Objective 11. Predict heat and work in physical and chemical reactions.
Key ideas: Energy is involved in every physical and chemical process. Use in heating or cooling. See hot and cold packs.
Heat = amount of energy transferred due to a difference in T
Heat gained by cold object = - heat lost by hot object
Physical heat transfer: $q = ms\ \Delta T$
Chemical heat transfer: $q = \Delta H$
Calculate ΔH using Hess' law: $\Delta H = \Sigma\ n\ \Delta H_f$ (products) – $\Sigma\ n\ \Delta H_f$ (reactants)
In a chemical reaction, bonds break (endothermic) and form (exothermic) ==> balance determines ΔH
Chem 1A: gases are compressible so you can use gas expansion to produce work or you have to supply work to compress a gas. Work = $w = -p\ \Delta V$
1st law of thermodynamics: $\Delta E = q + w$. Internal energy can be converted to heat or work or both (energy can be neither created nor destroyed).

Practice Problem solutions:
When a substance gets hotter or colder (physical heat transfer), use $q = m\ s\ \Delta T$.
When a chemical reaction occurs, heat is gained or lost (chemical heat transfer). Use $q = \Delta H$.
When a hot object touches a cold object, heat is transferred:
heat gained by the cold object = - heat lost by the hot object.

1. Agree or disagree with the following statements. Give reasons to support your answer.
a. Temperature measures the amount of heat.
b. Your put your hand in cold water. Your hand gains heat and the water loses heat.
c. You can cool yourself on a hot day by pouring warm water on yourself and letting it evaporate. What loses heat?
d. You feel colder when you stand in 60°F air than when you sit in 60°F water.

Answers:
a. Disagree. Temperature measures the average kinetic energy of a substance (how fast the atoms/molecules in the substance move). Heat is related to temperature by $q = m\ s\ \Delta T$.
b. Disagree. Your hot hand loses heat to the cold water, which gains heat.
c. Agree. As long as the water you pour on yourself is cooler (lower temperature) than you, the water gains heat while you lose heat.
d. Disagree. Air has a lower specific heat and lower mass (air is a gas) than water (liquid) so more heat is transferred from your warm self to the water than to the air.

2. You add 1 cup (240 ml) of hot (T = 75°C) water to 1 cup (240 ml) of cold (T = 15°C) water. The final temperature is 45°C.
a. The hot water loses 30,100 J of heat. Is this a physical or chemical heat transfer? What formula or equation do you want to use to calculate heat? Show how to calculate this heat.
b. How much heat is gained by the cold water?
c. You know that the heat gained by the cold object = - heat lost by the hot object.
Or $m_{hot}\ s_{hot}\ (T_f - T_{ihot}) = -\ m_{cold}\ s_{cold}\ (T_f - T_{icold})$
Confirm the final temperature is 45°C by substituting the numerical masses, specific heats, and T_i's and then solving for T_f.

Answers:
a. physical heat transfer. $q = m\ s\ \Delta T = (240\ g\ H_2O)(4.18\ J/g\ ^oC)(45^oC - 75^oC) = -30{,}100\ J$. Note: 240 ml water = 240 g water since density of water = 1 g/ml.
b. Cold water gains 30,100 J because hot water loses -30,100 J. (heat gained by cold water = - heat lost by hot water)
c. $m_{hot}\ s_{hot}\ (T_f - T_{ihot}) = -\ m_{cold}\ s_{cold}\ (T_f - T_{icold})$
$(240\ g\ H_2O)(4.18\ J/g\ ^oC)(T_f - 75^oC) = -\ (240\ g\ H_2O)(4.18\ J/g\ ^oC)(T_f - 15^oC)$
$T_f = 45^oC$

