Part 1: (18 points total) Define 3 out of the following 6 terms as they are used in the fields of thermodynamics and/or mechanics. Keep your definitions brief and to the point. Use of equations, when appropriate, is encouraged, but you need not perform calculations.

1.1) Define the terms reversible and irreversible as they are used to describe thermodynamic processes.

1.2) Define Euler’s criterion for exactness. How is this criterion applied in thermodynamics?

1.3) What are Maxwell Relations? Give two examples. How are these relationships applied in thermodynamics?

1.4) What is the Gibbs phase rule? Give an example of how this rule is used in thermodynamics.

1.5) Define the term adiabatic as it is used in thermodynamics. When is an adiabatic process isentropic?

1.6) Thermodynamic properties (e.g. \( \frac{\partial U}{\partial V} \), \( C_p - C_v \), \( \frac{\partial H}{\partial P} \), etc.) can be expressed as functions of P, V, T and what three measurable physical quantities?

Part 2 (20 points) Answer two out of the four questions below. Answers should be no longer than 200 words. In some cases a brief calculation might be useful and would save a lot of words.

2.1) An elastomeric substance like rubber is composed of long molecular polymers. In the resting, un-stretched state the polymers are coiled into non-linear shapes. When the elastomer is stretched the molecules assume more or less linear shapes. Suppose a rubber band is stretched reversibly. Will heat flow in or out of the rubber band? Explain your answer using the state functions and the appropriate law of thermodynamics.

2.2) Consider two identical pieces of spring steel. The compositions, weights and shapes of the pieces of steel are the same. Suppose one piece of steel is coiled up using a light, chemically inert thread. Now both pieces of steel are dissolved completely in strong acid
solutions. Will the temperature changes $\Delta T$ that result from the two reactions be the same or different? If they are different which will be higher? Explain your answer.

2.3) Suppose an ideal gas expands adiabatically into a vacuum. Which terms will be zero and which will be non-zero: $\Delta U$, $\Delta S$, $\Delta H$, $\Delta G$, $\Delta T$, $q$, and $w$? You may and should show equations to support your answers, but you do not have to do detailed calculations.

2.4) The heat capacity at constant pressure of 1 atm for water $C_p$ increases from zero at 0K to about 37 J K$^{-1}$ mol$^{-1}$ at 273K. When water has melted to a liquid the $C_p$ is about 75 J K$^{-1}$ mol$^{-1}$ and remains roughly constant until 373K. Once water vaporizes $C_p$ drops back to about 33 J K$^{-1}$ mol$^{-1}$. Explain these trends in heat capacity with temperature. You do not have to explain the exact numerical values for $C_p$, but give reasons in terms of molecular motions for these trends.

**Part 3: (30 points) Perform two out of the four calculations given below.**

3.1) A piece of zinc (Zn) at 293K that weighs 60 grams is dropped into 200 grams of water which has a temperature of 373K. The heat capacity of Zn is 0.389 J K$^{-1}$ gm$^{-1}$ and the heat capacity of water near 373K is 4.22 J K$^{-1}$ gm$^{-1}$. Calculate the temperature reached when the Zn and water attain thermal equilibrium. Which Law of Thermodynamics guides your solution?

3.2) Four moles of an ideal monatomic gas initially at $P=10$ atm and $V=10$ L, expand reversibly until $P=1$ atm and $V=300$ L. Calculate $\Delta S$ for the gas.

3.3) The internal pressure $\left(\frac{\partial U}{\partial V}\right)_T$ measures intermolecular interactions. Calculate the internal pressure of Cu(s). Assume at $P=1$ atm and $T=298$ K the thermal expansivity $\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p = 16.5 \times 10^{-6} K^{-1}$ and the isothermal compressibility $\kappa = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T = 0.72 \times 10^{-6} bar^{-1}$.

3.4) Glucose $C_6H_{12}O_6$ is degraded to lactic acid $CH_3CH(OH)COOH$ by the net reaction

$$C_6H_{12}O_6 \rightarrow 2CH_3CH(OH)COOH$$

using the information in the table calculate $\Delta H^0$ at $T=310$ K for the conversion of glucose to lactic acid. All heats of formation are for $T=298$ K. Assume heat capacities are temperature dependent between $T=298$ K and $T=310$ K.

