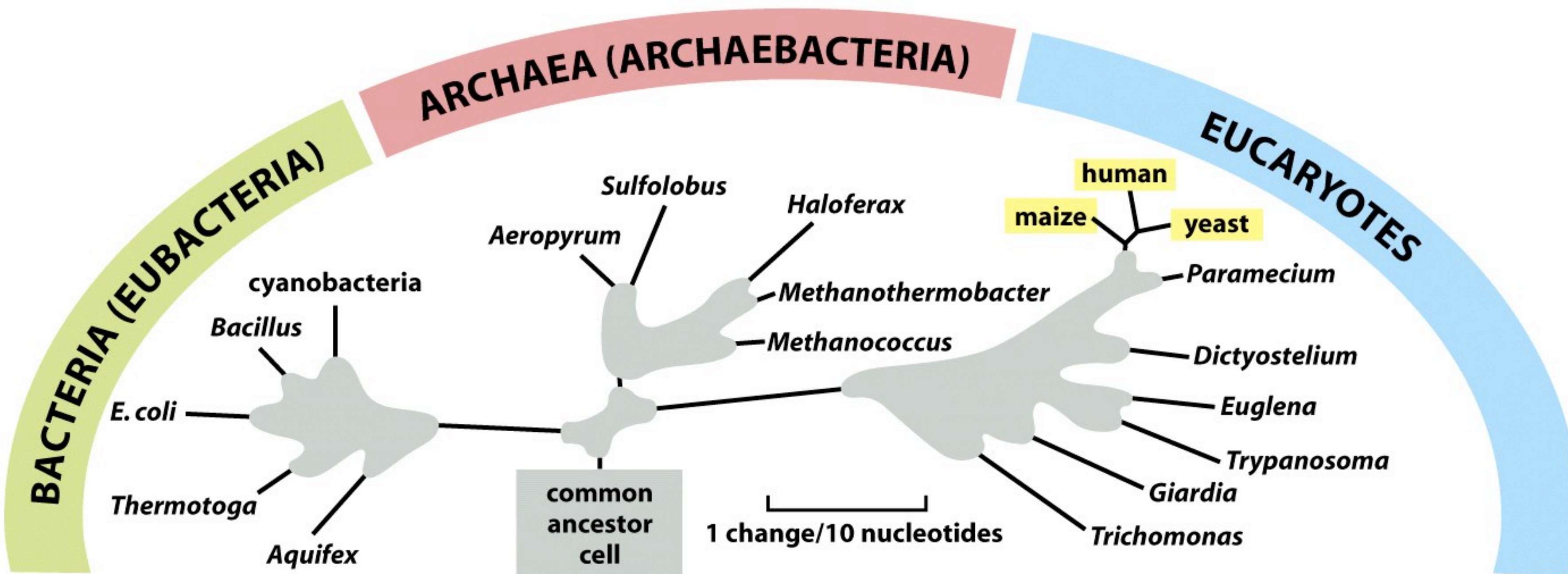
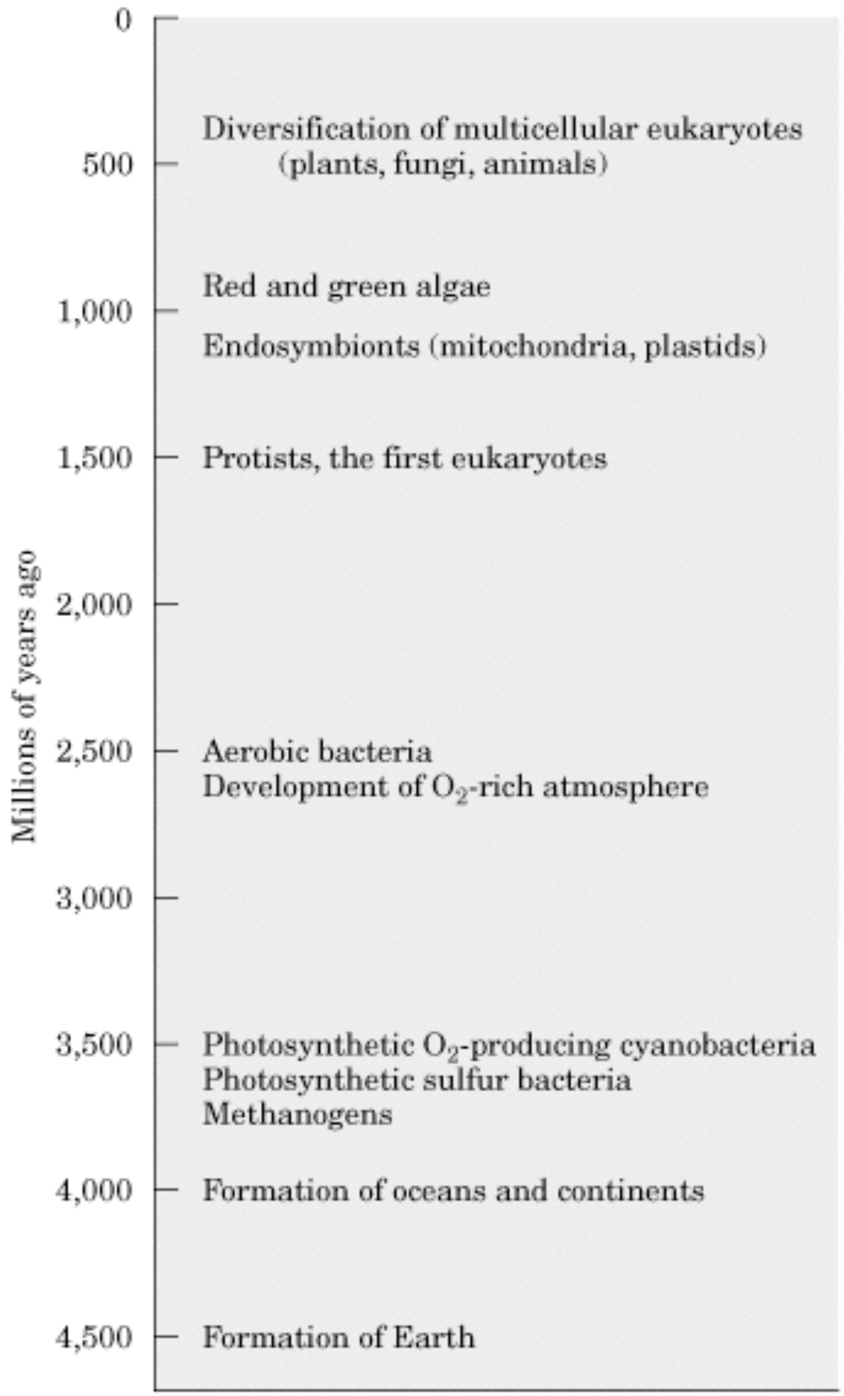
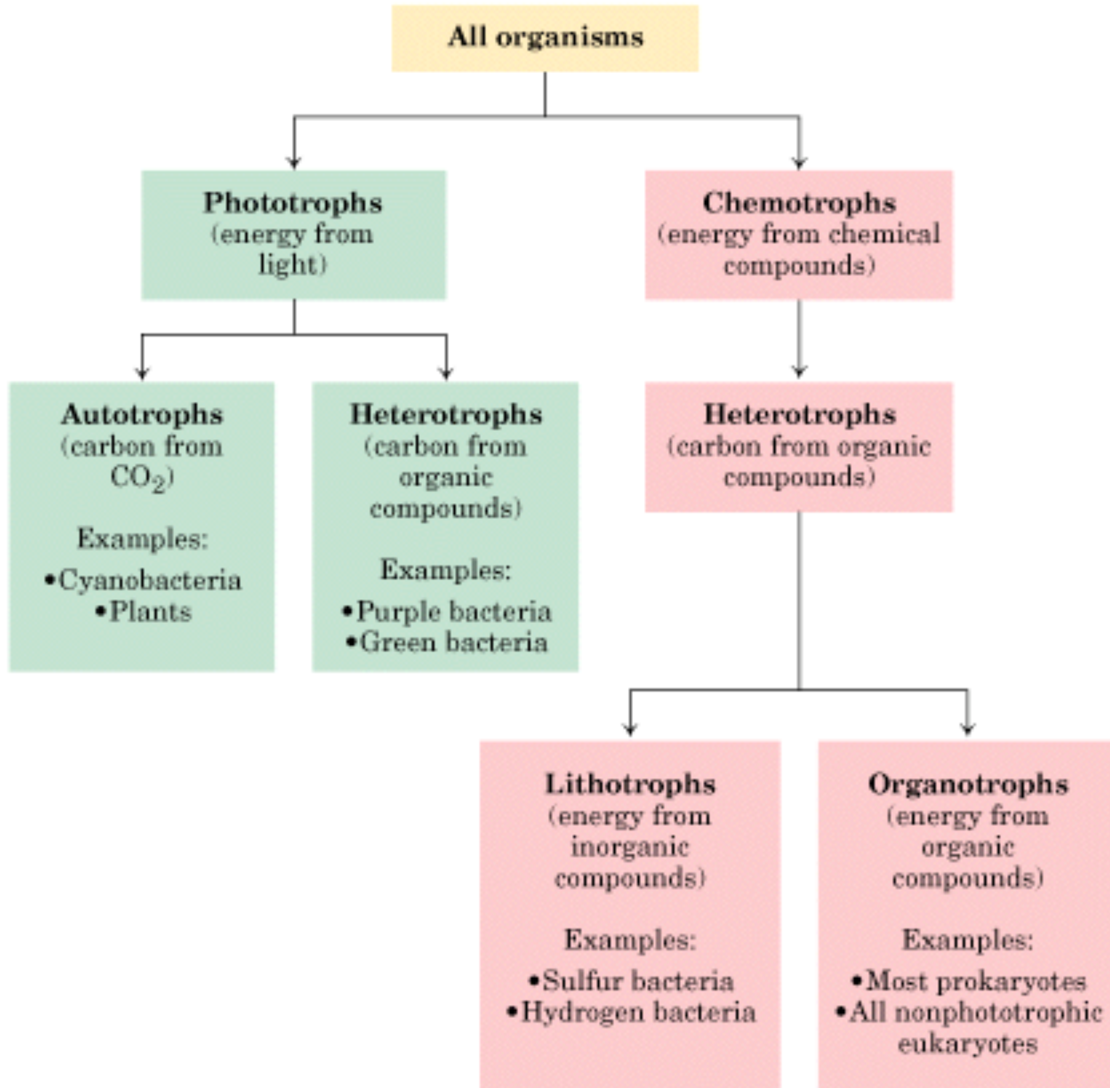
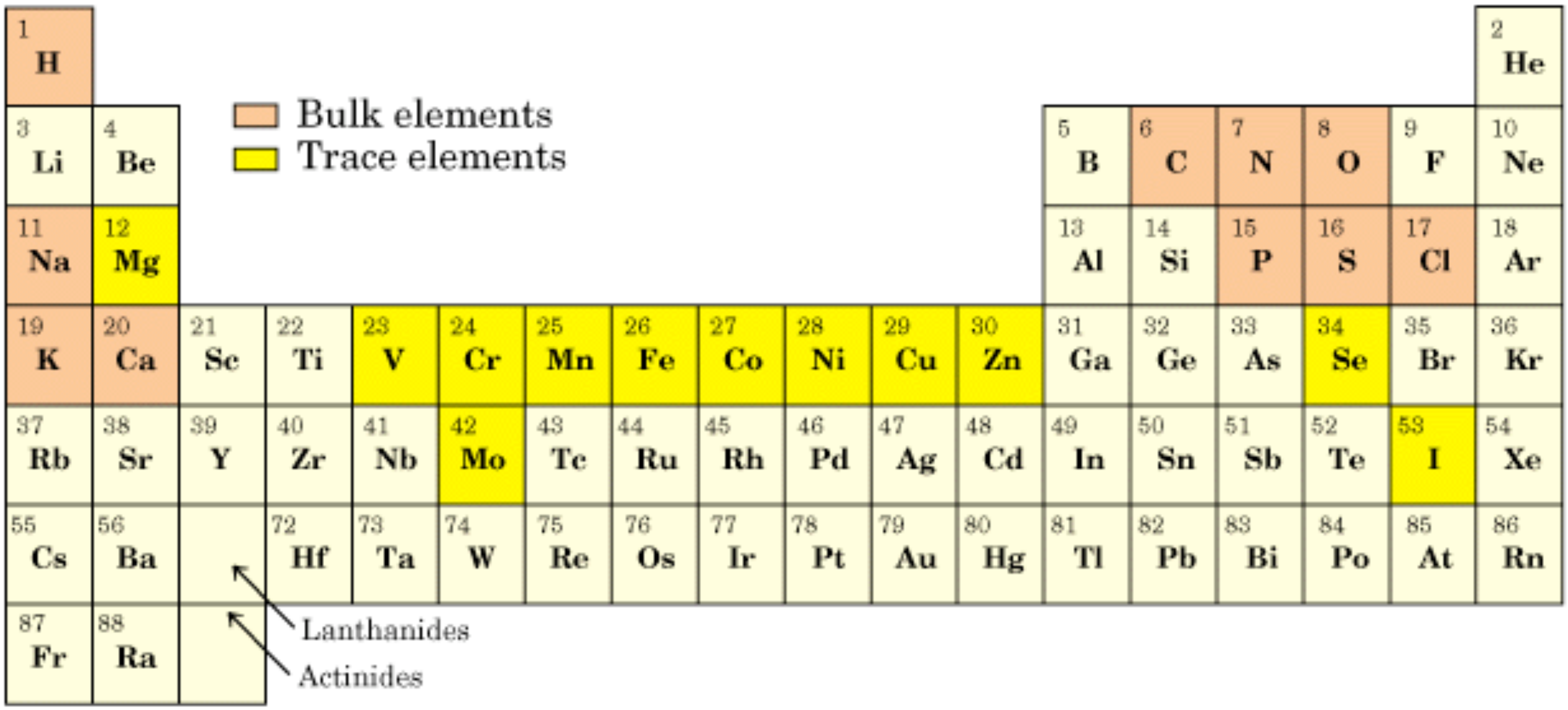


Figure 1-21 *Molecular Biology of the Cell*, Fifth Edition (© Garland Science 2008)


Millions of years ago
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
