Phillips • Kondev • Theriot

Physical Biology of the Cell

CELL ENERGETICS

Inside a cell: physics at the nanoscale

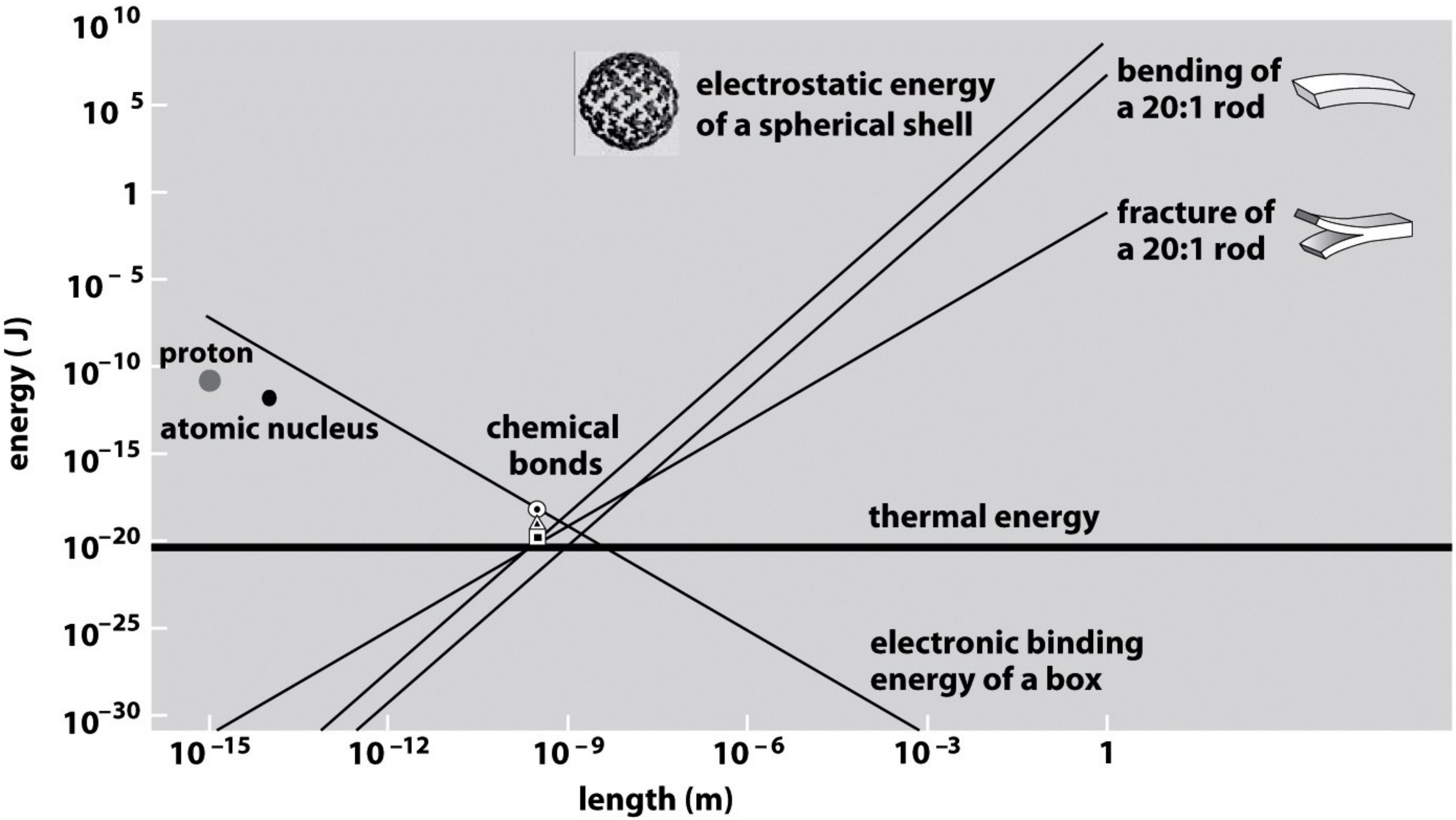

Figure 5.1 Physical Biology of the Cell (© Garland Science 2009)

$K_B T_{amb}$= 4.1 pn x nm

Key Points.