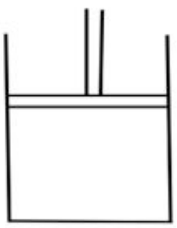
3. When salt dissolves in water, the reaction is endothermic ($NaCl\ (s) \rightarrow Na^+\ (aq) + Cl^-\ (aq)$, ΔH = 4.1 kJ/mole).
a. The water ______ (gains or loses) heat.
b. The chemical reaction ($NaCl\ (s) \rightarrow Na^+\ (aq) + Cl^-\ (aq)$) _______ (loses/gains) heat. Confirm your answer by calculating ΔH using Hess' law.
c. The temperature of the water will _______ (rise/fall/stay the same).
d. NaCl can be used in a ______ (hot/cold) pack.
e. 30 g of NaCl is dissolved in 100 g of water at 25°C. The final temperature of the water is 19.9°C.
You know: heat gained by _____ = - heat lost by _______.
When a substance gets hotter or colder (physical heat transfer), use $q = m\ s\ \Delta T$. Should you use this equation for the water or NaCl dissolving in water?

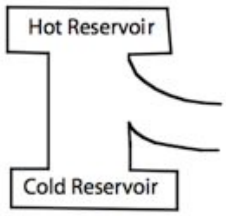
When a chemical reaction occurs, heat is gained or lost (chemical heat transfer). Use $q = \Delta H$. Should you use this equation for the water or NaCl dissolving in water?
Show how the final temperature is calculated.
Answers:
a. water loses heat.
b. $NaCl (s) \rightarrow Na^+ (aq) + Cl^- (aq)$ gains heat. Confirm your answer by calculating ΔH using Hess' law.
ΔH_f, kJ/mole -411 -239.7 -167.2
$\Delta H = \Sigma n \Delta H_f$ (products) – $\Sigma n \Delta H_f$ (reactants) = [(-239.7) – (-167.2)] – [-411] = 4.1 kJ/mole ==> endothermic (heat gained)
c. The temperature of the water will fall.
d. NaCl can be used in a cold pack.
e. 30 g of NaCl is dissolved in 100 g of water at 25°C. The final temperature of the water is 19.9°C.
You know: heat gained by NaCl dissolving in water reaction = - heat lost by water
When a substance gets hotter or colder (physical heat transfer), use $q = m s \Delta T$. Should you use this equation for the water or NaCl dissolving in water? Use for water.
When a chemical reaction occurs, heat is gained or lost (chemical heat transfer). Use $q = \Delta H$. Should you use this equation for the water or NaCl dissolving in water? Use for NaCl dissolving in water
Show how the final temperature is calculated.
heat gained by NaCl dissolving in water reaction = - heat lost by water
4.1 kJ/mole (1000 J/1 kJ)(1 mole/58.5 g)(30 g NaCl) = - (100 g H_2O)(4.18 J/g °C)(T_f – 25°C)
Solve for T_f = 19.9°C

