1. 
   a. Arrange the following compounds in order of increasing basicity: Cl\(^-\), (CH\(_3\))\(_2\)P\(^-\), CH\(_3\)S\(^-\).
      
      ___________<___________<___________
   
   b. Arrange the following compounds in order of increasing acidity: CH\(_3\)CH\(_2\)SeH, CH\(_3\)CH\(_2\)SH, CH\(_3\)CH\(_2\)OH.
      
      ___________<___________<___________
   
   c. Arrange the following equilibrium constants K\(_1\), K\(_2\), and K\(_3\) in order of increasing value:
      
      CCl\(_3\)\(\text{CH}_2\)OH + H\(_2\)O \(\rightleftharpoons\) CCl\(_3\)\(\text{OH}\) + H\(_3\)O\(^+\)
      
      CCl\(_3\)\(\text{CH}_2\)OH + H\(_2\)O \(\rightleftharpoons\) CCl\(_3\)\(\text{O}^-\) + H\(_3\)O\(^+\)
      
      CH\(_3\)\(\text{CH}_2\)OH + H\(_2\)O \(\rightleftharpoons\) CH\(_3\)\(\text{OH}^-\) + H\(_3\)O\(^+\)
      
      ___________<___________<___________
   
   d. Rank the following in order of increasing acidity: __ < __ < __
      
      (a) ethane 
      (b) ethanol (CH\(_3\)CH\(_2\)OH) 
      (c) ethylamine (CH\(_3\)CH\(_2\)NH\(_2\))
   
   e. Rank the following in order of increasing basicity: __ < __ < __
      
      (a) hydroxide ion 
      (b) acetate ion 
      (c) chloride ion
2. Explain each of the following.

a. 4-Nitrobenzoic acid is a stronger acid than benzoic acid.

\[
\text{benzoic acid} \quad \text{4-nitrobenzoic acid}
\]

b. The pH of a solution of methane in pure water is 7, even though the \( pK_a \) of methane is ca. 50.

3. The following reactions are called cycloaddition reactions, because they involve the addition of two components together to form a ring.

a. Use curved-arrow notation to show the mechanism (flow of electrons) in the following reaction. (This cycloaddition reaction is named the Diels-Alder reaction after its discoverers.)

b. Use curved arrow notation to shown the flow of electrons in the following reaction. (This one is called a dipolar cycloaddition reaction, because the first reactant has two formal charges, which comprise a dipole.)

c. In part a, skeletal structures are used to represent the reactants and product. Write the \textit{molecular formulas} of these compounds:

first reactant \__________ second reactant \__________ product \__________
4. Draw the products of each of the following reactions indicated by curved arrow notation. Make sure to show all lone pairs of electrons, all important resonance structures, and all formal charges.

a. The Michael addition reaction

```
Ph\|\|Ph
O\ H
\|\|\|\|\|\|\|
H + \text{CH}_3\text{S}^- \rightarrow
```

b. The Williamson ether synthesis

```
\text{CH}_3\text{O}^- \quad \text{CH}_3\text{CH}_2\text{Br}^+ \rightarrow
```

5. Draw the products of each of the following reactions indicated by curved arrow notation. Make sure to show all lone pairs of electrons, all important resonance structures, and all formal charges.

a. The Cope rearrangement

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\rightarrow
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b. The Grob fragmentation

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\rightarrow
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6. Acetone undergoes base-catalyzed *aldol* reaction with benzaldehyde to form 4-hydroxy-4-phenyl-2-butanone, as shown below.

\[
\begin{align*}
\text{acetone} & \quad + \quad \text{benzaldehyde} \quad \xrightarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{4-hydroxy-4-phenyl-2-butanone} \\
\text{H}_3\text{C} & \quad \text{H} \quad \text{O} & \quad \text{Ph} & \quad \text{H} \quad \text{O} & \quad \text{H}_3\text{C} \quad \text{OH}^- \quad \text{H}_2\text{O} \\
\text{C} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 & \quad \text{O} & \quad \text{Ph} & \quad \text{H} & \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{OH}^- \quad \text{H}_2\text{O} \\
\text{C} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 & \quad \text{O} & \quad \text{Ph} & \quad \text{H} & \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{OH}^- \quad \text{H}_2\text{O} \\
\text{C} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 & \quad \text{O} & \quad \text{Ph} & \quad \text{H} & \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{OH}^- \quad \text{H}_2\text{O} \\
\end{align*}
\]

The mechanism of this reaction involves three steps and is shown below using curved-arrow notation.

