1. Given the reaction: \( \text{HCOOH} \rightarrow \text{CO} + \text{H}_2\text{O} \)

   a) This reaction, without a catalyst, is very slow at room temperature. Suggest why.

   Reaction has a large activation energy and particles do not possess sufficient KE at room temperature to overcome Ea and have a successful collision.

   b) This reaction is thought to take place by means of the following mechanism when the catalyst \( \text{H}^+ \) is added:

   \[
   \text{Step 1: HCOOH} + \text{H}^+ \rightarrow \text{HCOOH}_2^+ \quad \text{(fast)}
   \]

   \[
   \text{Step 2: HCOOH}_2^+ \rightarrow \text{H}_2\text{O} + \text{HCO}^+ \quad \text{(slow)}
   \]

   \[
   \text{Step 3: HCO}^+ \rightarrow \text{CO} + \text{H}^+ \quad \text{(fast)}
   \]

   c) Identify the two **intermediates** \( \text{HCOOH}_2^+ \), \( \text{HCO}^+ \)

   d) Identify the **catalyst** in this mechanism \( \text{H}^+ \)

   e) Another catalyst is discovered which increases the rate of only Step 1. How will this affect the rate of the overall reaction?

   **NO EFFECT.**

   Explain your answer.

   RATE OF THE OVERALL REACTION IS DETERMINED BY THE SLOWEST STEP, FOR THIS REACTION, THIS IS STEP 2.

   f) Which step has the greatest **activation energy**? **STEP 2**

   g) How many "bumps" will the potential energy diagram for the catalyzed reaction?

   3

   h) Which step is called the **rate determining step** in this mechanism? **STEP 2**

   i) In order to have successful collisions, the colliding particles must have **both** the proper amount of **energy** and the proper **GEOMETRY**
On the set of axes below, draw the shape of the curve you might expect for the reaction in this question. The overall reaction is exothermic! Make sure you get the "bumps" the correct relative sizes.

![Graph showing potential energy vs. progress of reaction]

2. Given the following mechanism, answer the questions below:
   
   Step 1: \[ O_3 + NO \rightarrow NO_2 + O_2 \] (slow)
   
   Step 2: \[ NO_2 + O \rightarrow NO + O_2 \] (fast)

   a) Give the equation for the overall reaction.

   \[ O_3 + O \rightarrow 2 O_2 \]

   b) What could the catalyst be in this mechanism? \textbf{NO}

   c) What is an intermediate in this mechanism? \textbf{NO}_2
The following are proposed reaction mechanisms. For each, either find the overall reaction or the missing step. In addition, list all reaction intermediates and catalysts for each reaction.

1. Step 1: \( A + B \rightarrow I_1 \)  
   Step 2: \( I_1 + A \rightarrow I_2 \)  
   Step 3: \( I_2 + C \rightarrow D \)  
   Overall Reaction: \( \)  

2. Step 1: \( H + I \rightarrow J \)  
   Step 2: \( J + K \rightarrow L + H \)  
   Step 3: \( 2L \rightarrow M + N \)  
   Overall Reaction: \( \)  

3. Step 1: \( Se + O_2 \rightarrow SeO_2 \)  
   Step 2: \( SeO_2 + O_2 \rightarrow SeO_4 \)  
   Overall Reaction: \( \)  

4. Overall reaction: \( OCl^- + I^- \rightarrow OI^- + Cl^- \)  
   Step 1: \( OCl^- + H_2O \rightarrow HOCl + OH^- \)  
   Step 2: \( I^- + HOCl \rightarrow HOI + Cl^- \)  
   Step 3: \( \)  

5. Step 1: \( HCOOH + H^+ \rightarrow HCOOH_2^+ \)  
   Step 2: \( HCOOH_2^+ \rightarrow HCO^+ + H_2O \)  
   Step 3: \( HCO^+ \rightarrow H^+ + CO \)  
   Overall Reaction: \( \)  

6. Overall reaction: \( H_2 + Cl_2 \rightarrow 2HCl \)  
   Step 1: \( \)  
   Step 2: \( Cl + H_2 \rightarrow HCl + H \)  
   Step 3: \( H + Cl_2 \rightarrow HCl + Cl \)  
   Step 4: \( Cl + Cl \rightarrow Cl_2 \)  