4. Work is the ability to move matter. In chemistry, work is produced or supplied by a gas (not a liquid or solid):
$w = - p \Delta V$. Recall $\Delta V = V_f - V_i$.
When $w > 0$, work is supplied (you have to supply work on a gas).
When $w < 0$, work is produced (a gas produces work).
a. When a gas expands, is V_f >, =, or < than V_i? Is w >, =, or < than 0?
b. When a gas is compressed, is V_f >, =, or < than V_i? Is w >, =, or < than 0?
c. You have a flat tire. You pump air into the tire. Is work produced or supplied? State whether ΔV is > 0, < 0, or = 0 to support your answer. What volume is changing?
d. You pump too much air into your tire. You open the valve to let some air out. Is the air expanding or compressing as it leaves the tire? Is work produced or supplied? State whether ΔV is > 0, < 0, or = 0 to support your answer. What volume is changing?
e. Person blows up balloon. How can a balloon be used to produce work? What volume is changing?
f. Some chemical reactions involve gases. This means a chemical reaction can be used to produce work. To determine whether a reaction produces work, write a balanced chemical equation and compare the moles of gas reactants to gas products.
If the moles of gas products > moles of gas reactants, Δn = moles of gas products - moles of gas reactants is greater than 0. Since n is directly proportional to V according to the ideal gas equation ($PV = nRT$), if $\Delta n > 0$, then $\Delta V > 0$, so $w < 0$. This reaction produces work.
If the moles of gas products < moles of gas reactants, Δn = moles of gas products - moles of gas reactants is ______ than 0. Since n is directly proportional to V according to the ideal gas equation ($PV = nRT$), if Δn ___ 0, then ΔV _____ 0, so w ___ 0. This reaction ______ work.
If the moles of gas products = moles of gas reactants, will a chemical reaction produce work?
Answers:
a. When a gas expands, is V_f > than V_i. w is < than 0.
b. When a gas is compressed, V_f < than V_i. w is > than 0.
c. You have a flat tire. You pump air into the tire. Work is supplied.
ΔV is < 0. The volume of air in the pump is changing (getting compressed) when air is pumped from the pump into the tire.
d. You pump too much air into your tire. You open the valve to let some air out.
The air is expanding as it leaves the tire.
Work is produced.
ΔV is > 0. The volume air outside the tire is changing (expanding) as it exits the tire.
e. Person blows up balloon. A balloon be used to produce work if the balloon is expanding against something. The volume of the balloon is changing (expanding).
f. Some chemical reactions involve gases. This means a chemical reaction can be used to produce work. To determine whether a reaction produces work, write a balanced chemical equation and compare the moles of gas reactants to gas products.

If the moles of gas products > moles of gas reactants, Δn = moles of gas products - moles of gas reactants is greater than 0. Since n is directly proportional to V according to the ideal gas equation (PV = nRT), if $\Delta n > 0$, then $\Delta V > 0$, so $w < 0$. This reaction produces work.
If the moles of gas products < moles of gas reactants, Δn = moles of gas products - moles of gas reactants is less than 0. Since n is directly proportional to V according to the ideal gas equation (PV = nRT), if Δn __less than _ 0, then ΔV __ less than __ 0, so w _greater than__ 0. This reaction __does not produce_ work. Work is supplied to this reaction.
If the moles of gas products = moles of gas reactants, will a chemical reaction produce work?
No. $\Delta n = 0$, then $\Delta V = 0$, so $w = 0$.

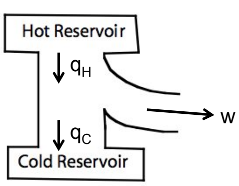
5. Two diagrams of a car engine are shown below.





Heat Engine schematic

car engine cylinder and piston
Describe how a heat engine works by answering the following questions.
a. What chemical reaction occurs inside the car engine cylinder? Identify the fuel that is used and its chemical formula. Then, write the chemical equation that represents this reaction.
b. Is this reaction exothermic or endothermic? (What formula or equation do you want to use to help you answer this question?)
c. Does this reaction produce work? (See Question 4f.)
d. What is the function of the fuel in a heat engine?
e. In the heat engine schematic diagram, what occurs in the hot reservoir? In the diagram, label q_H (heat to or from the hot reservoir), q_C (heat to or from the cold reservoir), and w (work). Show the direction of the heat flow and work with an arrow.
f. Is all of the heat produced in the hot reservoir converted to work? (If all the heat is converted to work, the efficiency is 100%. Is a car engine 100% efficient?)
Answers:
a. Combustion reaction: fuel + O_2 --> CO_2 + H_2O
Gasoline is a mixture of many substances. A major component is octane, C_8H_{18}.
2 C_8H_{18} + 25 O_2 --> 16 CO_2 + 18 H_2O
b. Combustion reactions are exothermic. Use Hess' law to calculate ΔH of reaction.
c. Octane combustion produces work.
2 C_8H_{18} (l) + 25 O_2 (g) --> 16 CO_2 (g) + 18 H_2O (g)
25 moles gas reactants ---> 34 moles gas products so $\Delta n > 0$, which means $\Delta V > 0$ and $w < 0$.
d. Fuel produces heat and work.
e. Hot reservoir = combustion reaction



f. Not all of the heat produced in the hot reservoir is converted to work.
Efficiency = output/input = work produced/heat from hot reservoir
Gas engine efficiency = 20%