- Metabolism: cellular transformation of chemicals within a cell
  - Energy in a cell is stored and transferred through ATP
    - The main source of ATP is glucose (glycolysis)
- Energy storage: ATP, ADP, NADH, NADPH, H^+ gradients

GLYCOLYSIS

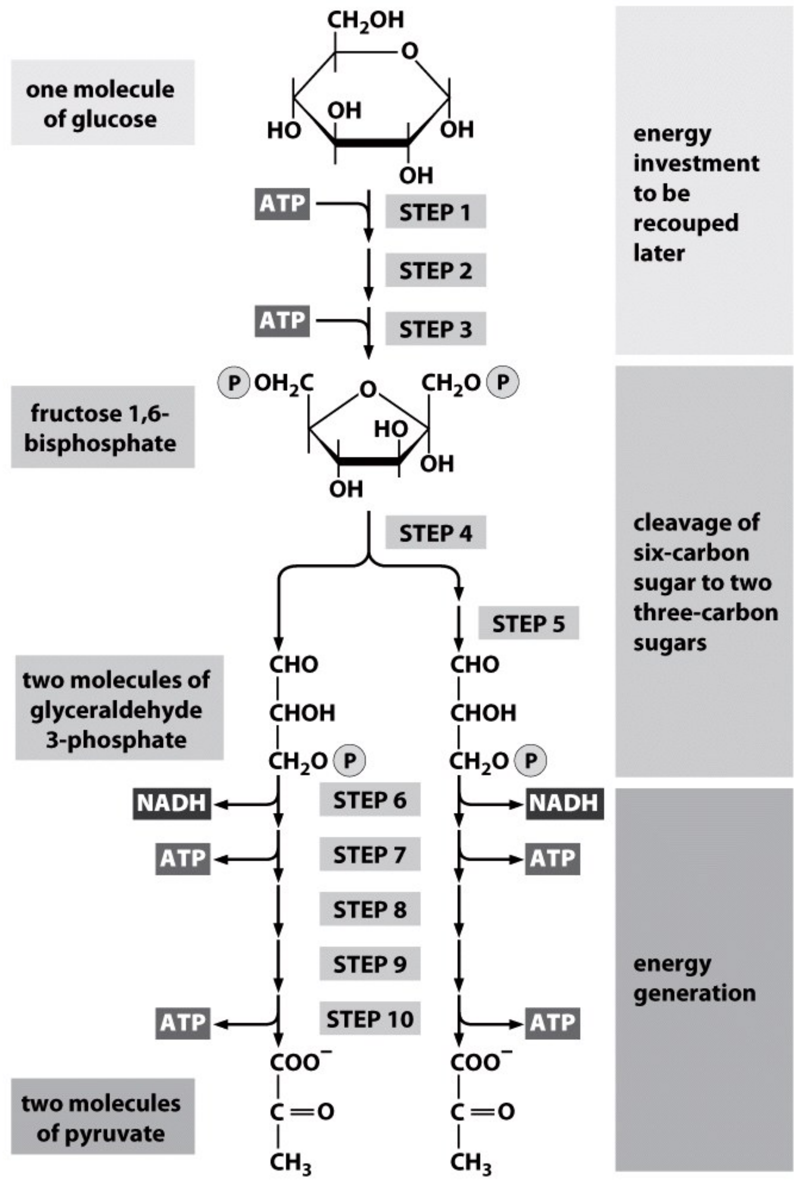

Figure 5.2 Physical Biology of the Cell (© Garland Science 2009)

