Chapter 3: Thermodynamics of Biological Systems

Slide 2

Energy and Work

• Work = force x distance
• Energy = ability to do work
• Mechanical Energy
  • Kinetic Energy = \( \frac{1}{2}mv^2 \)
    • (Energy from motion)
  • Potential Energy
    • (Energy from attraction or repulsion)

Both Work and Energy are products of intensive and extensive factors: force x distance (mechanical work) pressure x volume change (work of expansion) voltage x current (electrical work) etc.

One of the triumphs of the energy concept was the recognition that there is a relationship between heat and work.

Experiments of Joule showed mechanical work (turning a paddle wheel) could heat water just as an electrical heater could, showing the connection between heat and work. An earlier idea viewed heat as a caloric, some substance that flowed from one body to another. The Calorie (with a capital C), a familiar term in measuring energy content of food substances, is actually one kilocalorie.
Energy and Work, con’t.

• Internal Energy (E or U)
  • An inherent property of matter
  • Independent of any microscopic interpretation of matter, but
  • Interpreted in terms of kinetic and potential energy of atoms and electrons.

Thermodynamics Studies Energy Change $\Delta E$ (or $\Delta U$)

• System and Surroundings
• Isolated Systems (See Figure 3.1)
  • No exchange between system and surroundings
• Closed Systems (See Figure 3.1)
  • Heat exchange and work exchange between system and surroundings (note book error)
• Open Systems (See Figure 3.1)
  • Matter, as well as heat and work, can exchange between system and surroundings.

Equilibrium versus Non-equilibrium Thermodynamics

• Equilibrium Thermodynamics deal with closed systems.
• Biological problems deal with open systems.
• While the field of non-equilibrium thermodynamics should apply to open systems, data from equilibrium thermodynamics can be useful.

The system is any portion of the universe you choose to study. It can be the earth, an individual organism, an individual cell, a test tube of reagents, or simply that part of a solution undergoing a chemical reaction. The surroundings is everything else in the universe.

Equilibrium thermodynamics represent idealized conditions—where any change is carried on with the system and surroundings always in the state of equilibrium with one another. One can calculate maximum or minimum values for thermodynamic quantity changes.
State Functions

- State of a system depends only on pressure, volume, temperature and composition of a system.
- State functions depend only on initial and final state: e.g. internal energy change
  \[ \Delta E = E_{\text{final state}} - E_{\text{initial state}} \]
- We can generally measure changes in state functions such as E even if we don’t know the inherent value.

State Functions, con’t.

- A state function is independent of the path of a change.
- Heat and work are not state functions. They depend on path.
  - Battery discharge, energy of battery converted all to heat
  - Battery used to run a motor, energy of battery converted to heat and work.

First Law of Thermodynamics

- Conservation of Energy
  - Energy is neither created nor destroyed.
- In terms of change of state of a closed system
  \[ \Delta E = q + w \]
  - (q = heat absorbed by system)
  - (w = work done on system)
- Says nothing about spontaneity of a process.

The distance between two locations, such as Tallahassee and Jacksonville, is equivalent to a state function. The travel distance in traveling from Tallahassee to Jacksonville would depend on the route taken, and would not be a state function.

Sign conventions: q and w are positive when energy is added to the system, and negative if energy is transferred from the system to surroundings. You might find an alternative statement of the first law in older textbooks which says \( \Delta E = q-w \). In this case, work is defined as positive for work done by the system on the surroundings. Therefore the analogy is to a steam engine, in which both q and w would be positive.
Enthalpy

- In a constant volume change, no other work done, ΔE = q, which is q_v.
- In a constant pressure change, some work of expansion or contraction will be done.
  - ΔE = q_p - PΔV, or q_p = ΔE + PΔV
  - ΔH, the enthalpy change is defined as q_p
  - ΔH (q_p) and ΔE (q_v) can be measured in a calorimeter, and are both state functions.

Actually, enthalpy, H is defined as H=E+PV, which reduces to this relationship when P is constant. One would measure q_v in a constant volume calorimeter, and q_p in a constant pressure calorimeter. Since the changes in biological systems we are interested in generally occur at constant pressure, the enthalpy change is a more appropriate measure of energy change. Think of it as the energy change not devoted to pressure-volume work when a gas is produced or consumed in a process.

Some Thermodynamic Terms

- Equilibrium
  - Macroscopic properties of system do not change with time
- Spontaneous Process
  - A change that occurs naturally.
  - System moves toward equilibrium.
  - Process capable of doing work.

Some Thermodynamic Terms, con’t.

- Non-spontaneous process
  - Does not occur naturally without intervention.
  - Requires work from surroundings to proceed.
- Reversible process
  - A change carried out so that system and surroundings are always in a state of equilibrium.
Spontaneity—Example in Gas Expansion ($P_1V_1$ to $P_2V_2$)

- Let gas expand against surroundings pressure.
  - Work done = $P_2(V_2 - V_1)$, spontaneous
- Let gas expand at initial pressure
  - Work done = $P_1(V_2 - V_1)$, not-spontaneous
- Let gas expand “reversibly” (at equilibrium)
  - Work done = $\int_{P_1}^{P_2} PdV = RT \ln \frac{V_2}{V_1}$

Spontaneity, con’t.

