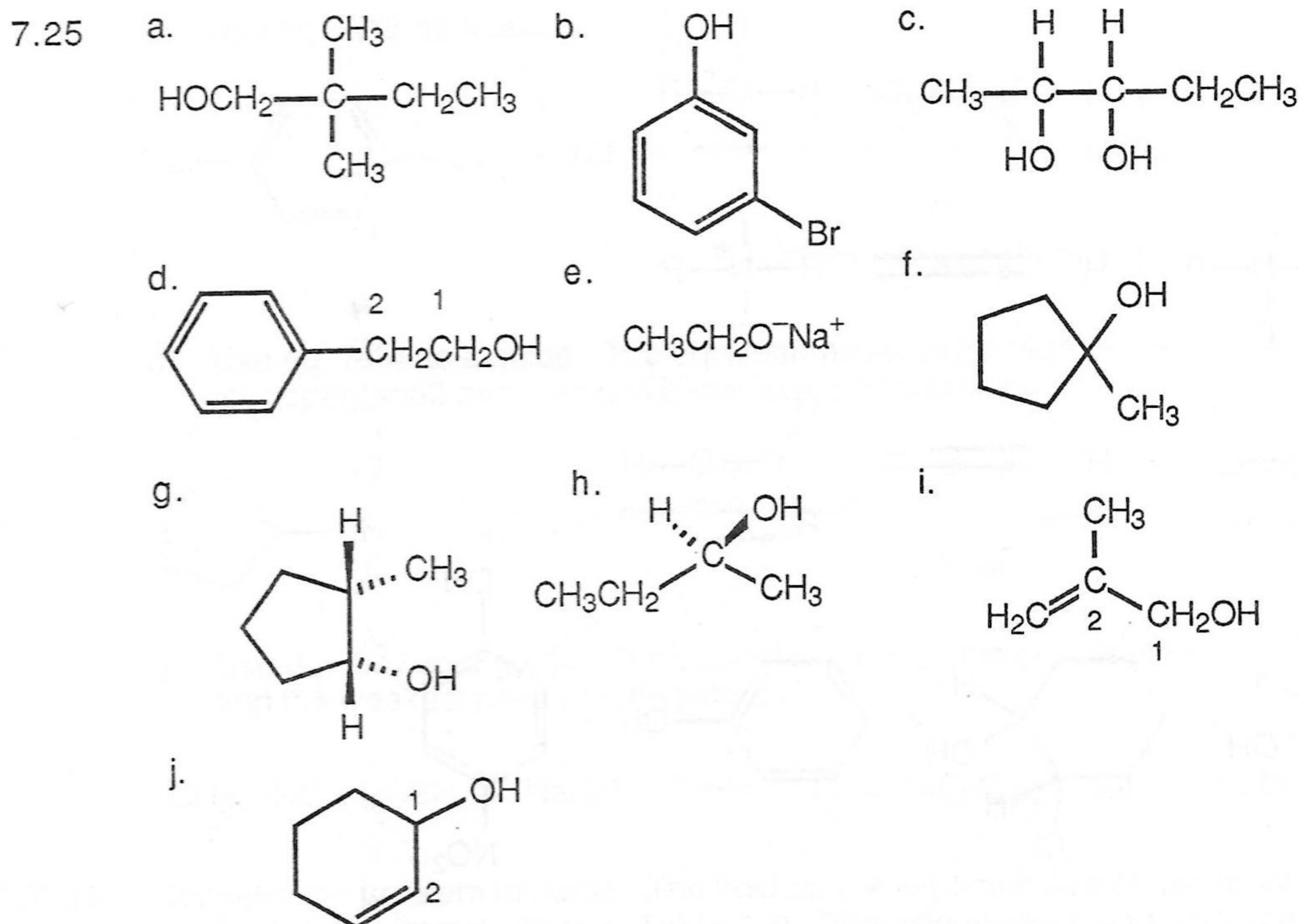


- c. Thiols are stronger acids than alcohols and alkoxides are stronger bases than thiolates.



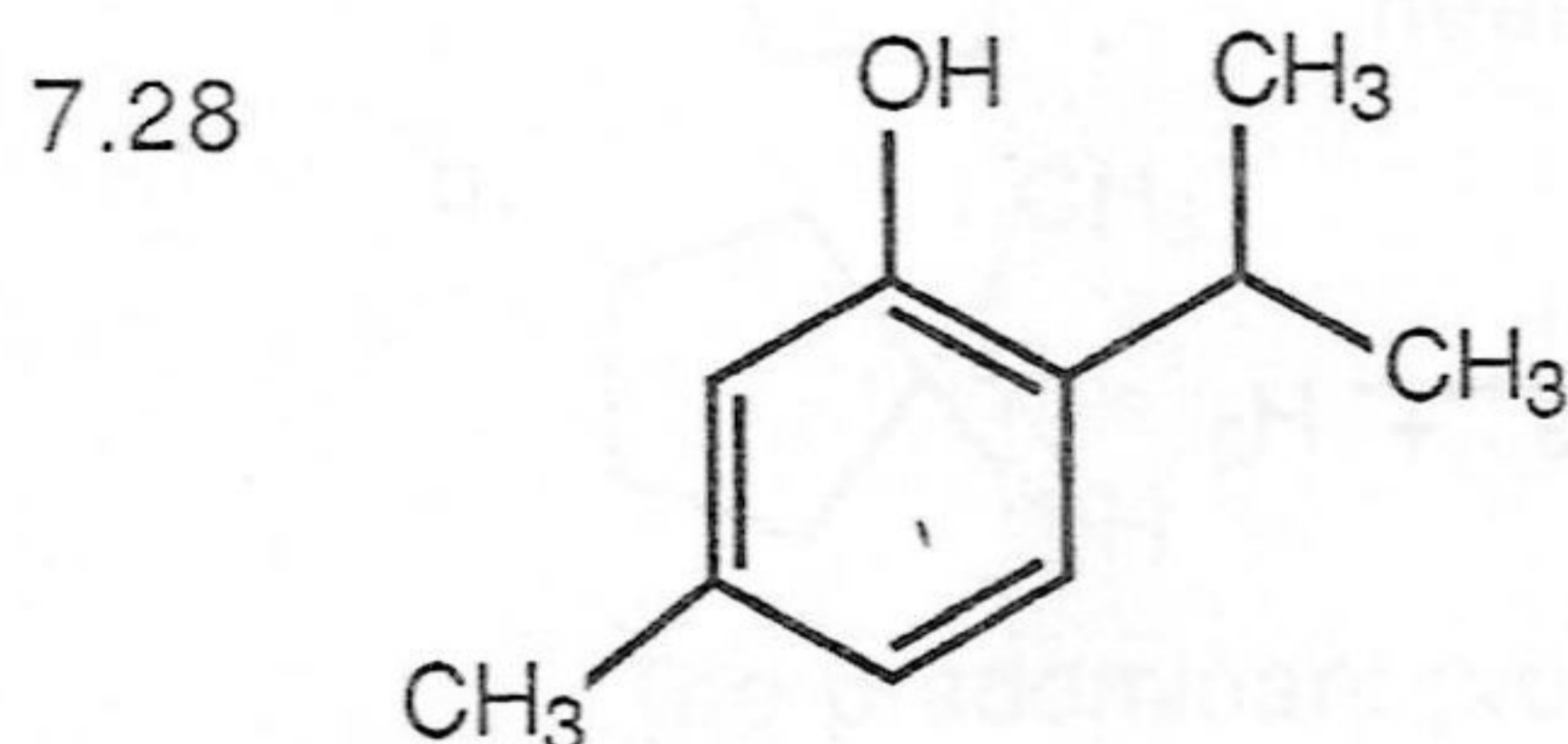
Additional Problems

- 7.24 a. 3-pentanol
 b. 2-methyl-3-pentanol
 c. 2-chloro-3-pentanol
 d. 4-chloro-2-pentanol; the alcohol gets a lower number than the chloro group



