I. Multiple Choice (problems with asterisks must show work)

*1. Hess' Law: Use the standard reaction enthalpies given below to determine $\Delta H^\circ_{\text{rxn}}$ for the following reaction:

\[ 2 \text{NO}_2(g) \rightarrow 2 \text{NO}(g) + \text{O}_2(g) \quad \Delta H^\circ_{\text{rxn}} = ? \]

Given:

\[ \text{N}_2(g) + \text{O}_2(g) \rightarrow 2 \text{NO}(g) \quad \Delta H^\circ_{\text{rxn}} = 183 \text{ kJ/mol} \]

\[ -2 \left( \frac{1}{2} \text{N}_2(g) + \text{O}_2(g) \rightarrow \text{NO}_2(g) \right) \quad \Delta H^\circ_{\text{rxn}} = 33 \text{ kJ/mol} \]

A. 1.50 \times 10^2 \text{ kJ/mol}  
B. 117 \text{ kJ/mol}  
C. 333 \text{ kJ/mol}  
D. -115 \text{ kJ/mol}  
E. -238 \text{ kJ/mol}  

*2. Reaction Stoichiometry: When 20.15 g MgO is decomposed at constant pressure according to the equation below, how much heat will be transferred?

\[ 2 \text{MgO(s)} \rightarrow 2 \text{Mg(s)} + \text{O}_2(g) \quad \Delta H^\circ_{\text{rxn}} \]

\[ \Delta H^\circ_{\text{rxn}} = 0 + 0 - 2(-601.7) = 1203.4 \text{ kJ/mol} \]

A. 1.20 \times 10^3 \text{ kJ of heat is released}  
B. 6.02 \times 10^2 \text{ kJ of heat is absorbed}  
C. 6.02 \times 10^2 \text{ kJ of heat is released}  
D. 3.01 \times 10^2 \text{ kJ of heat is absorbed}  

*3. Specific Heat Capacity: What mass of ice at 0.0 °C must be added to 50.0 g H₂O at 25.0 °C to cool it to 0.0 °C? The heat of fusion of ice is 334 J°g⁻¹.

(A) 0.625 g  
(B) 3.75 g  
(C) 15.7 g  
(D) 50.0 g

\[ \Delta H_f^\circ (\text{g}) = -m \cdot c_w \cdot \Delta T \]

\[ \Delta H_f^\circ (\text{g ice}) = -(75.0 \text{ g})(4.184 \text{ J/°C})(0.0-25.0) \]

4. The enthalpy change, $\Delta H_{\text{rxn}}$, of a process is defined as:

A. The maximum amount of useful work that can be done in a system.  
B. The increase or decrease in temperature in a system.  
C. The quantity of heat transferred in or out of a system as it undergoes a change at constant pressure.  
D. The change in molecular disorder in a system.

5. $\Delta H^\circ$ to $\Delta H_{\text{rxn}}$: What is $\Delta H_{\text{rxn}}$ for the reaction shown?

\[ 2 \text{H}_2\text{S(g)} + 3 \text{O}_2(g) \rightarrow 2 \text{H}_2\text{O}(l) + 2 \text{SO}_2(g) \]

\[ \Delta H^\circ_{\text{rxn}} = [2 \cdot (-296.4)] + [2 \cdot (-20.15)] - \text{[2 \cdot (-20.15) + 3 (0)]} \]

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\Delta H^\circ_{\text{rxn}}$ (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂S(g)</td>
<td>-20.15</td>
</tr>
<tr>
<td>H₂O(l)</td>
<td>-285.8</td>
</tr>
<tr>
<td>SO₂(g)</td>
<td>-296.4</td>
</tr>
</tbody>
</table>

(A) -19.4 kJ mol⁻¹  
(B) -374.7 kJ mol⁻¹  
(C) -562.1 kJ mol⁻¹  
(D) -1124.1 kJ mol⁻¹
6. For which of the following substances does $\Delta H_f = 0$? Or asked another way, which of these substances is the lowest energy form of an element?
A. CO$_2$(g)  
B. H$_2$O(g)  
C. Na(s)  
D. Br$_2$(g)  
E. C(diamond)

7. The dissolution of barium hydroxide in water is an exothermic process. Which of the following statements is correct?
A. The entropy of solid barium hydroxide plus pure water is less than that of the solution, at the same temperature.  
B. The entropy of solid barium hydroxide plus pure water is greater than that of the solution, at the same temperature.  
C. The entropy of solid barium hydroxide plus pure water is the same as that of the solution, at the same temperature.  
D. The temperature of the solution is lower than of the barium hydroxide and water before mixing.  
E. When barium hydroxide dissolves in water, the system does work on the surroundings