- Reversible process will
  - produce **maximum work** on surroundings
  or
  - require **minimum work** needed to occur

Entropy

- Heat change in a reversible process ($q_{rev}$) defines another state function, entropy.
  - Entropy change, $\Delta S = q_{rev}/T$
- Another definition of entropy is based upon the extent of potential disorder of a system ($W$, which is the number of microscopic states of a system).
  - $S = klnW$ ($k$ = the Boltzmann constant, which is $R/N$)
- Both definitions lead to notion of entropy as a measure of disorder.

Illustrated by drawing graphs on board. Sorry that I haven’t yet been able to develop these graphs in a computer format.
Second Law of Thermodynamics

- The second law speaks to the spontaneity of a process.
- Total entropy increases in a spontaneous process.
- Must include entropy change of surroundings as well as system.

Third Law of Thermodynamics

- Entropy of a crystalline, perfectly ordered substance is 0 at $T = 0$ K.
- One can calculate the entropy of a substance by calculating the heat energy necessary to heat the substance to the appropriate temperature.
- Therefore one can define an absolute entropy value, even though absolute energy and enthalpy values cannot be defined.

Free Energy

- Gibbs Free Energy, $G$ is defined as $G = E + PV - TS$
- For Constant $T$ and $P$ changes: $\Delta G = \Delta E + P \Delta V - T \Delta S$
- Part of the internal energy change is required for expansion work ($P \Delta V$), part is required for the thermal disorder of increasing entropy. The rest is available to do useful work.
Interpretations of Free Energy

- The **maximum useful work** that can be obtained from a process
- Spontaneous processes will always yield less than the maximum work
- The **minimum work necessary** to cause a non-spontaneous process to occur.

One would only get the maximum work from a spontaneous process, or require the minimum work of a non-spontaneous process, if the change were carried out reversibly, that is slowly with all intermediate steps at equilibrium. By “useful work” is meant work other than the pressure volume work inherent in a volume change, such as the production of a gas in a chemical reaction.

Interpretations of Free Energy, con’t.

- As a criterion of equilibrium related only to measurements of the system.
- $\Delta G < 0$, spontaneous process
  - (capable of doing work, where $\Delta G$ is maximum work available)
- $\Delta G > 0$, not a spontaneous process
  - (work required to make change occur; $\Delta G$ is the minimum work necessary)
- $\Delta G = 0$, system at equilibrium

Free Energy and Entropy

- At constant Temperature and Pressure
  - $\Delta G = \Delta H - T \Delta S$
- The enthalpy change is related to making and breaking chemical bonds
- The entropy change is related to order-disorder transitions
- Free energy is that part of enthalpy not related to the order-disorder transitions
Temperature Effect on $\Delta G$

- The effect of Temperature on $\Delta G$ depends on the sign of $\Delta H$ and $\Delta S$
- Sign of $\Delta H$ indicates whether process is *exothermic* or *endothermic*
- Sign of $\Delta S$ indicates whether process proceeds to *more* or *less order*

<table>
<thead>
<tr>
<th>$\Delta H$</th>
<th>$\Delta S$</th>
<th>Spontaneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-$</td>
<td>$+$</td>
<td>Spontaneous at all $T$</td>
</tr>
<tr>
<td>$+$</td>
<td>$-$</td>
<td>Non-spontaneous at all $T$</td>
</tr>
<tr>
<td>$+$</td>
<td>$+$</td>
<td>Spontaneous at high $T$</td>
</tr>
<tr>
<td>$-$</td>
<td>$-$</td>
<td>Spontaneous at low $T$</td>
</tr>
</tbody>
</table>

Free Energy and Entropy (ice to water as an example)

- For the transition ice $\rightarrow$ water
  - At $T = 0^\circ C$, equilibrium, $\Delta G = 0$, $\Delta H=\Delta S$
  - At $T > 0^\circ C$, $\Delta H<\Delta S$, so $\Delta G < 0$,
    - melting is spontaneous
  - At $T < 0^\circ C$, $\Delta H>\Delta S$, so $\Delta G > 0$,
    - melting is not spontaneous
Chemical Potential

• The chemical potential ($\mu$) of a substance is the partial molar free energy change associated with formation or disappearance of the substance.

$$\mu_i = \left( \frac{\delta G_i}{\delta n_i} \right)_{T,P,n_1,n_2,...}$$

Effect of Concentration on Chemical Potential

• Chemical potential is related to the activity (or concentration) of the substance:

$$\mu_i = \mu_i^0 + RT \ln a_i$$ or

$$\mu_i = \mu_i + RT \ln [i]$$

• (The higher the concentration, the greater the order, and the lower the entropy, hence increasing the concentration is unfavorable)