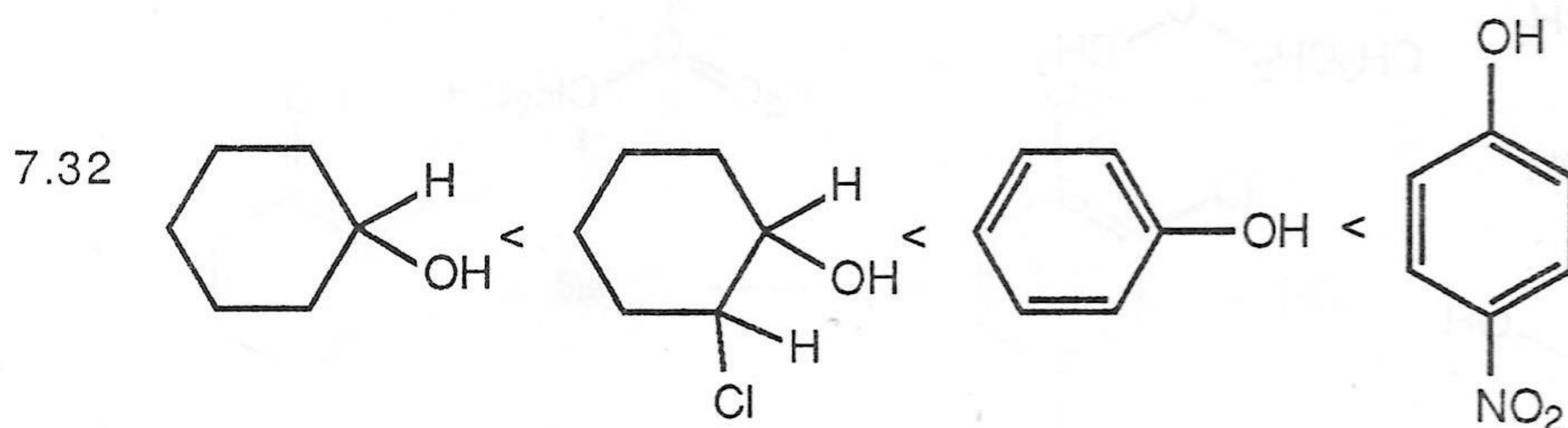
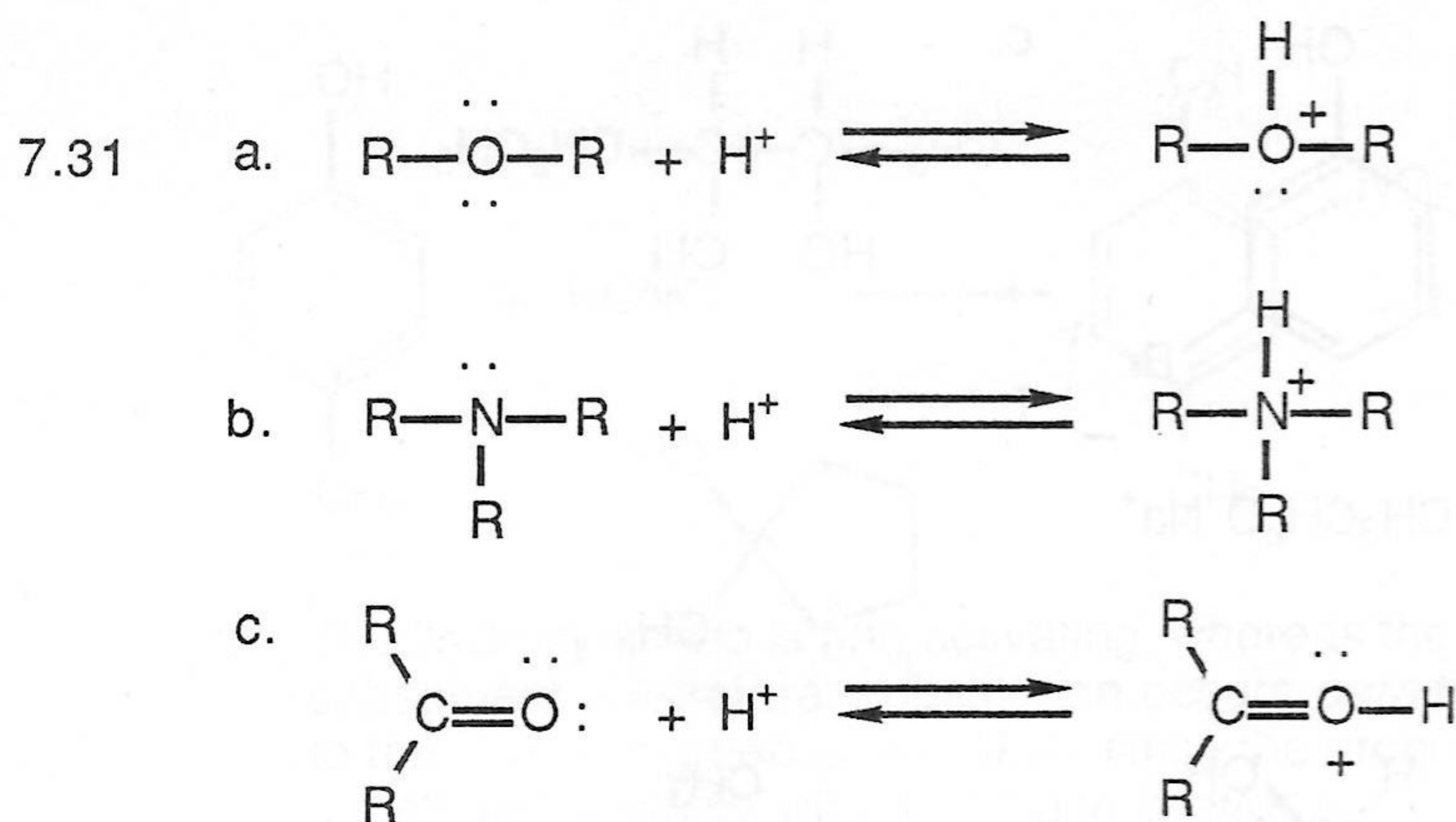
- 7.26
- | | |
|---------------------------|--|
| a. 3,3-dimethyl-2-butanol | b. 3-bromo-2-methyl-2-butanol |
| c. 2,4,6-trichlorophenol | d. cyclopropanol |
| e. <i>o</i> -bromophenol | f. <i>trans</i> -2-methylcyclobutanol |
| g. 2-buten-1-ol | h. 2-propanethiol (or isopropyl mercaptan) |
| i. 1,2,3,4-butanetetraol | j. potassium <i>i</i> -propoxide |

- 7.27
- 2-Methyl-1-butanol; the longest chain was not selected.
 - 3,3-Dimethyl-2-butanol; the hydroxyl should get the lower number.
 - 2-Propen-1-ol (or allyl alcohol); the hydroxyl group should get the lower number.
 - 4-Chloro-2-pentanol; the hydroxyl group should get the lower number.
 - 2,5-Dibromophenol; give substituents the lowest possible numbers.

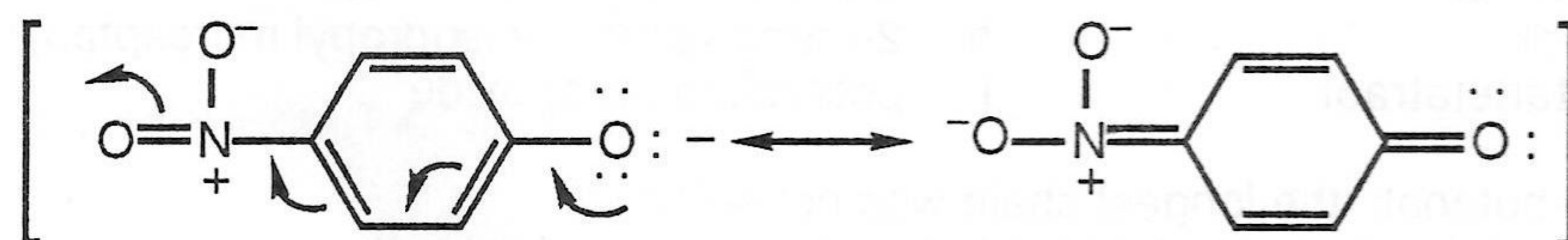


- 7.29
- | | | | |
|--------------|------------|--------------|--------------|
| a. primary | d. primary | f. tertiary | g. secondary |
| h. secondary | i. primary | j. secondary | |

- 7.30
- Ethyl chloride < 1-hexanol < ethanol. Both alcohols can hydrogen bond with water and will be more soluble than the alkyl chloride. The lower molecular weight alcohol will be more soluble (it has a shorter hydrophobic carbon chain).
 - 1-Pentanol < 1,5-pentanediol < 1,2,3,4,5-pentanepentaol. All three compounds have the same number of carbon atoms. Water solubility will therefore increase with increasing numbers of hydroxyl groups (that is, as the ratio of hydroxyl groups to carbon atoms increases).



The two alcohols are less acidic than the two phenols. The electron-withdrawing chlorine substituent makes 2-chlorocyclohexanol a stronger acid than cyclohexanol. The electron-withdrawing nitro substituent makes *p*-nitrophenol a stronger acid than phenol. The negative charge in the *p*-nitrophenoxide ion can be delocalized to the nitrogen:

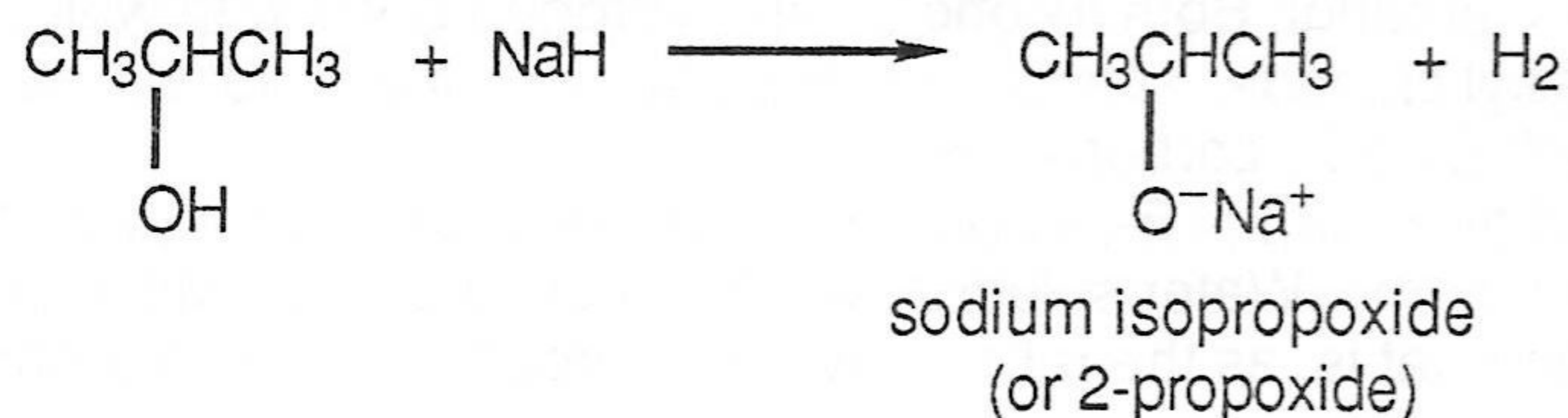


7.33 Since *t*-butyl alcohol is a weaker acid than ethanol ($\text{p}K_a = 18$ and $\text{p}K_a =$ approximately 16, respectively), it follows that if we consider the conjugate bases, *t*-butoxide ion is a stronger base than ethoxide ion.