7. Step 1: \( NO + O_2 \rightarrow NO_3 \)  
   Step 2: \( NO_3 + NO \rightarrow 2NO_2 \)  
   Overall reaction: \( \)  

8. Overall reaction: \( 2Ce^{4+} + Tl^+ \rightarrow 2Ce^{3+} + Tl^{3+} \)  
   Step 1: \( Ce^{4+} + Mn^{2+} \rightarrow Ce^{3+} + Mn^{3+} \)  
   Step 2: \( \)  
   Step 3: \( Mn^{4+} + Tl^+ \rightarrow Tl^{3+} + Mn^{2+} \)
9. Step 1: $H^+ + H_2O_2 \rightarrow H_3O_2^+$
Step 2: $Br^- + H_3O_2^+ \rightarrow HOBr + H_2O$
Step 3: $HOBr + H^+ \rightarrow H_2OBr^+$
Step 4: $Br^- + H_2OBr^+ \rightarrow H_2O + Br_2$
Overall reaction:

10. Overall reaction: $NH_4^+ + HNO_2 \rightarrow N_2 + 2H_2O + H^+$
Step 1: $HNO_2 + H^+ \rightarrow H_2O + NO^+$
Step 2: 
Step 3: $NO^+ + NH_3 \rightarrow NH_3NO^+$
Step 4: $NH_3NO^+ \rightarrow H_2O + H^+ + N_2$

11. Overall reaction: $I^- + OCl^- \rightarrow Cl^- + OI^-$
Step 1: 
Step 2: $HOCl + I^- \rightarrow Cl^- + HOI$
Step 3: $HOI + OH^- \rightarrow H_2O + OI^-$

ANSWERS:

<table>
<thead>
<tr>
<th>Missing Step/Reaction</th>
<th>Reaction Intermediates</th>
<th>Catalysts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2A + B + C \rightarrow D</td>
<td>$I_1, I_2$</td>
<td></td>
</tr>
<tr>
<td>2 I + K + L \rightarrow M + N</td>
<td>$J, L$</td>
<td>$H$</td>
</tr>
<tr>
<td>3 Se + 2O_2 \rightarrow SeO_4</td>
<td>SeO_2</td>
<td></td>
</tr>
<tr>
<td>4 OH^- + HOI \rightarrow H_2O + OI^-</td>
<td>HOCl, OH^-, HOI</td>
<td>$H_2O$</td>
</tr>
<tr>
<td>5 HCOOH \rightarrow H_2O + CO</td>
<td>HCOOH_{2^+}, HCO^+</td>
<td>$H^+$</td>
</tr>
<tr>
<td>6 Cl_2 \rightarrow 2Cl</td>
<td>Cl, H</td>
<td>Cl_2</td>
</tr>
<tr>
<td>7 2NO + O_2 \rightarrow 2NO_2</td>
<td>NO_3</td>
<td></td>
</tr>
<tr>
<td>8 Ce^{4+} + Mn^{3+} \rightarrow Ce^{3+} + Mn^{4+}</td>
<td>Mn^{3+}, Mn^{4+}</td>
<td>Mn^{2+}</td>
</tr>
<tr>
<td>9 2H^+ + 2Br^- + H_2O_2 \rightarrow 2H_2O + Br_2</td>
<td>H_3O_2^+, HOBr, H_2OBr^+</td>
<td></td>
</tr>
<tr>
<td>10 NH_4^+ \rightarrow NH_3 + H^+</td>
<td>NO^+, NH_3, NH_3NO^+</td>
<td>$H^+$</td>
</tr>
<tr>
<td>11 H_2O + OCl^- \rightarrow HOCl + OH^-</td>
<td>HOCl, HOI, OH^-</td>
<td>$H_2O$</td>
</tr>
</tbody>
</table>
Reaction Mechanism Examples

1. Given the reaction: \[\text{HCOOH} \rightarrow \text{CO} + \text{H}_2\text{O}\]

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   \begin{align*}
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   \text{Step 2: } & \quad \text{HCOOH}_2^+ \rightarrow \text{H}_2\text{O} + \text{HCO}^+ \quad \text{(slow)} \\
   \text{Step 3: } & \quad \text{HCO}^+ \rightarrow \text{CO} + H^+ \quad \text{(fast)}
   \end{align*}

c) Identify the two intermediates

d) Identify the catalyst in this mechanism

e) Another catalyst is discovered which increases the rate of only Step 1. How will this affect the rate of the overall reaction?

f) Which step has the greatest activation energy?

h) How many "bumps" will the potential energy diagram for the catalyzed reaction?

h) Which step is called the rate determining step in this mechanism?

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   a) Give the equation for the overall reaction.

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   c) What is an intermediate in this mechanism?