Free Energy Change in Chemical Reactions

• A chemical reaction represents the disappearance of reactants, the appearance of products:

$$\text{aA } + \text{bB} \underset{\text{C + D}}{\xrightarrow{\text{rt}} }$$

• Partial free energy change for each component is given by the chemical potential times the change in quantity:

$$\Delta G_i = \mu_i \Delta n_i$$
For the overall chemical reaction, we can derive the relationship:

\[ \Delta G = \Delta G^\circ + RT \ln \frac{[C][D]^c}{[A][B]^c} \]

(call \( \frac{[C][D]^c}{[A][B]^c} = Q \), the mass action ratio)

\( \Delta G^\circ \) is used when standard state of H\(^+\) = 10\(^{-7}\)

The reaction isotherm can be derived from the definition of the chemical potential. We will not go into that derivation here. This equation shows how changing concentrations of reactants and products will effect the free energy change of the reaction.

- Reactants and products at equilibrium
  \[ \Delta G = 0 \]
  \[ 0 = \Delta G^\circ + RT \ln Q \]
  \[ \Delta G^\circ = -RT \ln Q \]
- (when reactants are converted to products with everything at equilibrium concentrations)

- Reactants and products at standard states
  \[ Q = 1 \]
  \[ \Delta G = \Delta G^\circ \]

\( \Delta G^\circ \) is called the **standard free energy change** (when reactants are converted to products with everything at standard states)
Reaction Isotherm, con’t

- Reactants and products at other concentrations

\[ \Delta G = \Delta G^\circ + RT \ln \frac{[C][D]}{[A][B]} = -RT \ln K_{eq} + RT \ln Q \]

\[ \Delta G = RT \ln \frac{Q}{K_{eq}} \]

\[ \Delta G \text{ is also a partial molar free energy change, representing the slope of the curve at any position } Q. \]

\[ \Delta G \text{ Depends on Relationship of } Q \text{ to } K_{eq} \]

- \( Q/K < 1; \Delta G < 0; \) spontaneous

- \( Q/K > 1; \Delta G > 0; \) not-spontaneous

- \( Q/K = 1; \Delta G = 0; \) at equilibrium

Relationship of \( Q, K_{eq}, \) and \( \Delta G \)
RTlnQ is a Correction Factor to $\Delta G^\circ$

- $Q = 0.01$, $RT \ln Q = -11.4$ kJ/mol
- $Q = 0.1$, $RT \ln Q = -5.74$ kJ/mol
- $Q = 1$, $RT \ln Q = 0$ kJ/mol
- $Q = 10$, $RT \ln Q = +5.74$ kJ/mol
- $Q = 100$, $RT \ln Q = +11.4$ kJ/mol

Remember, $R$ is the gas constant given in appropriate units, i.e. 8.314 J/mol-K. Assume $T = 25^\circ C$, or 298 K.

Metabolic Reactions at Steady State

- Calculate $\Delta G$ from steady state concentrations
- It must be negative if reaction is proceeding
  - ($Q/K < 1$)
- If $Q/K > 0.05$, steady state is near equilibrium
- If $Q/K < 0.05$, steady state is displaced from equilibrium
- Regulatory steps are usually displaced from equilibrium

Coupling of Chemical Reactions

- For a reaction to proceed, $\Delta G$ must be negative.
- A reaction with a positive $\Delta G$ can be coupled to a reaction with a negative $\Delta G$ in order for the overall reaction to occur
- For example, consider

  $\text{glucose} + P_i \rightleftharpoons \text{glucose-6-phosphate} + H_2O$

  $\Delta G^\circ = +13.9$ kJ/mol (see Table 3.3)
Coupling of Chemical Reactions, con’t

- This reaction is coupled to hydrolysis of ATP
  \[
  \text{ATP} + \text{H}_2\text{O} \rightarrow \text{ADP} + \text{P}_i, \Delta G^o = -30.5 \text{ kJ/mol}
  \]
- Therefore, for the coupled reaction
  \[
  \text{ATP+glucose} \rightarrow \text{glucose-6-phosphate + ADP} \quad \Delta G^o = -30.5 + 13.9 = -16.6 \text{ kJ/mol}
  \]

ATP Hydrolysis is a Major Source of “Energy Coupling”

- ATP contains two phosphate anhydride bonds and 5 dissociable protons.
  - (See Fig. 3.15)
- \(\Delta G^o\) of ATP hydrolysis depends on pH
  - (See Fig. 3.16)
- \(\Delta G^o\) of contributions from H⁺ dissociation and electrostatic repulsion
  - (See Fig. 3.11)

Factors Affecting \(\Delta G^o\) of ATP

- Mg²⁺ concentration
  - (see Fig. 3.17)
- Mass action ratio (Q)
  - (see Fig. 3.18)
Other “High Energy Phosphate” Compounds

- Phosphoenolpyruvate has a very high negative ΔG of hydrolysis (-62.2 kJ/mol), enough to drive ATP synthesis
  - (See Fig 3.14)
- ADP
  - (See Fig. 3.11)
- Pyrophosphate
  - (See Fig. 3.10)
- Creatine phosphate is a “storage form” of ATP in muscle
  - (See Table 3.3)