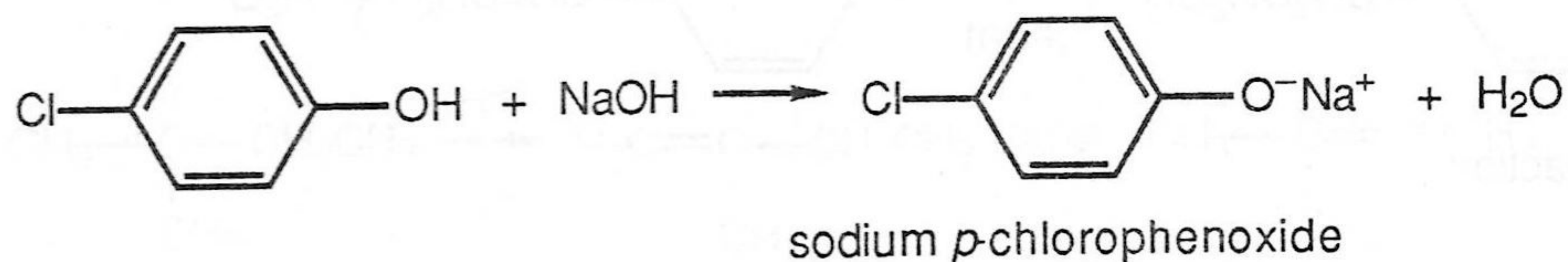
7.34 a. Use eq. 7.12 as a guide.



b. Use eq. 7.13 as a guide.



c. Use eq. 7.15 as a guide.



d. Use eq. 7.14 as a guide. The equilibrium lies on the side of the weakest acid (cyclopentanol) and weakest base (sodium hydroxide).

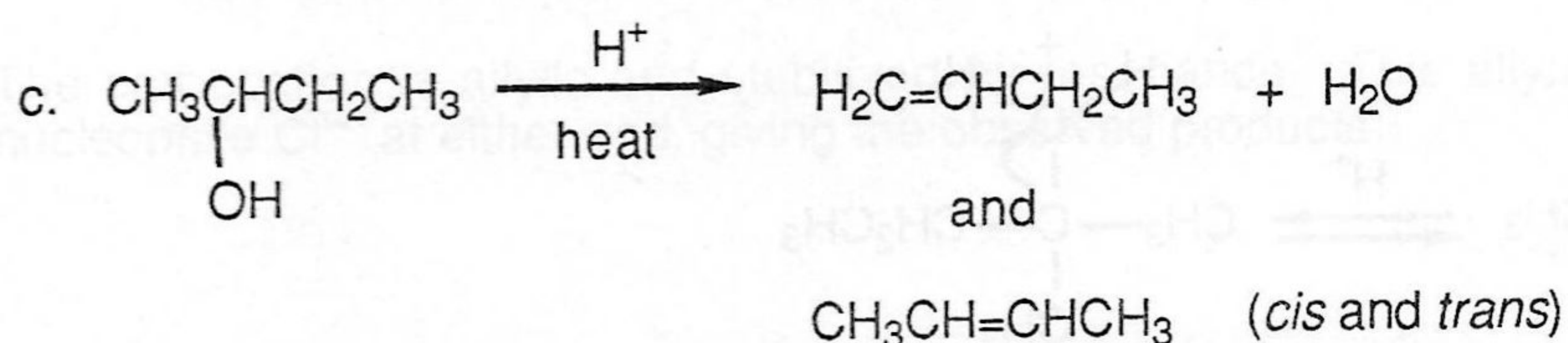
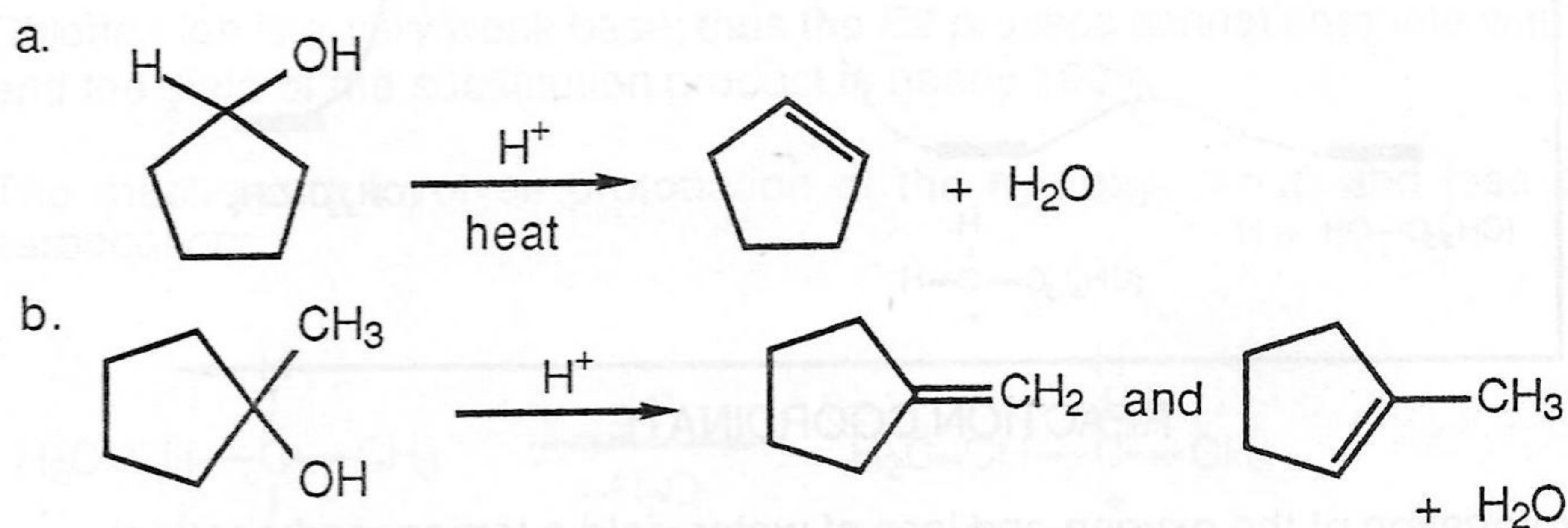


e. Use eq. 7.47 as a guide. The equilibrium lies on the side of the weakest acid (the alcohol) and the weakest base (the thiolate salt).

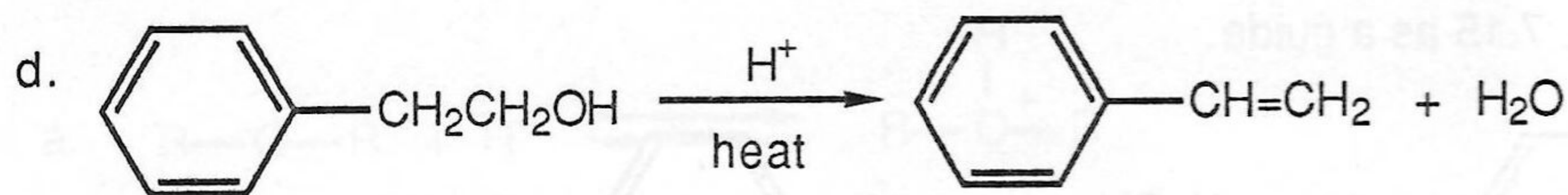


7.35 Consider the problem in part c. The acid on the left-hand side of the equation is a phenol with a pK_a of approximately 10 (see Table 7.2). The acid on the right-hand side of the equation is water with a pK_a of about 16. Thus, the equilibrium lies to the side of water, the weaker acid. In part d, we need to compare the pK_a 's of cyclopentanol and water. Table 7.2 suggests that the pK_a of cyclopentanol might be very close to that of water, so one might expect a mixture at equilibrium. It turns out that cyclopentanol, a secondary alcohol, is slightly less acidic than water and the equilibrium lies slightly to the left. The pK_a of a thiol is about 10 (see Sec. 7.16), so in part e the equilibrium clearly will lie to the right.