8. A function whose value depends only on its initial and final conditions is called a state function. Two examples of state functions in chemistry are:
A. $\Delta U$ and $\Delta H$  
B. work and heat  
C. $\Delta H$ and work  
D. $\Delta H$ and heat  
E. CA and MD

II. Short Answer (show work for all problems)
1. Use standard enthalpies of formation from the equation sheets or the back of your book to calculate $\Delta H_f^{\circ}$ for each reaction. Then draw a Reaction Energy diagram for each reaction using "Reaction Progress on the x-axis and Potential Energy on the y-axis.
Label $\Delta H_f^{\circ}$, reactants and products on each diagram.
A. $2\text{H}_2\text{S}(g) + 3\text{O}_2(g) \rightarrow 2\text{H}_2\text{O}(g) + 2\text{SO}_2(g)$

\[ \Delta H_f^{\circ} = -20.0 \quad 0 \quad -241.8 \quad -296.8 \]

B. $\text{SO}_2(g) + \frac{1}{2}\text{O}_2(g) \rightarrow \text{SO}_3(g)$

\[ \Delta H_f^{\circ} = -296.8 \quad 0 \quad -398.2 \]

\[ \Delta H_f^{\circ} = -398.2 - [(-296.8 + 0)] = -98.4 \text{ kJ/mol} \]

C. $\text{N}_2(g) + 4\text{H}_2\text{O}(g) \rightarrow \text{N}_2\text{O}_4(g) + 4\text{H}_2(g)$

\[ \Delta H_f^{\circ} = 0 \quad -241.8 \quad 11.1 \quad 0 \]

\[ \Delta H_f^{\circ} = 11.1 + 4(0) - [0 + 4(-241.8)] = 978.3 \text{ kJ/mol} \]
3. **Heat exchange between two materials:** A 9 g gold ring initially at 100.0°C is submerged into 45.43 g of water at 21.6°C in a coffee cup calorimeter. What is the final temperature of both substances at thermal equilibrium—when all temperature changes are complete and the final temperature of the pure gold and water are equal?

\[
\begin{align*}
q_{\text{ring}} &= -q_{\text{water}} \\
M_{\text{ring}} c_{S, \text{ring}} (\Delta T_{\text{ring}}) &= -M_w c_{S, w} \Delta T_w \\
(9.00g)(0.129 \frac{J}{g^\circ C})(T_f - 100.0^\circ C) &= -(45.43g)(\frac{1.184 \frac{J}{g^\circ C}}{\text{g}^\circ C})(21.6^\circ C)
\end{align*}
\]

Thought process: the product of these numbers is a lot less than these. So the final \( T_f \) must be much closer to 21.6°C than 100°C.

\[
1.161T_f - 116.1 = -(190.1T_f - 4106) \\
191.3T_f = 4222 \\
T_f = 22.1^\circ C
\]

4. **Heat exchange between a solution and a reaction:** When 22.3 mL of 1.00 M AgNO₃ is mixed with 21.7 mL of 1.50 M NaCl, the temperature of the mixture rises from 21.6°C to 29.7°C. Assume the properties of water for \( C_p \) and density.

A. Write the balanced overall and net ionic equation for the reaction that occurred.

overall: \( \text{AgNO}_3(aq) + \text{NaCl}(aq) \rightarrow \text{AgCl(s)} + \text{NaNO}_3(aq) \)

NIE: \( \text{Ag}^+(aq) + \text{Cl}^-(aq) \rightarrow \text{AgCl(s)} \)

B. Calculate \( \Delta H^\circ \) for the reaction you wrote in part A using the data in the problem statement.

\[
\begin{align*}
q_{\text{rxn}} &= -q_{\text{solv}} \\
\Delta H_{\text{rxn}} \text{ (mol reacted)} &= -M_{\text{solv}} C_p, \text{solv} \Delta T_{\text{solv}} \\
\text{Find mol reacted: find LR} \\
\boxed{0.0223 \text{ L} 1.00 \text{ mols AgNO}_3 \text{ in 1 L soln}} &= \boxed{0.0223 \text{ mol}} \boxed{0.0217 \text{ L} 1.50 \text{ mols NaCl} = 0.0326} \\
\text{LR (all stoichiometry is 1:1:1:1)} \\
\Delta H_{\text{rxn}} (0.0223 \text{ mol}) &= -(44.0 \text{ g})(4.184 \frac{J}{g^\circ C})(29.7 - 21.6) \\
\Delta H_{\text{rxn}} &= 6.69 \times 10^4 \frac{J}{\text{mol}} = 66.9 \text{ kJ/mol}
\end{align*}
\]
5. **Heat exchange between water and a reaction**: Dry ice is solid carbon dioxide. Instead of melting, solid carbon dioxide sublimes according to the equation,

\[ \text{CO}_2(s) \rightarrow \text{CO}_2(g) \]