Basic interconversion

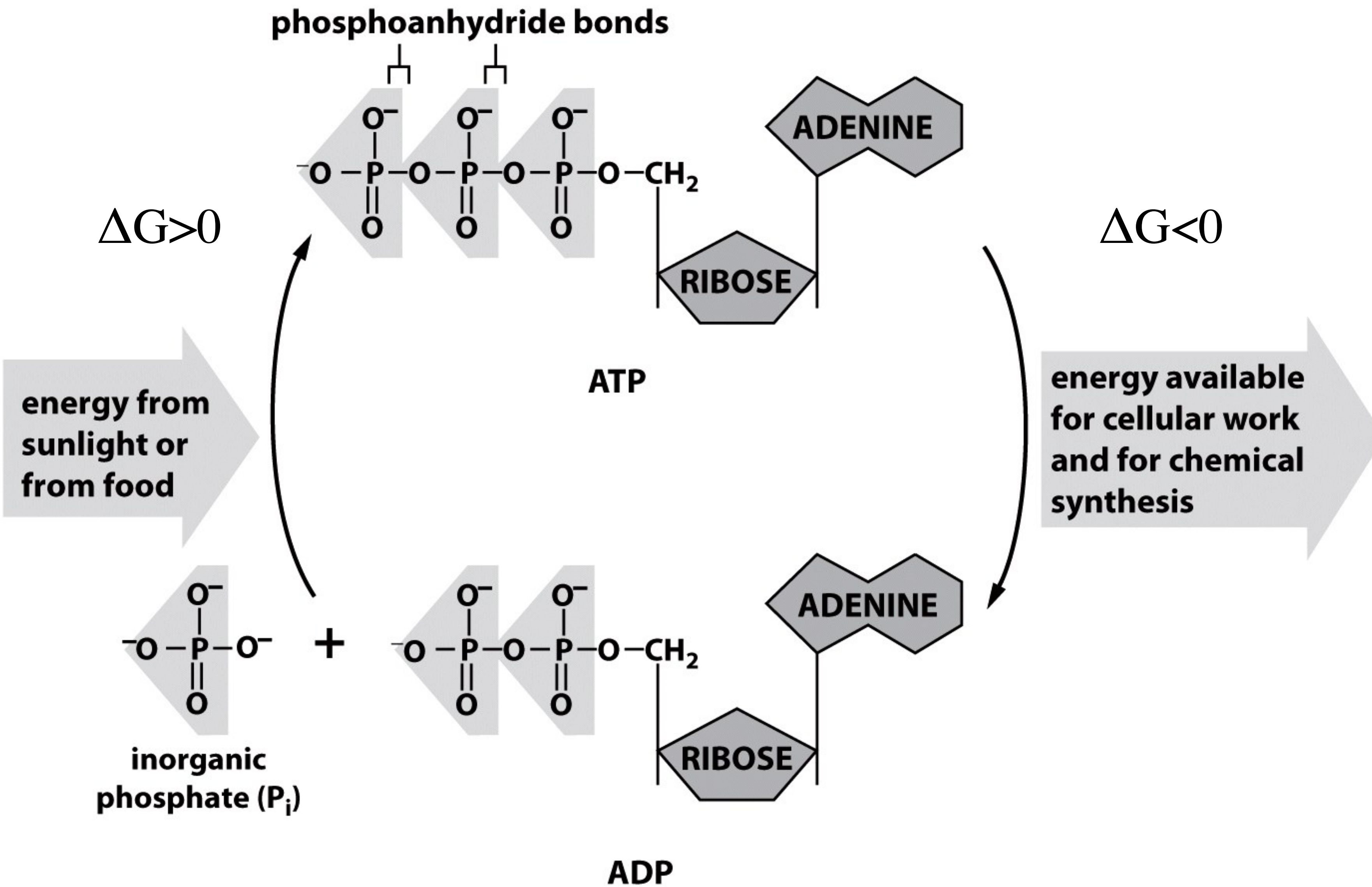

Figure 5.3a Physical Biology of the Cell (© Garland Science 2009)

20 kT of released energy

Applications of the Equilibrium Constant

$$\text{ATP} \rightleftharpoons \text{ADP} + \text{P}$$

$$\Delta G = \Delta G_0 + kTlnK_{eq}$$

$$\Delta G_0 = -12.5\ kT/molecule$$

$$\Delta G = \Delta G_0 + kTln\frac{[ADP][P]}{[ATP]}$$

In cells, typical concentrations of all three molecules are:

$[ADP] = 8\ x\ 10^{-3}$ $[P] = 0.4\ x\ 10^{-3}$ $[ATP] = 8\ x\ 10^{-3}$

all concentrations are measured relative to the standard state $(1\ M)$

$$\Delta G = -20\ kT/molecule$$

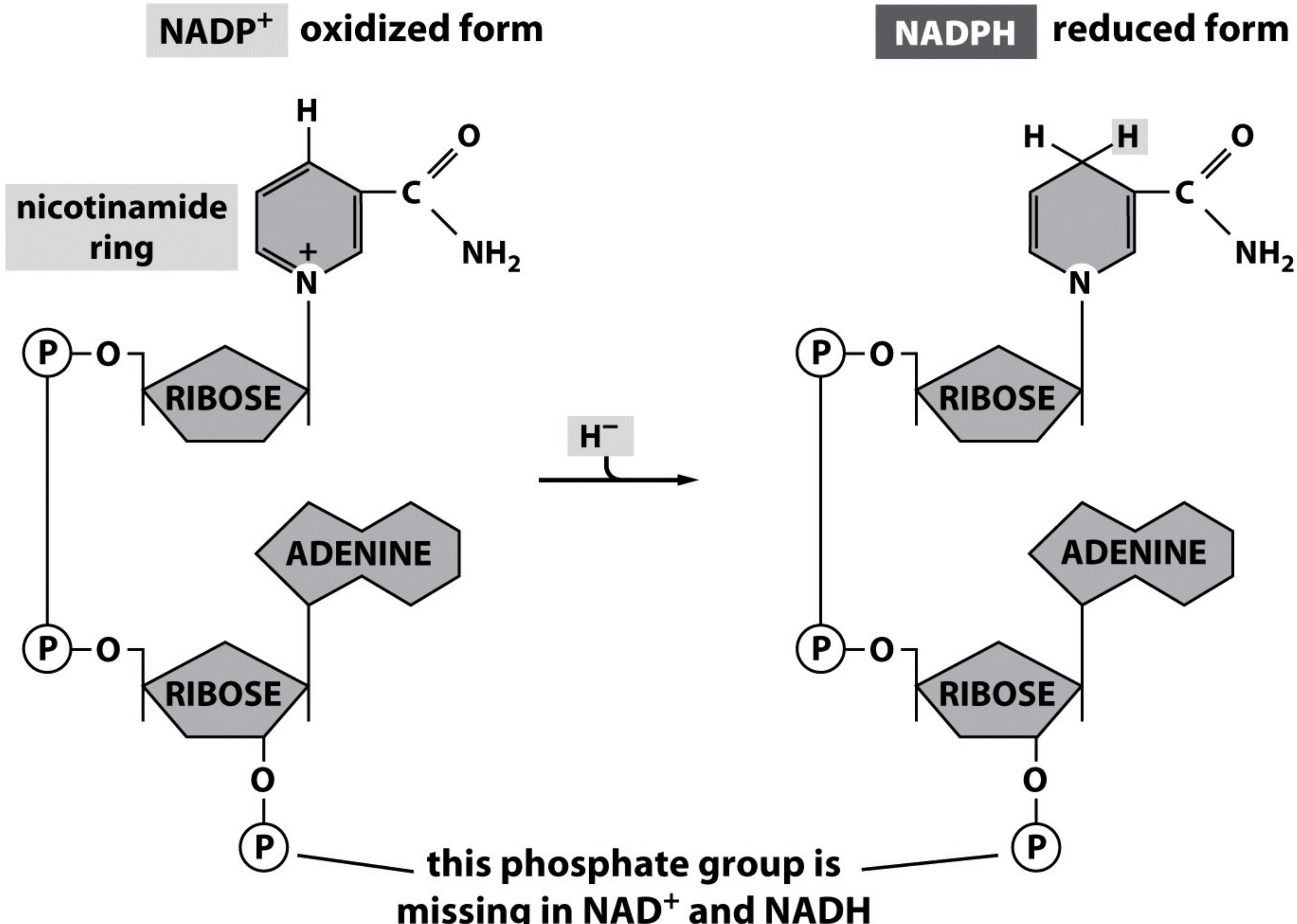

Figure 5.3b Physical Biology of the Cell (© Garland Science 2009)