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\Delta H^0$ (kJ mol$^{-1}$)</th>
<th>$C_p^0$ (JK$^{-1}$ mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>-1274.45</td>
<td>218.86</td>
</tr>
<tr>
<td>Lactic Acid</td>
<td>-694.04</td>
<td>127.61</td>
</tr>
</tbody>
</table>
Part 4: (32 points). Perform one out of the two multi-step calculations.

4.1) The heat capacity of liquid ammonia is \( C_{p}^{\text{liq}} = 74.8 \text{JK}^{-1} \text{mol}^{-1} \). Ammonia boils at \( T=240 \text{K} \) at \( P=1 \text{atm} \) and has a heat of vaporization of \( \Delta H_{\text{vap}} = 23241 \text{Jmol}^{-1} \). The heat capacity of gaseous ammonia is temperature dependent and follows the empirical relationship

\[
C_{p}^{\text{gas}} = (33.6 + 29.3 \times 10^{-4} T + 21.3 \times 10^{-5} T^2) \text{JK}^{-1} \text{mol}^{-1}
\]

where \( T \) is the numerical value of the temperature in Kelvin units.

a) Calculate the enthalpy change \( \Delta H \) when 2 moles of ammonia go from the liquid state at \( T=233 \text{K} \) to ammonia gas at \( T=473 \text{K} \). Assume constant pressure of 1 atm.

b) Calculate the entropy change for ammonia when it undergoes the temperature change described in part a.

c) Assuming the surroundings in thermal contact with the ammonia are maintained at \( T=473 \text{K} \). Calculate the enthalpy and entropy changes of the surroundings.

d) Using your answers from parts a-c, calculate the entropy change of the universe.

4.2) A fuel cell is an electrochemical cell wherein a hydrocarbon (e.g. methane, propane, etc) is reacted with oxygen to form CO2 and H2O. The net chemical reaction for a propane fuel cell is:

\[
\text{CH}_3\text{CH}_2\text{CH}_3 (g) + 5\text{O}_2 (g) \rightarrow 3\text{CO}_2 (g) + 4\text{H}_2\text{O} (l)
\]

The following thermodynamic data are available for the components of the fuel cell at \( T=298 \text{K} \).

<table>
<thead>
<tr>
<th>Chemical/Property</th>
<th>( \Delta H_f^0 ) (kJ/mole)</th>
<th>( S^0 ) (J/K mole)</th>
<th>( C_p^0 ) (J/K mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane (g)</td>
<td>-103.85</td>
<td>269.91</td>
<td>73.5</td>
</tr>
<tr>
<td>Oxygen (g)</td>
<td>0</td>
<td>205.138</td>
<td>29.355</td>
</tr>
<tr>
<td>Carbon Dioxide (g)</td>
<td>-393.51</td>
<td>213.74</td>
<td>37.11</td>
</tr>
<tr>
<td>Water (l)</td>
<td>-285.83</td>
<td>69.91</td>
<td>75.29</td>
</tr>
</tbody>
</table>

a) Calculate the enthalpy \( \Delta H^0 \) and entropy \( \Delta S^0 \) changes for the propane fuel cell reaction at \( T=298 \text{K} \). Assume 1 mole of propane is converted.

b) Calculate the Gibbs energy change \( \Delta G^0 \) at \( T=298 \text{K} \). Will the fuel cell reaction be spontaneous at \( T=298 \text{K} \)? Also, what is the maximum non P/V work obtainable from the fuel cell? Assume one mole of propane is converted.

c) Calculate the change in Gibbs free energy at \( T=400 \text{K} \). What is the maximum non-PV work obtainable from the fuel cell at \( T=400 \text{K} \)? Assume the heat capacities are constant between \( T=298 \text{K} \) and \( T=400 \text{K} \).

d) At \( T=298 \text{K} \) and at \( T=400 \text{K} \), is the maximum work obtained from the fuel cell greater or less than the heat evolved by the fuel cell at constant pressure? If they are not equal, explain why they differ.