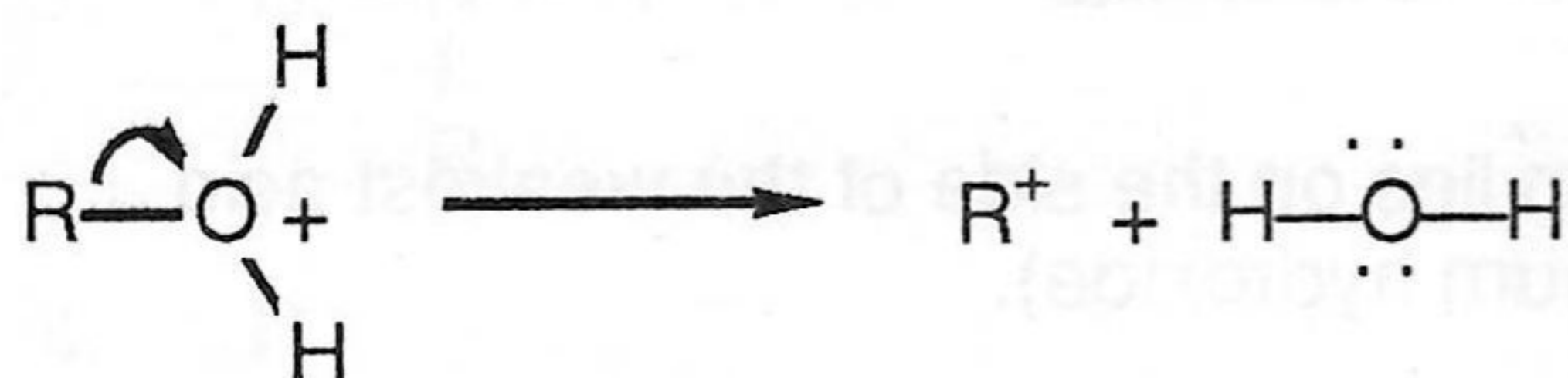
7.36 If you have any difficulty with this problem, review Sec. 7.8.



Of the three possible alkenes, *trans*-2-butene is the most stable and predominates.



7.37 In the reaction



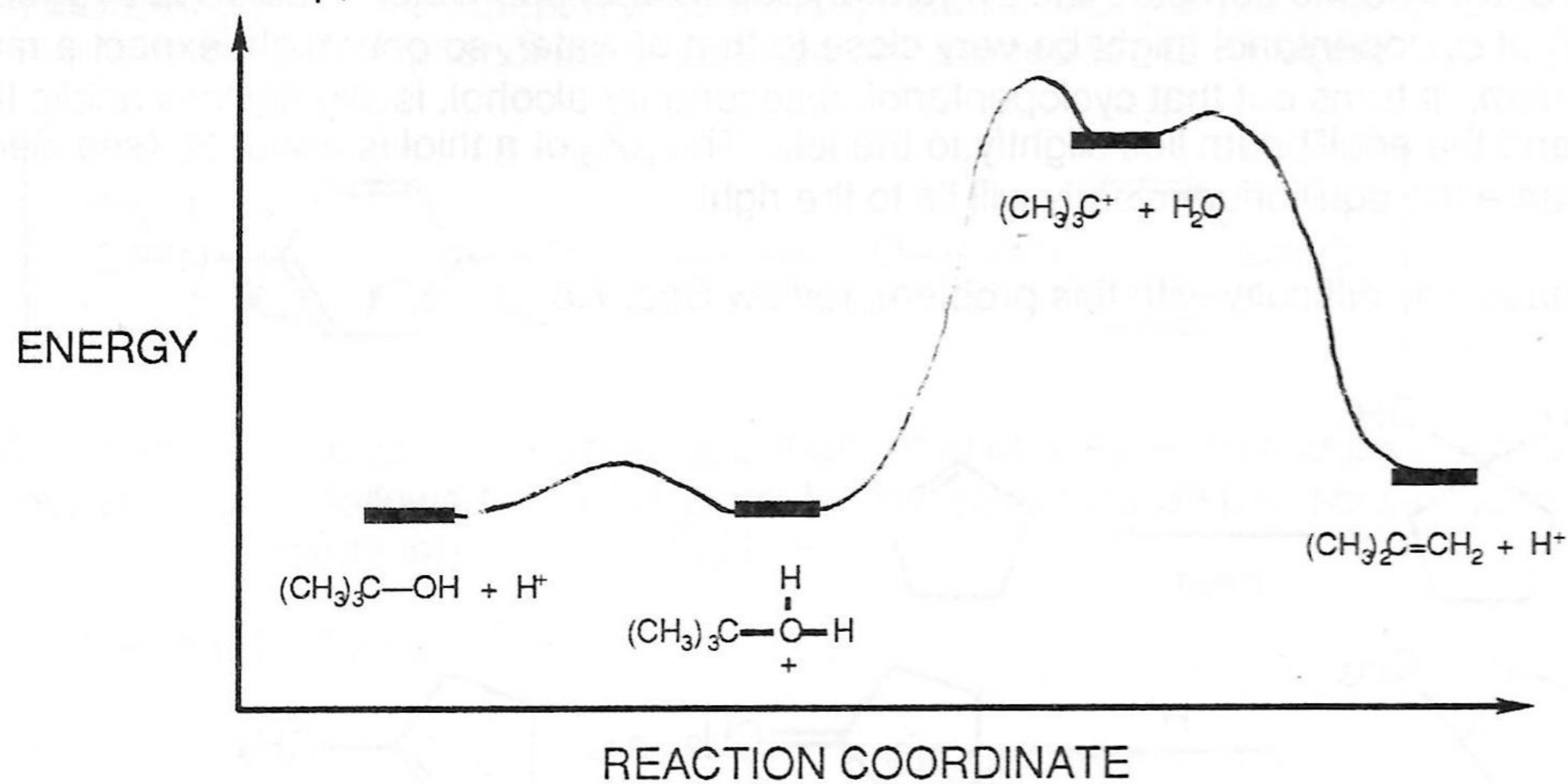
electrons flow toward the positive oxygen, and positive charge passes from the oxygen to carbon (R group).

In the reaction

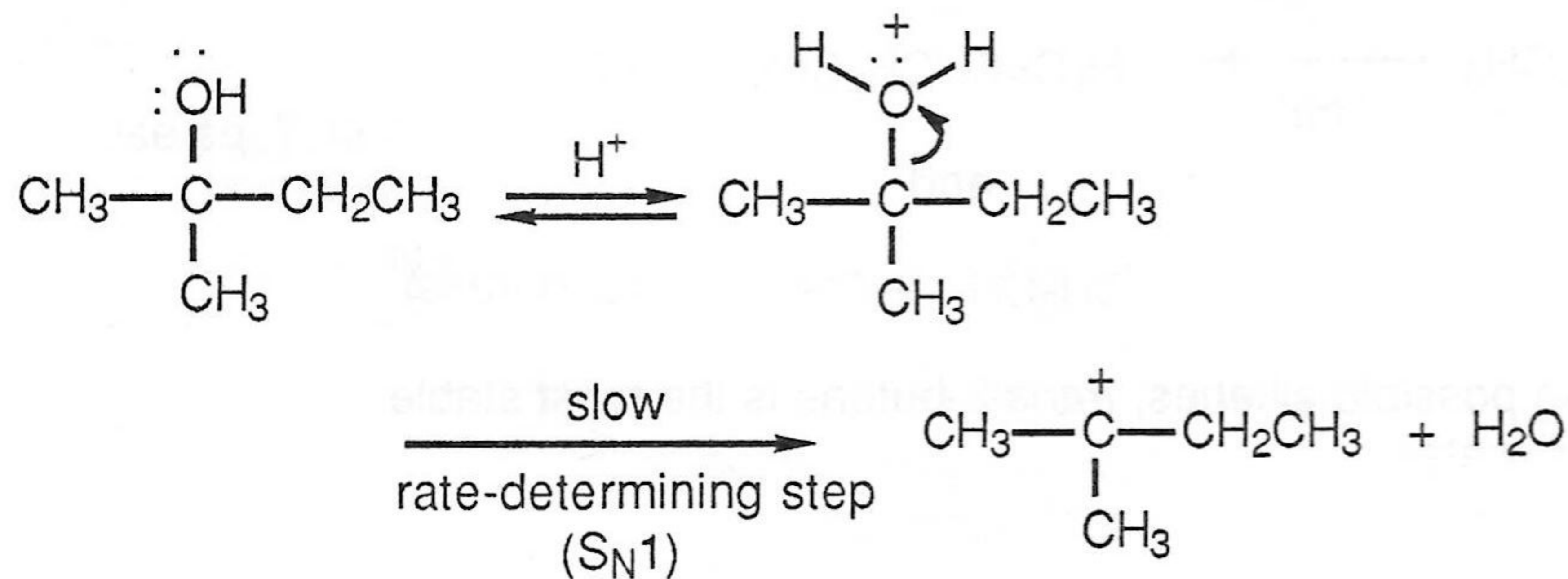


the oxygen is not charged and therefore is less electron-demanding and two oppositely charged species, R^+ and OH^- , must be separated. The second reaction thus requires much more energy than the first.

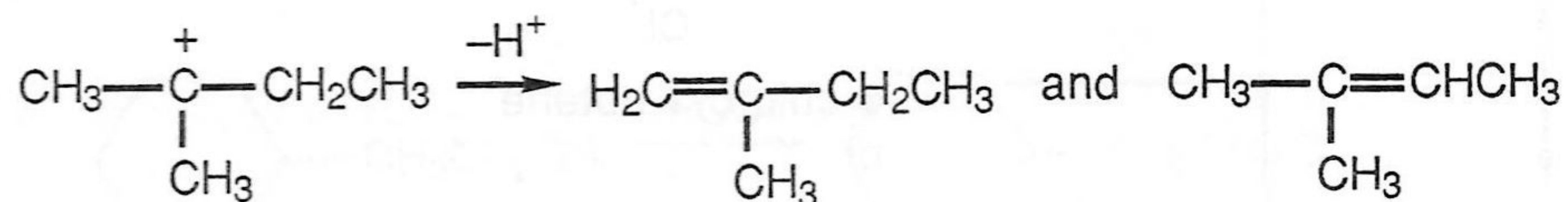
7.38 The second step, formation of a carbocation, is the rate-determining step.