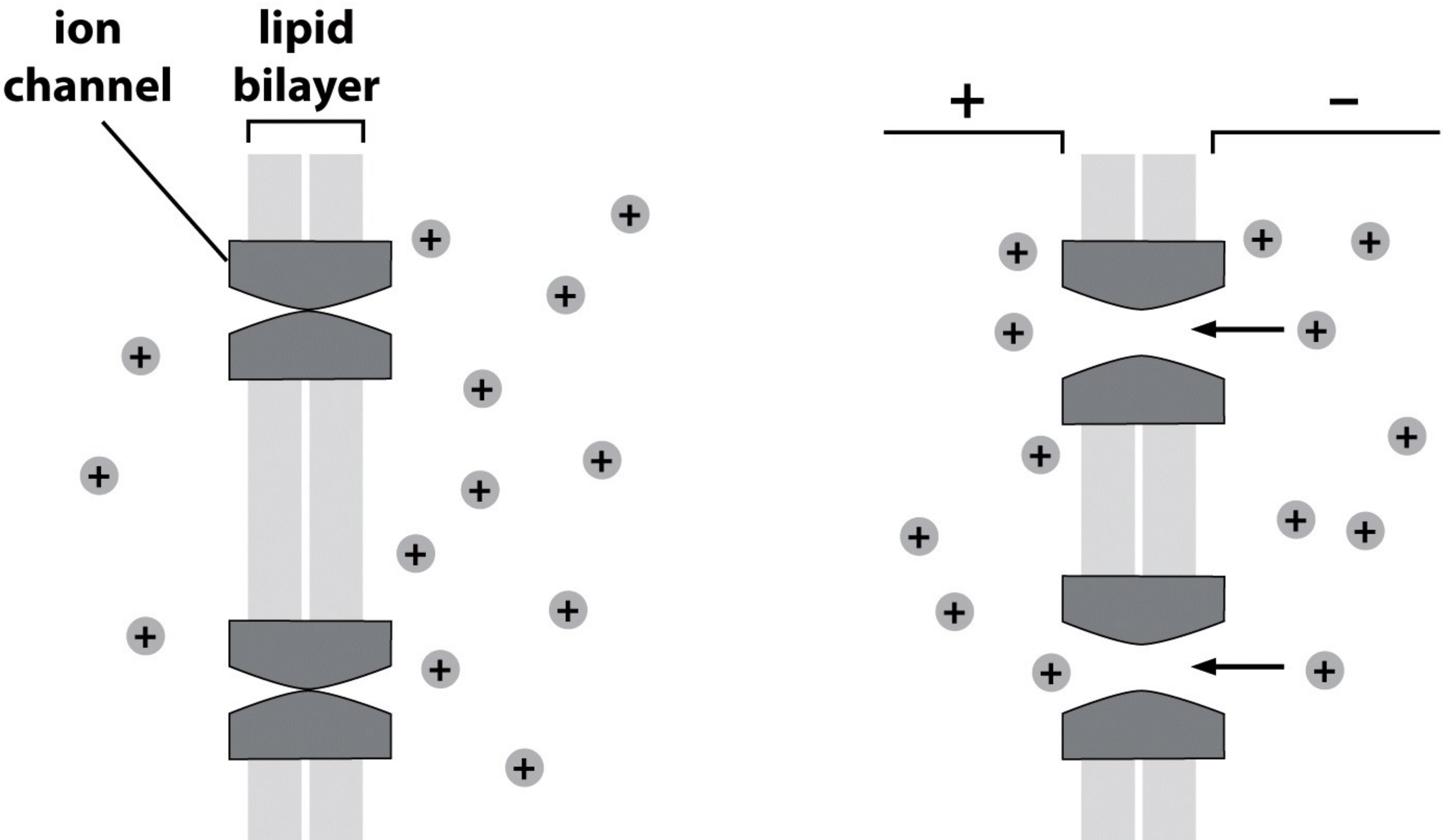

Figure 5.3c Physical Biology of the Cell (© Garland Science 2009)