6. Consider the four fuels in the table below.
Table. Heats of Combustion of Four Fuels.

Fuel	Molar Mass	$\Delta H_{combustion}$, kJ/mole	$\Delta H_{combustion}$, kJ/g	Work (>0, =0, <0)
H_2 (hydrogen)	2	-285	-143	
CH_4 (natural gas)	16	-802	-50.1	

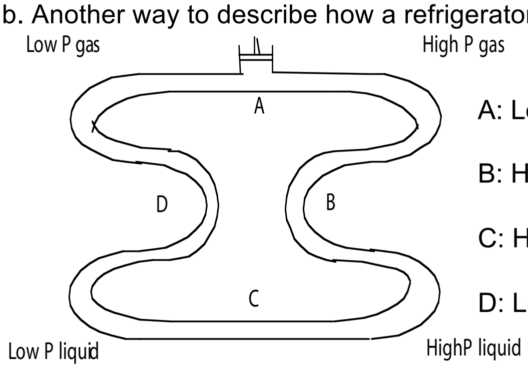
C_8H_{18} (octane in gasoline)	114	-5074	-44.5	
C_2H_5OH (ethanol)	46	-1234	-26.8	

a. Name one property of a fuel.
b. Show how to convert $\Delta H_{combustion}$ from kJ/mole to kJ/g. Which fuel produces the most heat per gram?
c. Fill in the Work column in the Table.
d. Hydrogen is not a good fuel for an internal combustion car engine. Explain why.
e. Honda makes a car that runs on natural gas. Based on work, is natural gas a good fuel for an internal combustion car engine? Give reasons.
f. Which is the best fuel for a car engine? Give reasons.
Answers:
a. fuel combustion reaction is exothermic (produces heat) and produces work. This reaction should be fast – want the fuel to explode against piston in engine to produce power (amount of energy produced per time).
b. $\Delta H_{combustion}$ in kJ/mole x (1 mole/ molar mass of fuel) = kJ/g.
Example for H_2: $\Delta H_{combustion}$ = -285 kJ/mole x (1 mole H_2/ 2 g H_2) = -143 kJ/g H_2 that reacts.
c. Steps: 1. Write a balanced combustion reaction equation.
2. Compare moles of gas reactants to gas products to determine whether Δn is > 0, = 0, or < 0.
3. Δn is directly proportional to ΔV.
4. use $w = -p\Delta V$ to determine sign of w. w > 0 means work needs to be supplied (absorbed) to reaction. w < 0 means work is produced by reaction.
$2 H_2 (g) + O_2 (g) \rightarrow 2 H_2O (g)$ 3 moles gas reactants --> 2 moles gas products, $\Delta n < 0$, $\Delta V < 0$, $w > 0$
$CH_4 (g) + 2 O_2 (g) \rightarrow CO_2 (g) + 2 H_2O (g)$ $\Delta n = 0$, $\Delta V = 0$, $w = 0$
$2 C_8H_{18} (l) + 25 O_2 (g) \rightarrow 16 CO_2 (g) + 18 H_2O (g)$ $\Delta n > 0$, $\Delta V > 0$, $w < 0$
$C_2H_5OH (l) + 3 O_2 (g) \rightarrow 2 CO_2 (g) + 3 H_2O (g)$ $\Delta n > 0$, $\Delta V > 0$, $w < 0$
d. Hydrogen is not a good fuel for an internal combustion car engine because this fuel does not produce work.
e. Natural gas, CH_4, is not a good fuel for an internal combustion car engine because this fuel does not produce work.
f. Of the four fuels in the table, C_8H_{18} is the best fuel because it produces the most heat per gram of fuel and most work.