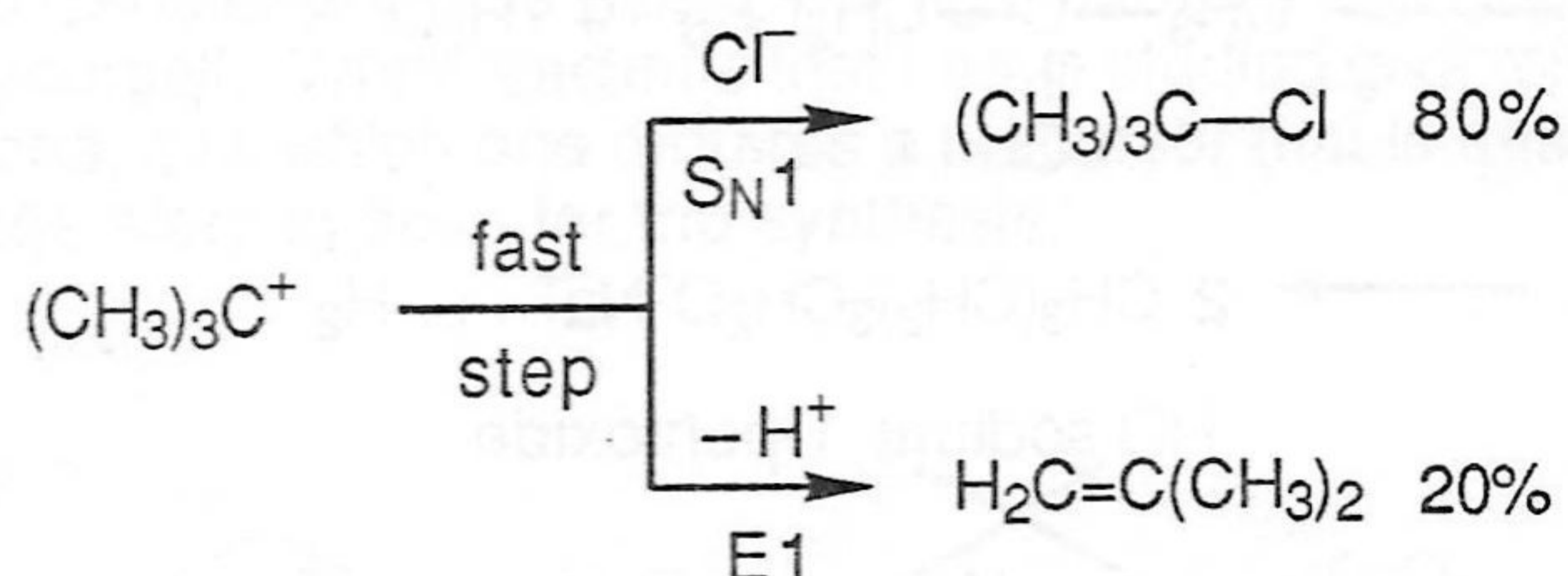
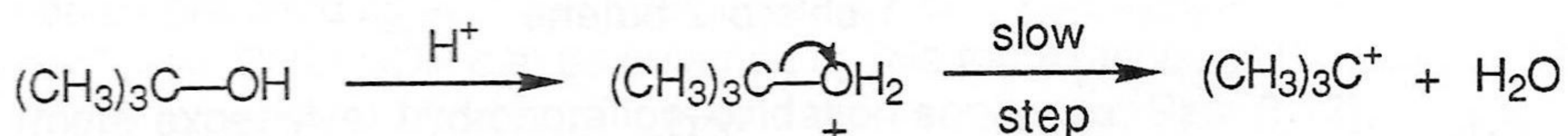
7.39 To begin, protonation of the oxygen and loss of water yield a tertiary carbocation:



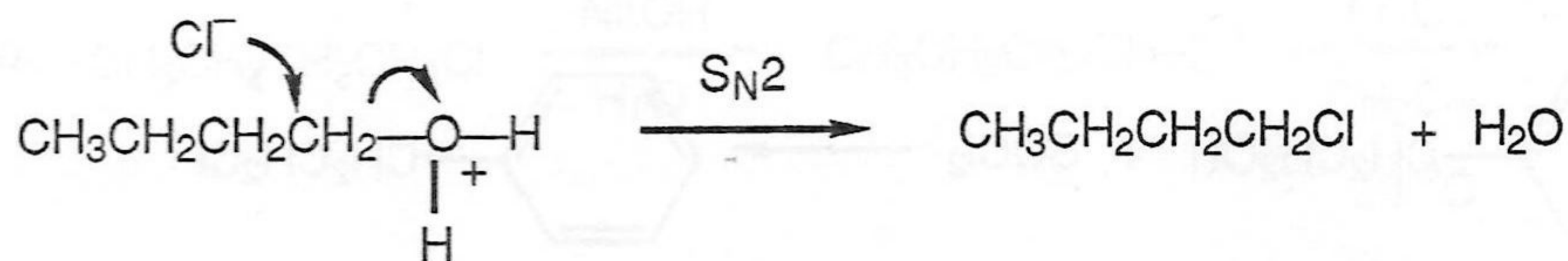
The carbocation can then lose a proton from a carbon adjacent to the one that bears the positive charge, to give either product:



- 7.40 The by-product in eq. 7.26 is isobutylene, formed by an E1 process that competes with the main $\text{S}_{\text{N}}1$ reaction:

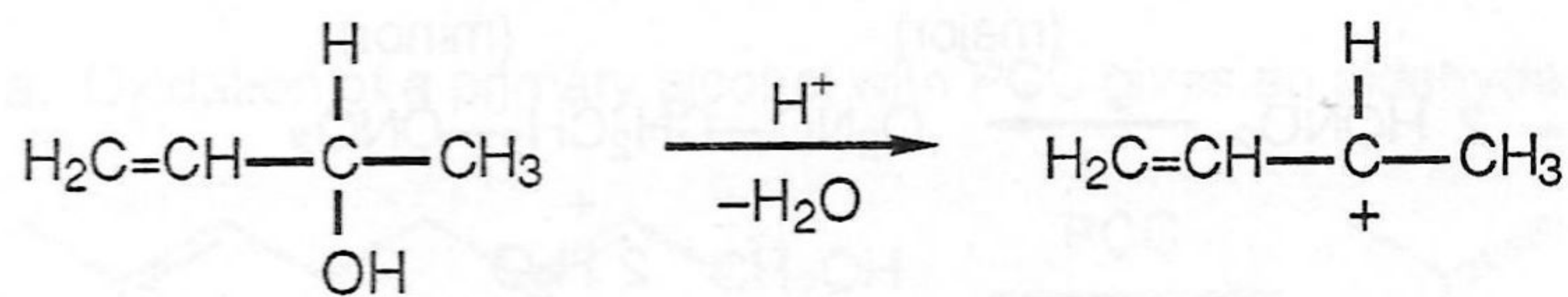


The reaction in eq. 7.28, on the other hand, involves a primary alcohol and proceeds by an $\text{S}_{\text{N}}2$ process:

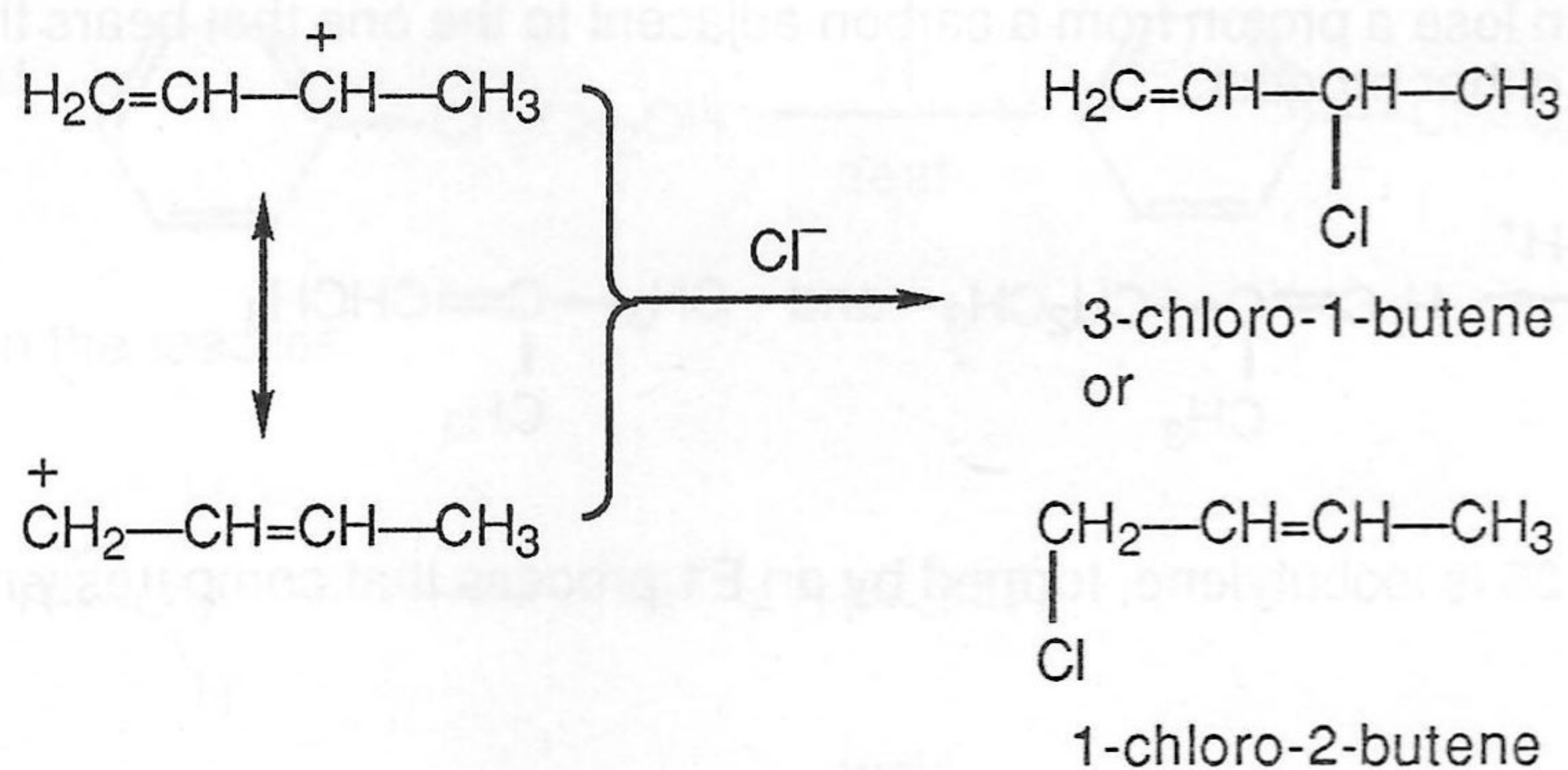


Chloride ion is a *very* weak base; thus the E2 process cannot compete with the $\text{S}_{\text{N}}2$ reaction, and the yield of the substitution product is nearly 100%.

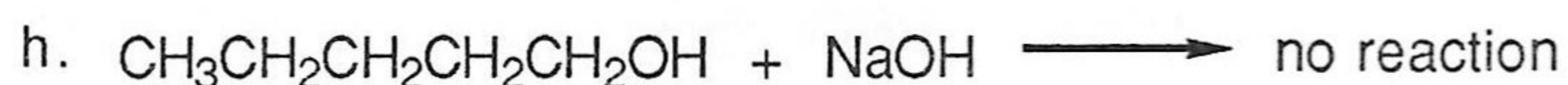
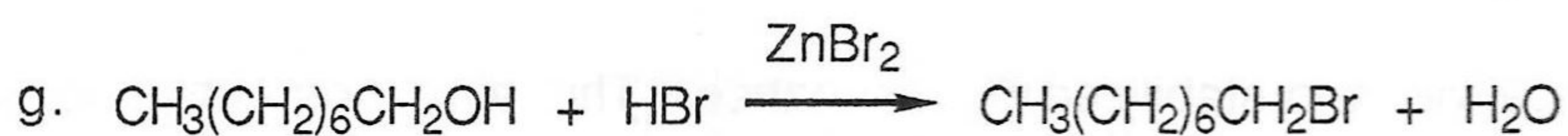
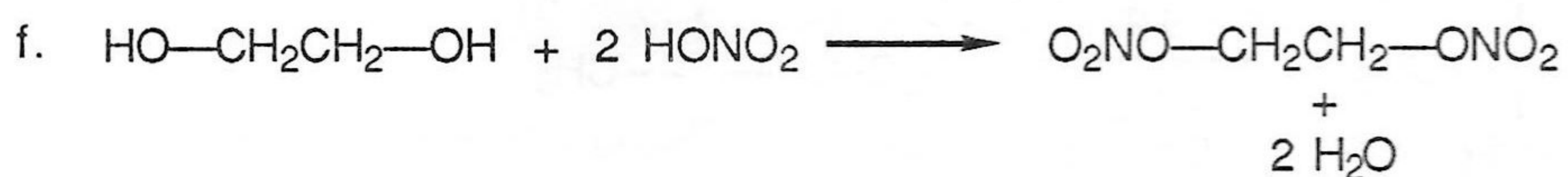
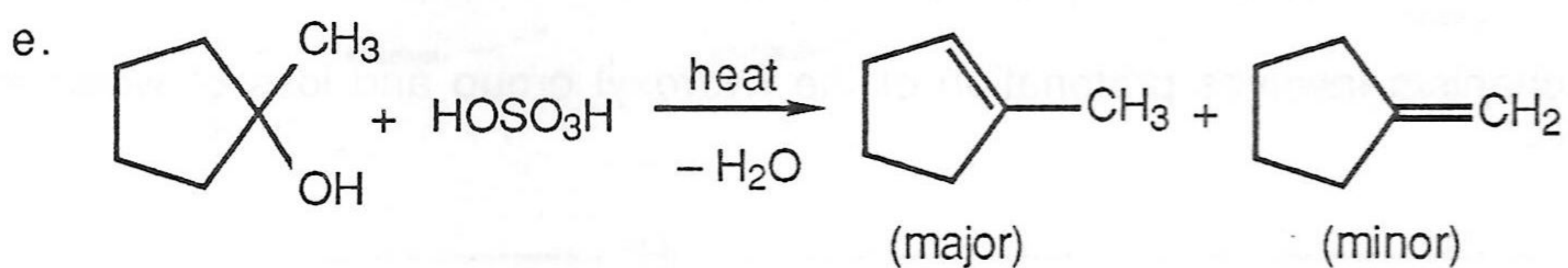
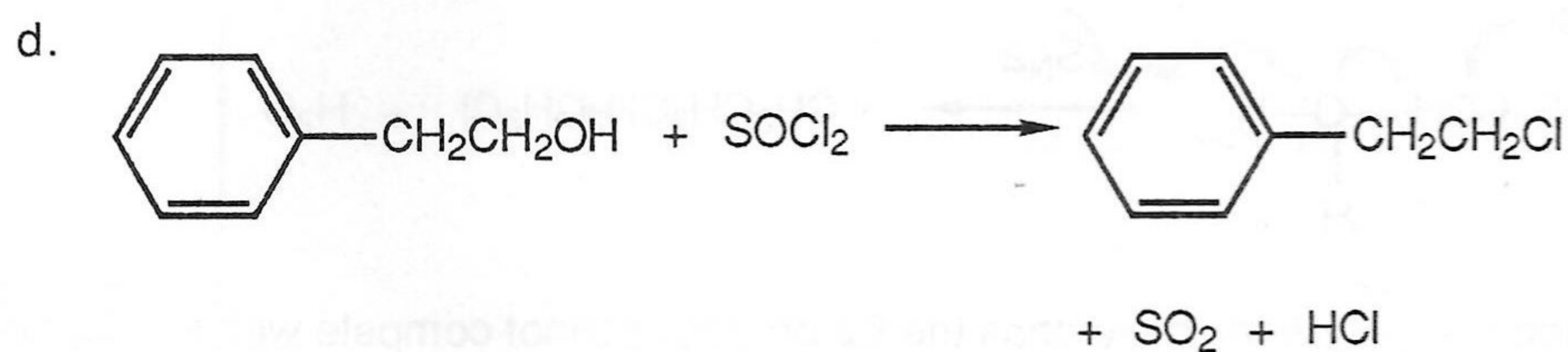
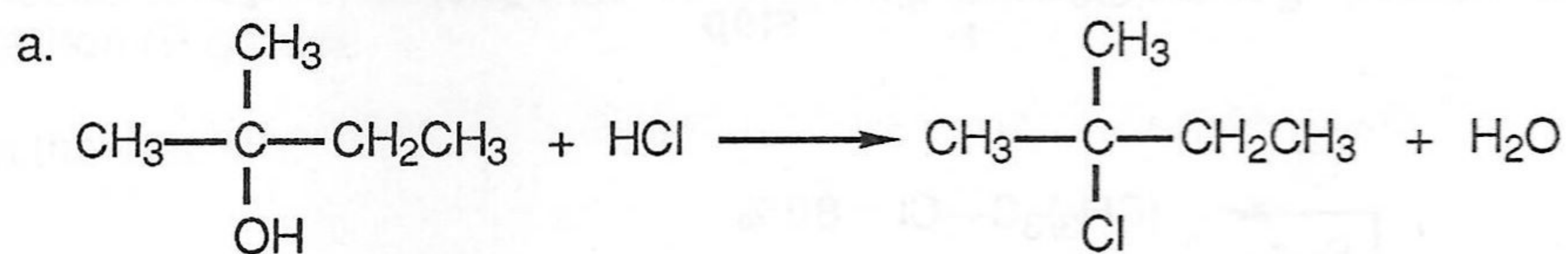
- 7.41 The mechanism involves protonation of the hydroxyl group and loss of water to form a carbocation:

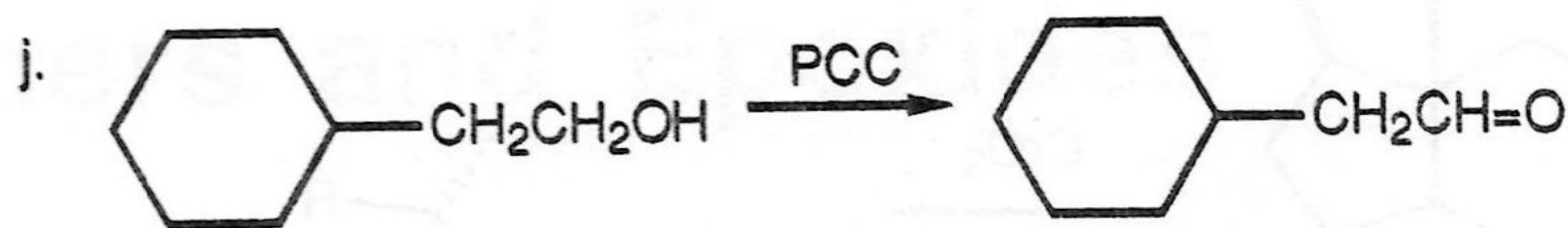
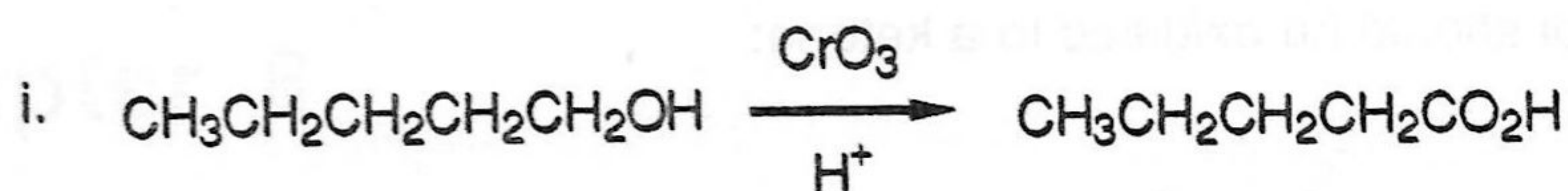


The carbocation is allylic and stabilized by resonance. This allylic ion can react with the nucleophile Cl^- at either end, giving the observed products:



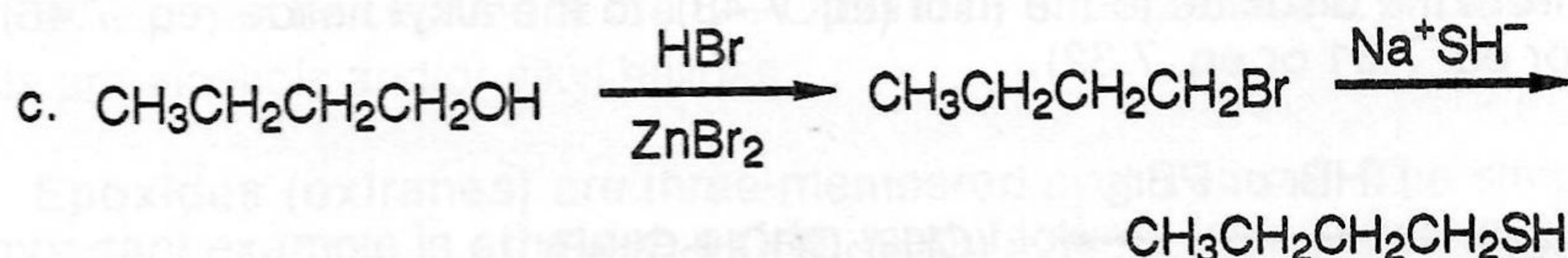
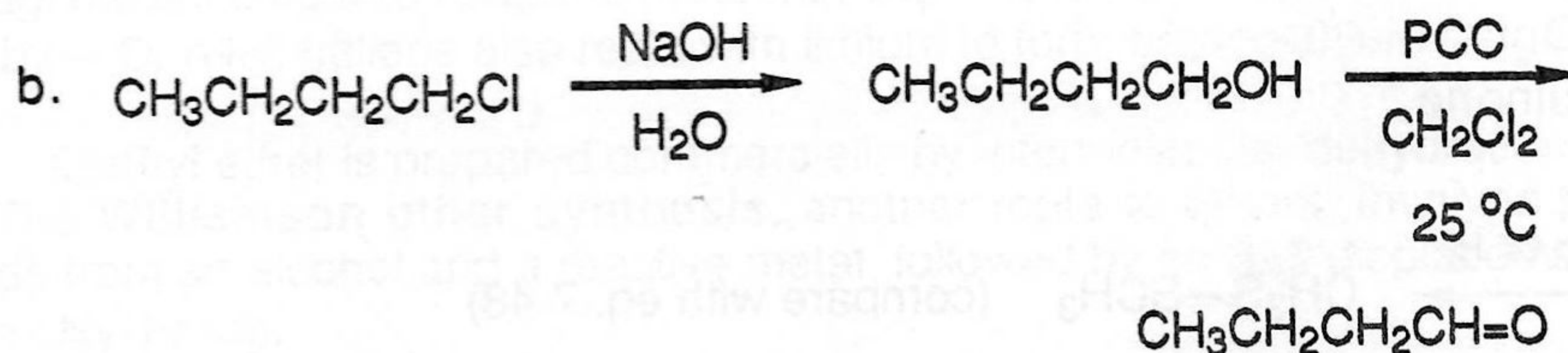
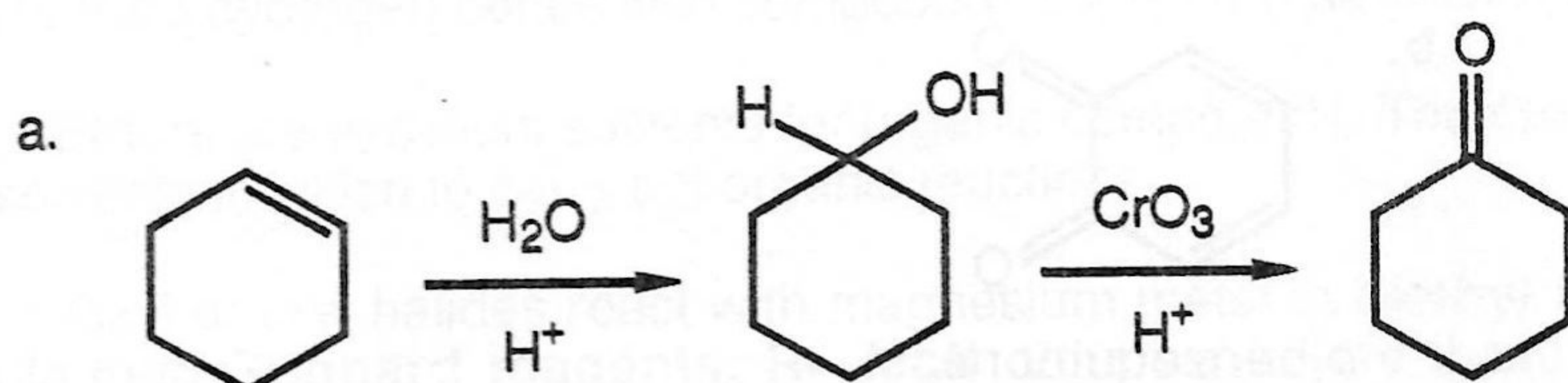
7.42



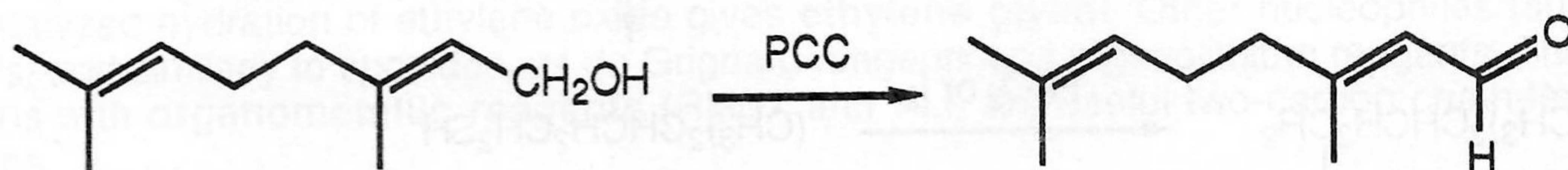


7.43 If necessary, review Secs. 3.8 through 3.10. 2-Butanol can be prepared by acid-catalyzed hydration of $\text{CH}_2=\text{CHCH}_2\text{CH}_3$ or $\text{CH}_3\text{CH}=\text{CHCH}_3$. *tert*-Butyl alcohol (2-methyl-2-propanol) can be prepared by acid-catalyzed hydration of $\text{CH}_2=\text{C}(\text{CH}_3)_2$. Neither $\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{OH}$ nor $(\text{CH}_3)_2\text{CHCH}_2\text{OH}$ can be obtained by this route [although they can be obtained by the (more expensive) hydroboration–oxidation sequence, Sec. 3.13].