The building of a living cell

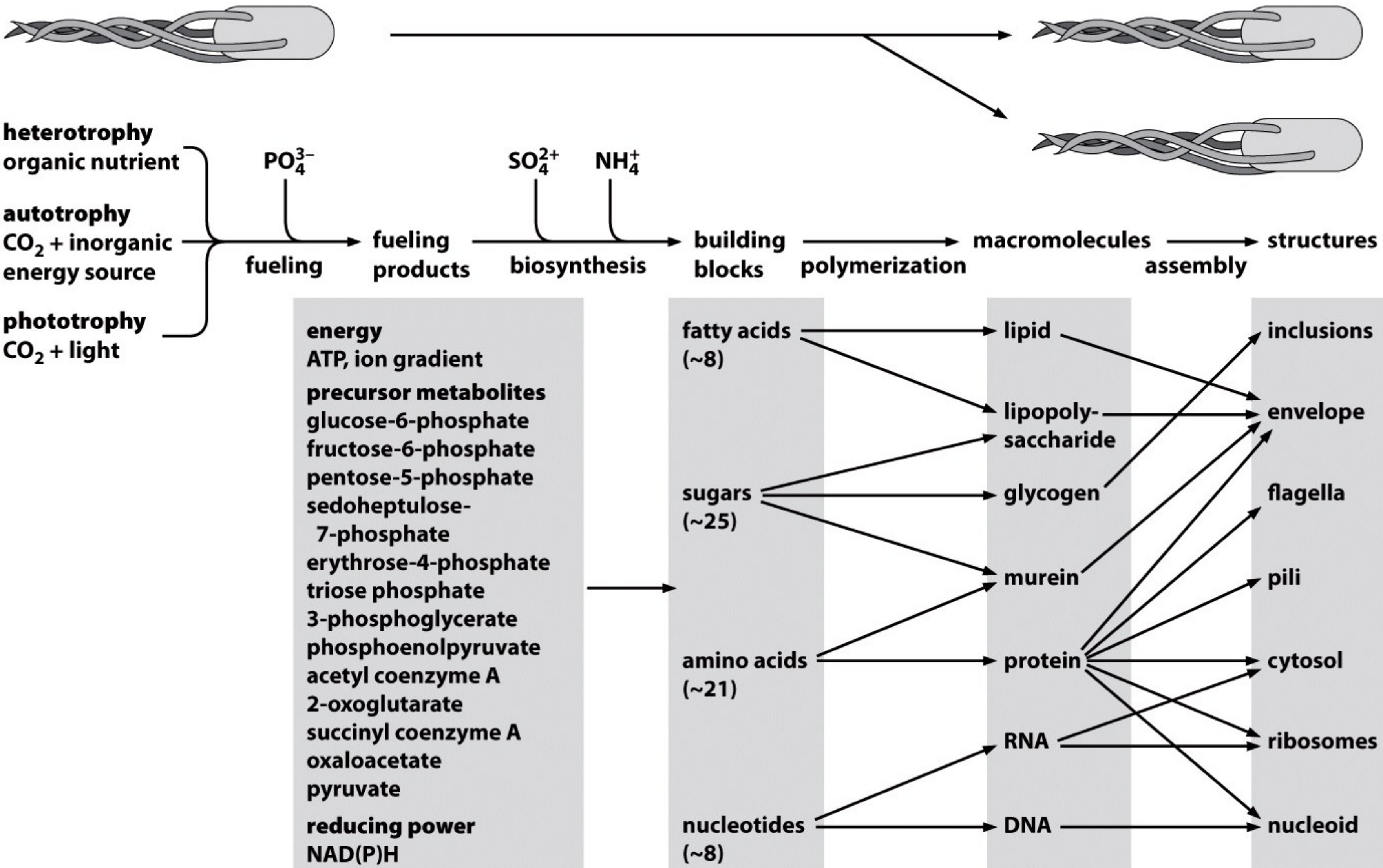

Figure 5.4 Physical Biology of the Cell (© Garland Science 2009)

Glycolysis 2: a story of many characters

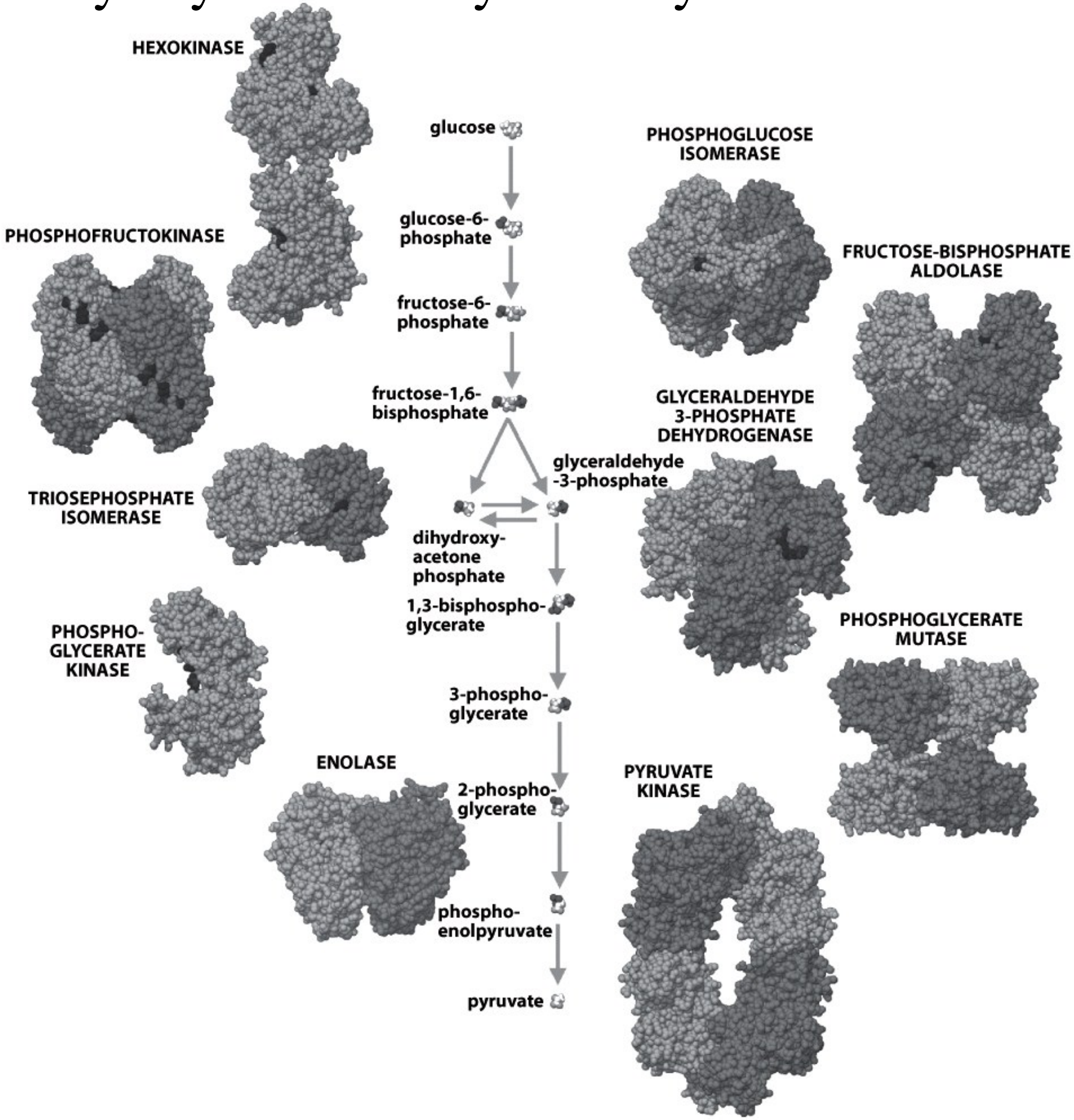

Figure 5.5a Physical Biology of the Cell (© Garland Science 2009)