7. Methyl tert-butyl ether (MTBE, $CH_3OC_4H_9$, ΔH_f = -315 kJ/mole) and ethanol (C_2H_5OH) are used as fuel additives to help oxygenate gasoline. MTBE was found to leak into ground water supplies where it is a health hazard.
a. Which fuel produces the most heat per gram of fuel burned? Show your calculations to support your answer.
b. Which fuel produces the most work? Give reasons.
Answers:
$2 CH_3OC_4H_9 (l) + 15 O_2 (g) \rightarrow 10 CO_2 (g) + 12 H_2O (g)$ $\Delta n > 0$, $\Delta V < 0$, $w < 0$. MTBE produces more work.
ΔH_f ($CH_3OC_4H_9$ (l)) = -315 kJ/mole
ΔH_f combustion reaction = -3100 kJ/mole x (1 mole / 88 g) = -35 kJ/g. MTBE produces more heat per g.

$C_2H_5OH (l) + 3 O_2 (g) \rightarrow 2 CO_2 (g) + 3 H_2O (g)$ $\Delta n > 0$, $\Delta V < 0$, $w < 0$
ΔH_f combustion reaction = -1234 kJ/mole x (1 mole / 46 g) = -26.8 kJ/g

8. A refrigerator is a heat engine in reverse. Describe how a refrigerator works.
a. Draw a schematic diagram (see the heat engine schematic diagram in Question 5) that shows heat in, heat out, and work.
b. Another way to describe how a refrigerator works is shown below:



A: Low P gas --> High P gas

B: High P gas --> High P liq

C: High P liq --> Low P liq

D: Low P liq --> Low P gas

The phase changes the refrigerant undergoes in a refrigerator cycle are shown in the diagram.
(i) For each step (A through D), determine whether the step is exothermic or endothermic.

Example: Step B: high P gas --> high P liquid. Gas to liquid phase change is condensation. Heat has to be removed (lost or released) to condense a gas to a liquid so this step is exothermic. The coils in the back of your refrigerator condense the gas refrigerant to a liquid so the air around the coils feels warm. Carefully put your hand next to the coils to feel the warm air.

(ii) For each step (A through D), determine whether work is produced or supplied.

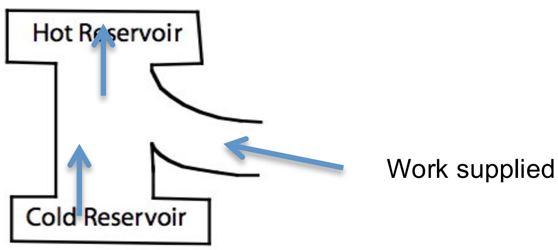
Example: Step B: high P gas --> high P liquid. See Question 4. Work = - p ΔV. Volume is proportional to moles to compare moles of gas reactants to moles of gas products. Δn = moles of gas products - moles of gas reactants so Δn = -1 so ΔV < 0 so w > 0. Work is supplied to condense a gas to a liquid.

(iii) In the schematic diagram of a refrigerator, circle the section that acts as the cold reservoir. Explain how this section works as the cold reservoir.

(iv) How is air cooled inside the refrigerator?

Answers:

a. Work is supplied to the refrigerator's compressor in Step A. Heat in is the heat gained by the refrigerant in Step D (evaporator). Heat out is the heat lost by the refrigerant in Step B (condenser).



b.

Step	q (>0, =0, <0)	Work (>0, =0, <0)
A: low P gas --> high P gas	=0	>0. gas is compressed (ΔV < 0) so work is required
B: high P gas --> high P liquid	<0 condensation is exothermic	>0, Δn < 0, ΔV < 0 so work is required
C: high P liquid --> low P liquid	=0	=0
D: low P liquid --> low P gas	>0 evaporation is endothermic	<0. Δn > 0, ΔV > 0 means expansion so work is produced

(iii) Step D is the cold reservoir where the air inside the refrigerator is cooled.

(iv) In Step D, Heat is gained by the refrigerant to evaporate it. Heat is lost by the air inside the refrigerator. So heat is transferred from the air to the refrigerant.