Last night when I was out clubbing, I went back stage to see how their fog machine worked. It turns out that the entire fog machine was comprised of 10.0 L of water at 75.0°C, some dry ice, a fan and some tubing. When dry ice is put into the hot water, the dry ice sublimes to \( \text{CO}_2(g) \). The \( \text{CO}_2(g) \) and some \( \text{H}_2\text{O}(g) \) form fog that then gets blown by the fan through the tubing.

Assuming no heat loss to the surroundings (all of the heat lost by the water cooling goes to sublimate the dry ice), I immediately calculated the grams of dry ice that were needed to exactly cool the water from 75.0°C to 25.0°C. I needed to recall that \( \Delta H^\circ_r \) for \( \text{CO}_2(s) \rightarrow \text{CO}_2(g) \) is -427.4kJ/mol (I always go out with Tru, but even the text didn't have this piece of info).

A. What is \( \Delta H^\circ_m \) for the sublimation of \( \text{CO}_2 \)? You'll need \( \Delta H^\circ_r \) for \( \text{CO}_2(g) \) from the “pink sheets”.

\[ \Delta H^\circ_r \rightarrow \text{CO}_2 \rightarrow \text{CO}_2(g) \]
\[ \Delta H^\circ_r = -427.4 \text{ kJ/mol} \]

\[ \Delta H^\circ_m = \frac{3.39 \text{ kJ}}{\text{mol}} \]

B. How many grams did I calculate?

\[ \Delta H^\circ_m = -9 \text{ water} \]
\[ \Delta H^\circ_f (\text{mol reacted}) = - M \text{ water} C_s, \text{ water} \Delta T \text{ water} \]
\[ 33.900 \times \frac{1}{\text{mol}} \text{ (mol CO}_2) = -(10,000 \text{ g}) \times (4.18 \times \frac{1}{\text{g} \cdot \text{°C}}) (75.0 - 25.0) \]
\[ \text{mol CO}_2 = 61.7 \text{ mol CO}_2 \times \frac{44.01 \text{ g CO}_2}{1 \text{ mol CO}_2} = 2.72 \times 10^3 \text{ g CO}_2 \]

C. How many L of \( \text{CO}_2 \) gas at 1 atm and 22°C would be created?

\[ V = \frac{n \text{ CO}_2 RT}{P_{\text{CO}_2}} = \frac{(61.7 \text{ mol})(0.08206 \text{ L atm/mol K})(295 \text{ K})}{1 \text{ atm}} \]
\[ V = 1.49 \times 10^3 \text{ L CO}_2(g) \]
6. Using Hess' Law calculate $\Delta H_{rxn}^\circ$ for the reaction:

$$5\text{ C(s)} + 6\text{ H}_2(\text{g}) \rightarrow \text{C}_5\text{H}_12(\text{l})$$

given the following reactions and $\Delta H_{rxn}^\circ$ values:

$$-1\left( \begin{array}{c}
\text{ C}_3\text{H}_8(\text{g}) + 8\text{ O}_2(\text{g}) \rightarrow 5\text{ CO}_2(\text{g}) + 6\text{ H}_2\text{O}(\text{g}) \\
5\text{ C(s)} + \text{ O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g}) \\
3\text{ H}_2(\text{g}) + \text{ O}_2(\text{g}) \rightarrow 2\text{ H}_2\text{O}(\text{g})
\end{array} \right) \quad \Delta H_{rxn}^\circ = -3505.8 \text{ kJ/mol}$$

$$\begin{array}{c}
5\text{ CO}_2(\text{g}) + 5\text{ H}_2(\text{g}) \rightarrow \text{C}_5\text{H}_12(\text{l}) + 8\text{ O}_2(\text{g}) \\
5\text{ C(s)} + 5\text{ O}_2(\text{g}) \rightarrow 5\text{ CO}_2(\text{g}) \\
6\text{ H}_2(\text{g}) + 3\text{ O}_2(\text{g}) \rightarrow 6\text{ H}_2\text{O}(\text{g})
\end{array} \quad \begin{array}{c}
\Delta H_{rxn}^\circ = 3505.8 \text{ kJ/mol} \\
\Delta H_{rxn}^\circ = -1967.5 \\
\Delta H_{rxn}^\circ = -1450.5
\end{array}$$