\[
\begin{align*}
(1) \quad \text{H}_3\text{C} & \quad \text{H} \quad \text{O} & \quad \text{Ph} & \quad \text{H} \quad \text{O} \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{H}_3\text{C} \quad \text{OH}^- \quad \text{H}_2\text{O} \\
(2) \quad \text{Ph} & \quad \text{H} \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{Ph} \quad \text{H} \quad \text{O} \quad \text{H}_3\text{C} \quad \text{CH}_3 \\
(3) \quad \text{Ph} & \quad \text{H} \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{Ph} \quad \text{H} \quad \text{O} \quad \text{H}_3\text{C} \quad \text{CH}_3 \\
\end{align*}
\]

The reverse reaction, called the retro-aldol reaction, is shown below:

\[
\begin{align*}
\text{4-hydroxy-4-phenyl-2-butanone} & \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{H}_3\text{C} \quad \text{O} & \quad \text{Ph} & \quad \text{H} \quad \text{O} \\
\text{acetone} & \quad \text{benzaldehyde} \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{H}_3\text{C} \quad \text{OH}^- \quad \text{H}_2\text{O} \\
\text{Ph} & \quad \text{H} \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{Ph} \quad \text{H} \quad \text{O} \quad \text{H}_3\text{C} \quad \text{CH}_3 \\
\text{Ph} & \quad \text{H} \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{Ph} \quad \text{H} \quad \text{O} \quad \text{H}_3\text{C} \quad \text{CH}_3 \\
\text{Ph} & \quad \text{H} \quad \text{O} & \quad \text{H}_3\text{C} & \quad \text{CH}_3 \quad \xleftarrow{\text{OH}^-/\text{H}_2\text{O}} \quad \text{Ph} \quad \text{H} \quad \text{O} \quad \text{H}_3\text{C} \quad \text{CH}_3 \\
\end{align*}
\]

Write the three-step mechanism of the reverse reaction, using curved arrow notation. Make sure to show all lone pairs of electrons and charges. (Hint: the reverse mechanism involves the same three steps but in reverse.)

(1)

(2)

(3)
The Mannich reaction is central to both the production of many nitrogen-containing compounds called *alkaloids*, both in nature (biosynthesis) and in the laboratory (chemical synthesis). An example of the Mannich reaction, involving the reaction of acetophenone, formaldehyde, and dimethylamine, is shown below. (27 points)

\[
\begin{align*}
\text{acetophenone} & + \text{formaldehyde} + \text{dimethylamine} \rightarrow \text{Mannich product} \\
\text{Ph} & - \text{C} - \text{CH}_3 + \text{H}-\text{H} + \text{CH}_3-\text{NHCH}_3 \rightarrow \text{Ph} - \text{C} - \text{NCH}_3 \\
\text{Mannich product} & + \text{H}_2\text{O} + \text{H}_3\text{O}^+ \\
\end{align*}
\]

(a) One key set of steps in the Mannich reaction involves the formation of an enol. Provide *curved arrows* in the equations below to help show the mechanism by which acetophenone forms acetophenone enol.

\[
\begin{align*}
\text{acetophenone} & \rightarrow \text{acetophenone enol} \\
\text{Ph} - \text{C} - \text{CH}_3 & \rightarrow \text{Ph} - \text{C} - \text{CH}_2 \text{H} + \text{H} - \text{H} \\
\text{acetophenone enol} & \rightarrow \text{intermediate} \\
\text{Ph} - \text{C} - \text{CH}_2 & \rightarrow \text{Ph} - \text{C} - \text{H} + \text{H} - \text{O} - \text{H} \\
\end{align*}
\]

(b) The final steps in the Mannich reaction involve the reaction of the enol with an iminium ion.

(1) Fill in the structure of the intermediate that forms when the enol reacts with the iminium ion. Make sure to show all charges and lone pairs of electrons.

(2) Provide a *curved-arrow mechanism* to show how the intermediate forms the Mannich product. Make sure to show all charges and lone pairs of electrons.

\[
\begin{align*}
\text{acetophenone enol} & + \text{iminium ion} \rightarrow \text{intermediate} \\
\text{Ph} - \text{C} - \text{CH}_2 & + \text{CH}_3-\text{NHCH}_3 \rightarrow \text{intermediate} \\
\text{intermediate} & \rightarrow \text{Mannich product} \\
\end{align*}
\]
8. In the Mannich reaction (above), the iminium ion forms reversibly from the reaction of formaldehyde with dimethylamine. The first three steps of this reaction involve the formation of an intermediate called a hemiaminal.

The mechanism of the formation of the hemiaminal involves three steps and is shown below using curved-arrow notation.

In the reverse reaction, shown below, the hemiaminal breaks down to formaldehyde and dimethylamine.

Write the three-step mechanism of the reverse reaction, using curved arrow notation. Make sure to show all lone pairs of electrons and charges. (Hint: the reverse mechanism involves the same three steps but in reverse.)

(1)

(2)

(3)