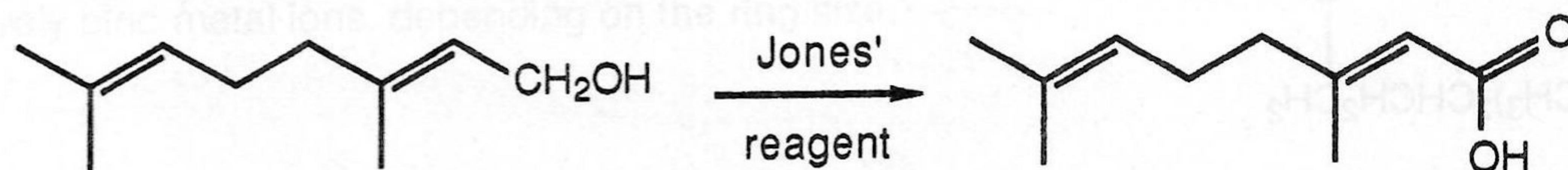
7.44 In problems of this type, working backward from the final product sometimes helps. Ask yourself: What reactions that I have studied give this type of product? If there is more than one, see which one requires a precursor that is easily obtained from the compound given as the starting point for the synthesis.



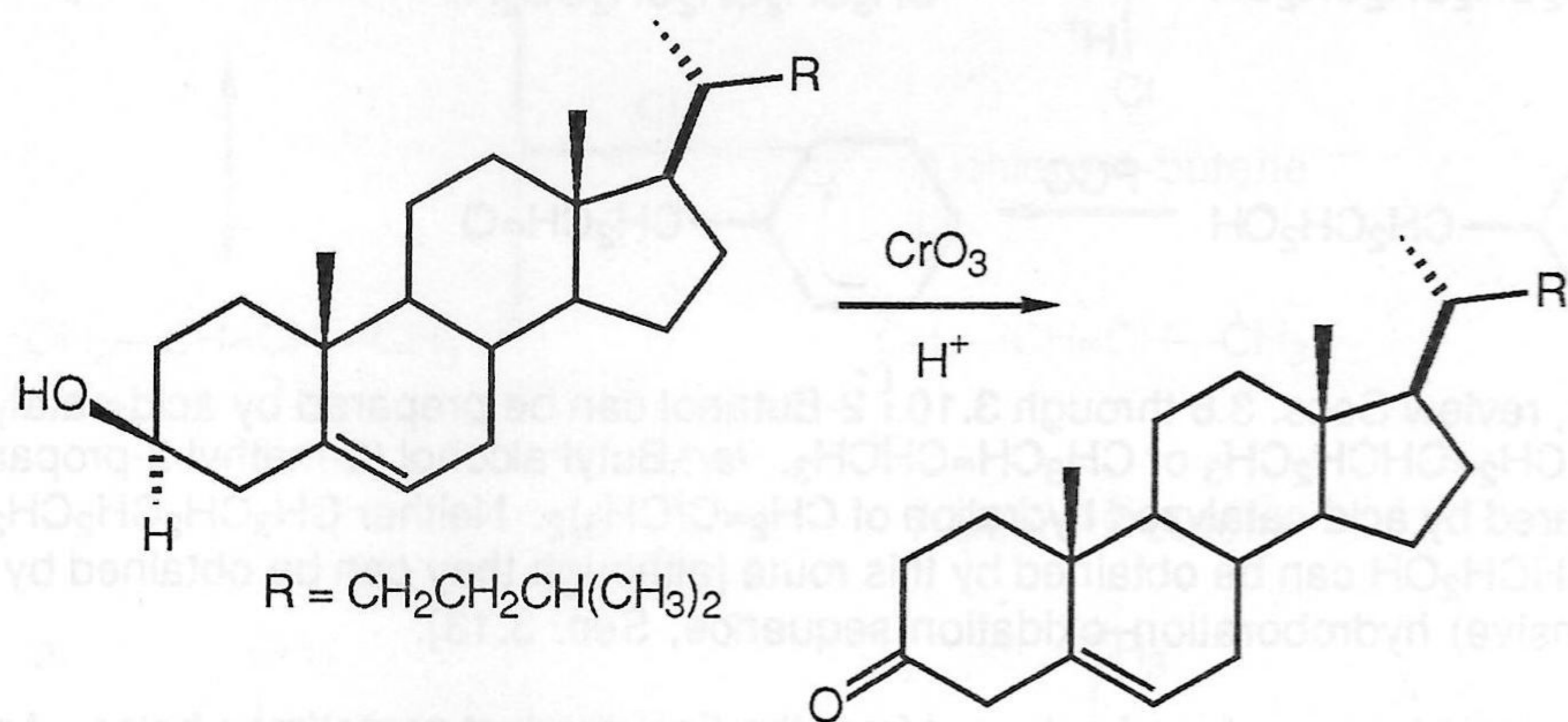
7.45 a. Oxidation of a primary alcohol with PCC gives an aldehyde:



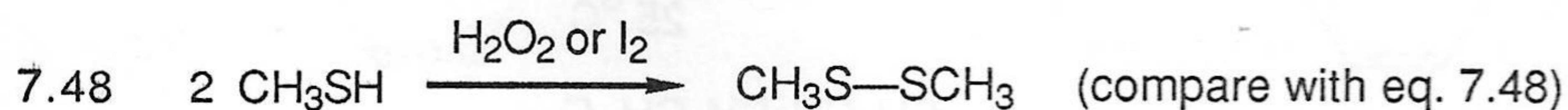
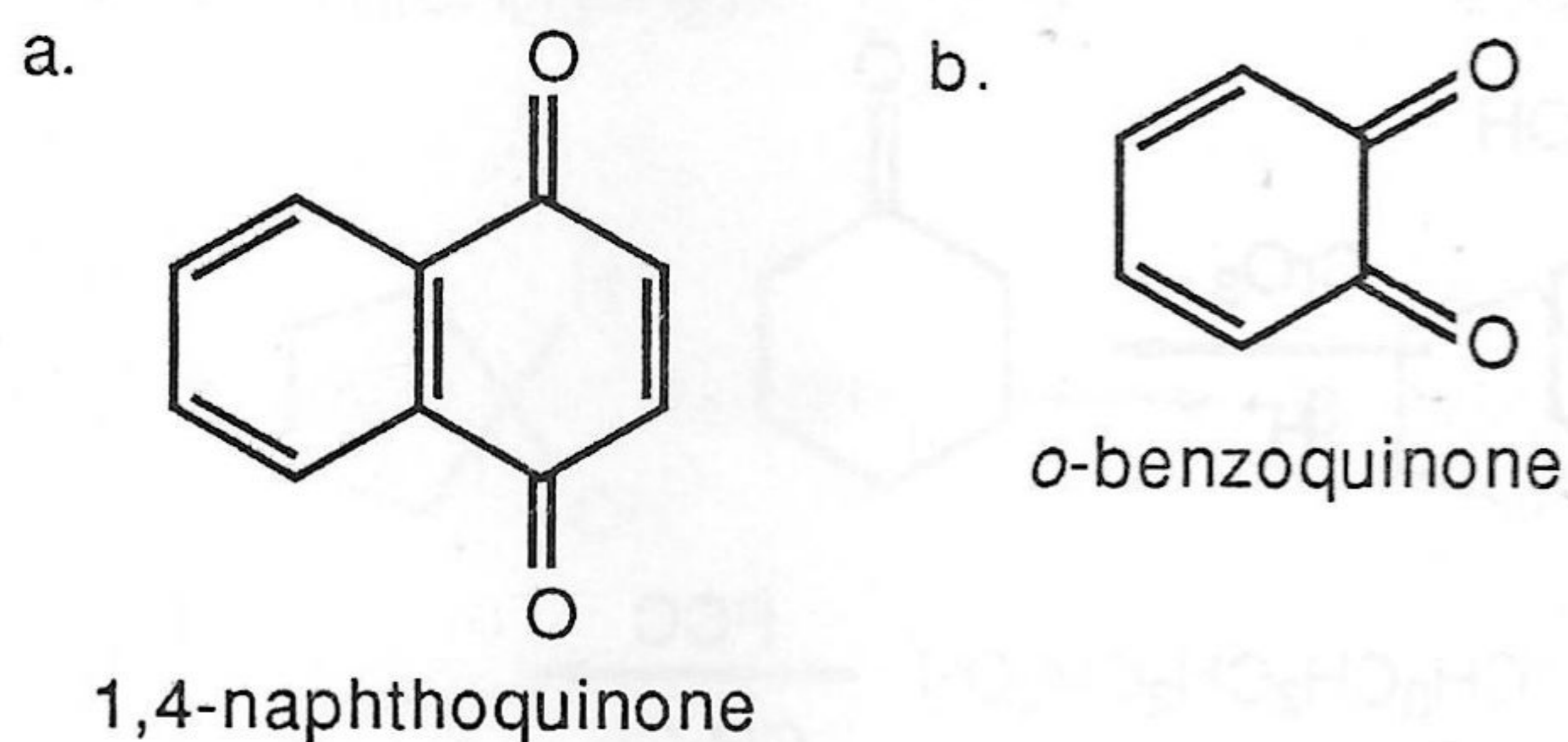
b. The primary alcohol would be oxidized to a carboxylic acid:



7.46 The secondary alcohol should be oxidized to a ketone:



7.47 The oxygens in the quinones are located on the same carbons as the hydroxyl groups in the starting phenols.



7.49 Work backward: from the disulfide to the thiol (eq. 7.48), to the alkyl halide (eq. 7.46), to the alcohol (eq. 7.30 or eq. 7.31 or eq. 7.32).