$$\begin{array}{c}
5\text{ C(s)} + 6\text{ H}_2(\text{g}) \rightarrow \text{C}_5\text{H}_12(\text{l}) \\
\Delta H_{rxn}^\circ = 87.8 \text{ kJ/mol}
\end{array}$$

7. Write out $\Delta H^\circ$ reactions (with $\Delta H^\circ$ values) for each of the following materials. Determine the oxidation numbers of each element and determine what (if anything) has been oxidized and reduced.

A. AgCl(s)

$$\text{Ag(s)} + \frac{1}{2}\text{Cl}_2(\text{g}) \rightarrow \text{AgCl(s)}$$

$\Delta H^\circ_{rxn} = 0$

B. H$_3$O(ℓ)

C. P(ℓ(g))
8. **Stoichiometry involving energy:** Liquid hydrogen peroxide, a component of many rocket fuel mixtures, releases oxygen gas on decomposition. A rocket contains, say, $3.00 \times 10^3$ kg of liquid hydrogen peroxide.

$$
2 \text{H}_2\text{O}_2(\ell) \rightarrow 2 \text{H}_2\text{O}(\ell) + \text{O}_2(g) \quad \Delta H_{\text{rxn}} = -196.1 \text{ kJ/mol}
$$

A. How much energy is released if all of the hydrogen peroxide is reacted?

\[
\frac{3.00 \times 10^3 \text{ kg H}_2\text{O}_2}{1 \text{ kg}} \times \frac{1000 \text{ g H}_2\text{O}_2}{1 \text{ kg}} \times \frac{1 \text{ mol H}_2\text{O}_2}{34.02 \text{ g H}_2\text{O}_2} \times \frac{-196.1 \text{ kJ}}{2 \text{ mol H}_2\text{O}_2} = 1.7 \times 10^7 \text{ kJ}
\]

B. How many liters of oxygen gas are released if all of the hydrogen peroxide is reacted? Assume atmospheric conditions of 1 atm and 25°C.

\[
\frac{3.00 \times 10^3 \text{ kg H}_2\text{O}_2}{1 \text{ kg}} \times \frac{1000 \text{ g H}_2\text{O}_2}{1 \text{ kg}} \times \frac{1 \text{ mol H}_2\text{O}_2}{34.02 \text{ g H}_2\text{O}_2} \times \frac{1 \text{ mol O}_2}{2 \text{ mol H}_2\text{O}_2} = 4.41 \times 10^4 \text{ mol O}_2
\]

\[
V = \frac{nRT}{P} = \frac{(4.41 \times 10^4 \text{ mol})(2)(298 \text{ K})}{1 \text{ atm}} = 1.1 \times 10^6 \text{ L}
\]

9. **PV Work:** How much work will be done in Joules when a piston expands from a volume of 13.27 L to a volume of 76.55 L against a pressure of 14.89 atm?

\[
W = -P \Delta V
\]

\[
= -(14.89 \text{ atm})(76.55 \text{ L} - 13.27 \text{ L})
\]

\[
= -942 \text{ L atm}
\]

\[
\frac{-942 \text{ L atm}}{1 \text{ L atm}} \times \frac{101.325 \text{ J}}{1 \text{ L atm}} = 9.54 \times 10^4 \text{ J}
\]

\[
= 95.4 \text{ kJ}
\]
10. PV Work:
A. How much work in Joules does it take to pump a bicycle pump if the initial volume is 4 L, the final volume is 0.2 L, and you apply 20 atmospheres of pressure to compress the pump in one step? The initial pressure is 1 atm.

\[ 1 \text{ L} \cdot \text{atm} = 101.325 \text{ J} \]

\[
W = -P \Delta V
= -20 \text{ atm} (0.2 \text{ L} - 4.0 \text{ L})
= \frac{76 \text{ L} \cdot \text{atm}}{1 \text{ L} \cdot \text{atm}}
= 7.7 \times 10^3 \text{ J}
= 7.7 \text{ kJ}
\]

B. From lecture, you remember that the amount of work is path-dependent, and being lazy as all good scientists are, you decide to see if it takes less work to compress the pump in two steps:

i. Step 1: compress at 4 atm. You’ll need to calculate the volume at this pressure.

ii. Step 2: compress at 20 atm.