Glycolysis 3 :A free energy cascade

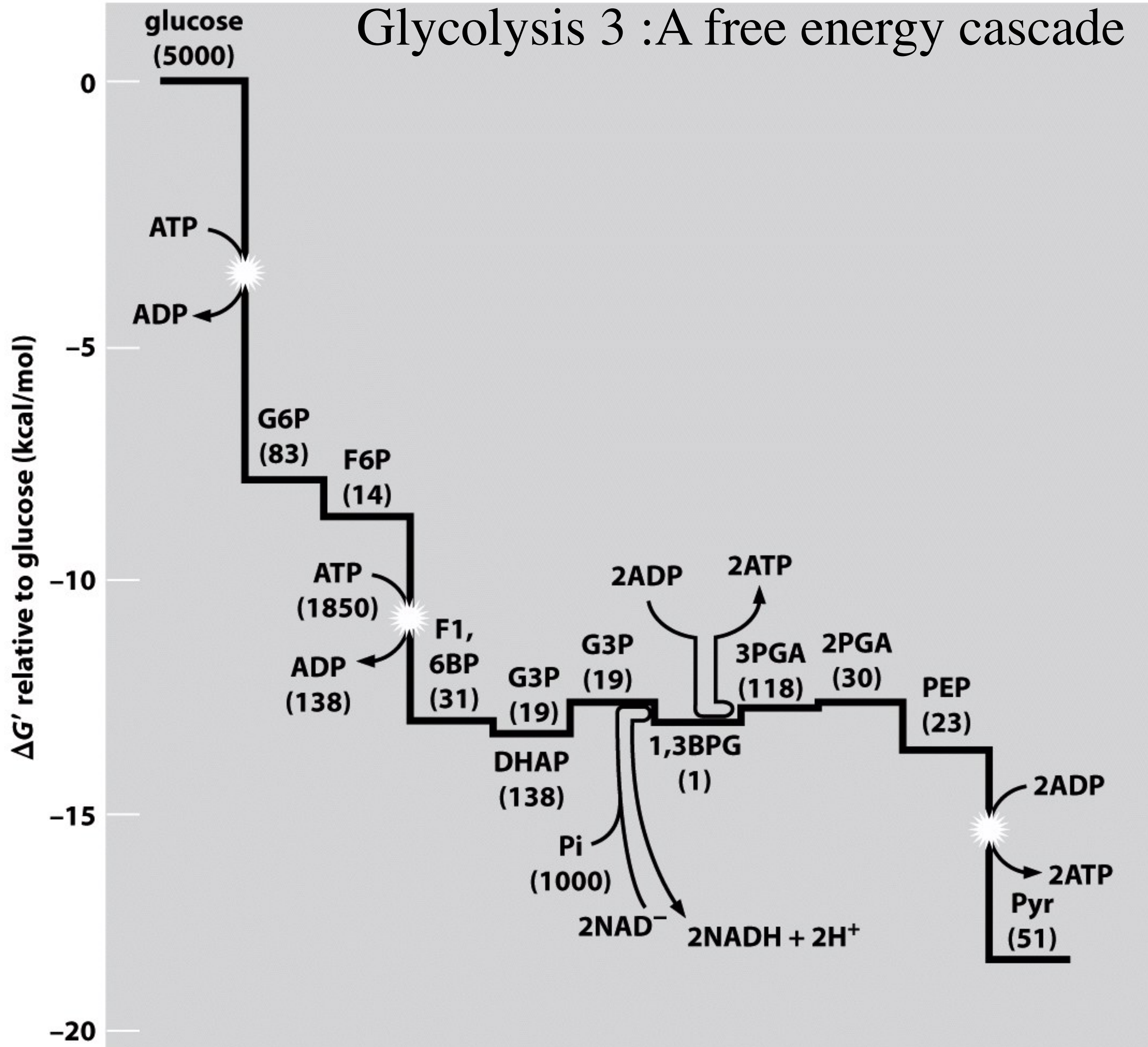

Figure 5.5b Physical Biology of the Cell (© Garland Science 2009)