How much work total is needed for these two steps?

i. \[ P_1V_1 = P_2V_2 \]
\[(1 \text{ atm})(4 \text{ L}) = (4 \text{ atm})V_2 \quad V_2 = 1 \text{ L} \]

\[ W_i = -P \Delta V = -4 \text{ atm} (1 \text{ L} - 4 \text{ L}) = +12 \text{ L} \cdot \text{atm} \]

ii. \[ P_1V_1 = P_2V_2 \]
\[(4 \text{ atm})(1 \text{ L}) = (20 \text{ atm})V_2 \quad V_2 = 0.2 \text{ L} \]

\[ W_{ii} = -P \Delta V = -20 \text{ atm} (0.2 \text{ L} - 1 \text{ L}) = 16 \text{ L} \cdot \text{atm} \]

\[ W_{\text{total}} = W_i + W_{ii} = 12 + 16 \text{ L} \cdot \text{atm} = 28 \text{ L} \cdot \text{atm} \]
\[ = 2.8 \times 10^3 \text{ J} \]
11. **PV Work**: “Wack-A-Pack” balloons inflate when you whack them. Inside each balloon are citric acid ($H_3C_6H_5O_7$), sodium bicarbonate ($NaHCO_3$), and water. The balloon has a volume of 266 mL when fully inflated. The temperature is 22.0°C and the atmospheric pressure is 754 mm Hg. If there are 0.50g of citric acid and 3.50g sodium bicarbonate are inside the balloon with 5 mL of water:

$$H_3C_6H_5O_7(aq) + 3 NaHCO_3(aq) \rightarrow Na_3C_6H_5O_7(aq) + 3 CO_2(g) + 3 H_2O(l)$$

A. What is the pressure inside the balloon after the reaction is over?
B. How much PV work is done as the balloon inflates? State any assumptions that are necessary to complete the calculation.

\[ \text{To find pressure, must find mol CO}_2 \text{ then } P_V = nRT \]

\[
\frac{2.00g \text{H}_3\text{C}_6\text{H}_5\text{O}_7}{192.12g \text{H}_3\text{C}_6\text{H}_5\text{O}_7} \cdot \frac{1mol \text{H}_3\text{C}_6\text{H}_5\text{O}_7}{3mol \text{CO}_2} = 0.0312 \text{ mol CO}_2
\]

\[
\frac{2.50g \text{Na}_2\text{CO}_3}{84.01g \text{Na}_2\text{CO}_3} \cdot \frac{1mol \text{Na}_2\text{CO}_3}{3mol \text{CO}_2} = 0.0298 \text{ mol CO}_2
\]

\[ P_{CO_2} = \frac{n_{CO_2}RT}{V} \]

\[ P_{CO_2} = \frac{(0.0298 \text{ mol})(0.08206 \text{ atm}L/K \cdot \text{mol})}{0.266 \text{ L}} = 2.71 \text{ atm} \]

12. Given the following chemical reactions and their enthalpies: (8 points)

\[
\begin{align*}
2 \text{C}_2\text{H}_2(g) + 5 \text{O}_2(g) &\rightarrow 4 \text{CO}_2(g) + 2 \text{H}_2\text{O}(l) & \Delta H_{\text{rxn}} &= -2599 \text{ kJ/mol} \\
2 \text{C}_2\text{H}_4\text{O}(g) + 5 \text{O}_2(g) &\rightarrow 4 \text{CO}_2(g) + 4 \text{H}_2\text{O}(l) & \Delta H_{\text{rxn}} &= -2385 \text{ kJ/mol} \\
\end{align*}
\]

Calculate $\Delta H_{\text{rxn}}$ for the following reaction:

\[ \text{C}_2\text{H}_2(g) + \text{H}_2\text{O}(l) \rightarrow \text{C}_2\text{H}_4\text{O}(g) \]

Then draw a reaction energy diagram for this reaction making sure to label the axes, reactants, products and the change in the standard enthalpy of reaction.

B. $W = -P \Delta V$

Assume bag inflates at a constant pressure of 2.71 atm and bag had zero volume before rxn.

\[ W = -2.71 \text{ atm} \cdot (0.266 \text{ L} - 0 \text{ L}) = 0.721 \text{ L \cdot atm} \]

\[ = 73.0 \text{ J} \]