Table 5.1 Amino acid abundance and cost of synthesis for making the amino acids under both aerobic and anaerobic growth conditions. "Glucose equivalents" refers to the number of glucose molecules that must be used to generate the carbon skeletons of each amino acid (for example, one mole of alanine, an amino acid containing three carbons, can be synthesized from one half mole of glucose, a sugar containing six carbons). "ATP equivalents" refers to the approximate amount of biosynthetic energy required to synthesize the amino acid from glucose as a starting material. A negative value indicates that synthesis of the amino acid from glucose is favorable so energy is generated rather than consumed. These numbers are not absolute; they depend on several assumptions about metabolic energetics and pathway utilization. We have assumed that the energetic value of one molecule of NADH or NADPH is equivalent to two ATP molecules. We have not accounted for the biosynthetic cost of sulfate, ammonium, or single carbon units. (Data from: F. C. Neidhardt et al., Physiology of the Bacterial Cell, Sunderland, Sinauer Associates, Inc, 1990; M. Schaechter et al., Microbe, Washington DC, ASM Press, 2006; and EcoCyc, Encyclopedia of *Escherichia coli* K-12 Genes and Metabolism, www.ecocyc.org.)

Amino acid	Abundance (molecules per cell)	Glucose equivalents	ATP equivalents (aerobic)	ATP equivalents (anaerobic)
Alanine (A)	2.9×10^8	0.5	−1	1
Arginine (R)	1.7×10^8	0.5	5	13
Asparagine (N)	1.4×10^8	0.5	3	5
Aspartate (D)	1.4×10^8	0.5	0	2
Cysteine (C)	5.2×10^7	0.5	11	15
Glutamate (E)	1.5×10^8	0.5	−7	−1
Glutamine (Q)	1.5×10^8	0.5	−6	0
Glycine (G)	3.5×10^8	0.5	−2	2
Histidine (H)	5.4×10^7	1	1	7
Isoleucine (I)	1.7×10^8	1	7	11
Leucine (L)	2.6×10^8	1.5	−9	1
Lysine (K)	2.0×10^8	1	5	9
Methionine (M)	8.8×10^7	1	21	23
Phenylalanine (F)	1.1×10^8	2	−6	2
Proline (P)	1.3×10^8	0.5	−2	4
Serine (S)	1.2×10^8	0.5	−2	2
Threonine (T)	1.5×10^8	0.5	6	8
Tryptophan (W)	3.3×10^7	2.5	−7	7
Tyrosine (Y)	7.9×10^7	2	−8	2
Valine (V)	2.4×10^8	1	−2	2

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Table 5.1 (part 2) Physical Biology of the Cell (© Garland Science 2009)

Table 5.2 Biosynthetic cost in ATP equivalents to synthesize the macromolecules of a single *E. coli* cell.

Class	Biosynthetic cost (aerobic) – ATP equiv.
Protein	4.5×10^9
DNA	3.5×10^8
RNA	1.6×10^9
Phospholipid	3.2×10^9
Lipopolysaccharide	3.8×10^8
Peptidoglycan	1.7×10^8
Glycogen	3.1×10^7

• Inside of cells is a violent place, full of incessant thermal motion.

• Physics won't tell you what any one molecule in cell would do, but can tell you the expected distribution of the measurement (Statistical Mechanics).

• Energy unit for biological molecules is a $kT = 4.2$ pN.nm

• Energy conservation is not a criterion to decide if a process will occur or not. Spontaneous processes in isolated systems occur because the final state is **the most probable states of these systems (2nd Law of Thermodynamics).**

• Entropy (degree of disorder) gets maximized in spontaneous processes in isolated systems.

• System in a heat bath is a better approximation for the cellular environment.

• Entropy is not the only decisive factor in determining how the reaction will occur. Instead, for systems in a heat bath, total entropy of the surrounding gets maximized. In better terms, the free energy of the system is minimized.

• Energetic and entropic terms usually compete to decide which way the reaction will proceed.

• **A system's useful energy is free energy, which is less than its total energy content**.

• For biological examples, we make no distinctions between Gibbs and Hemlholtz free energy.

Conditions of Equilibrium

- For an isolated system, entropy ($S = kln\Omega$) gets maximized.

  If subsystems interact thermally, T gets equilibrated.

  If subsystems interact mechanically, P gets equilibrated.

  If subsystems exchange particles, μ gets equilibrated.

- For a system in a heat bath, free energy gets minimized.

  If a system interacts mechanically with the reservoir, $H = E + PV$ gets minimized.

  If a system interacts thermally with the reservoir, $F = E - TS$ gets minimized.

  If a system interacts both thermally and mechanically with the reservoir, $G = E - TS + PV$ gets minimized.

- If a system is allowed to exchange particles with the reservoir, entropic term (TS) contains $-\mu N$.