Diversification of multicellular eukaryotes (plants, fungi, animals)
Red and green algae
Endosymbionts (mitochondria, plastids)
Protists, the first eukaryotes
Aerobic bacteria
Development of O_2-rich atmosphere
Photosynthetic O_2-producing cyanobacteria
Photosynthetic sulfur bacteria
Methanogens
Formation of oceans and continents
Formation of Earth


All organisms
Phototrophs
(energy from light)
Chemotrophs
(energy from chemical compounds)
Autotrophs
(carbon from CO_2)
Examples:
•Cyanobacteria
•Plants
Heterotrophs
(carbon from organic compounds)
Examples:
•Purple bacteria
•Green bacteria
Heterotrophs
(carbon from organic compounds)
Lithotrophs
(energy from inorganic compounds)
Examples:
•Sulfur bacteria
•Hydrogen bacteria
Organotrophs
(energy from organic compounds)
Examples:
•Most prokaryotes
•All nonphototrophic eukaryotes


Bulk elements
Trace elements
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
Lanthanides
Actinides

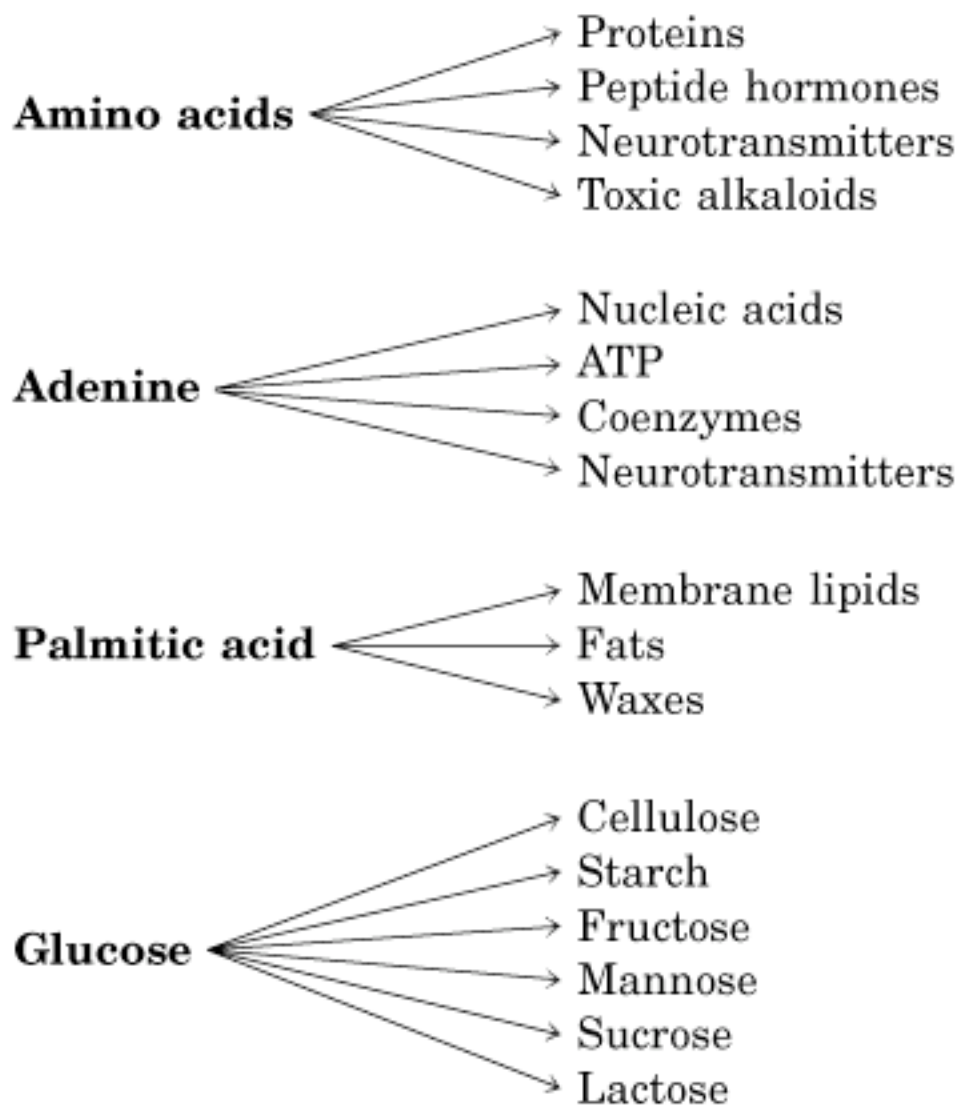
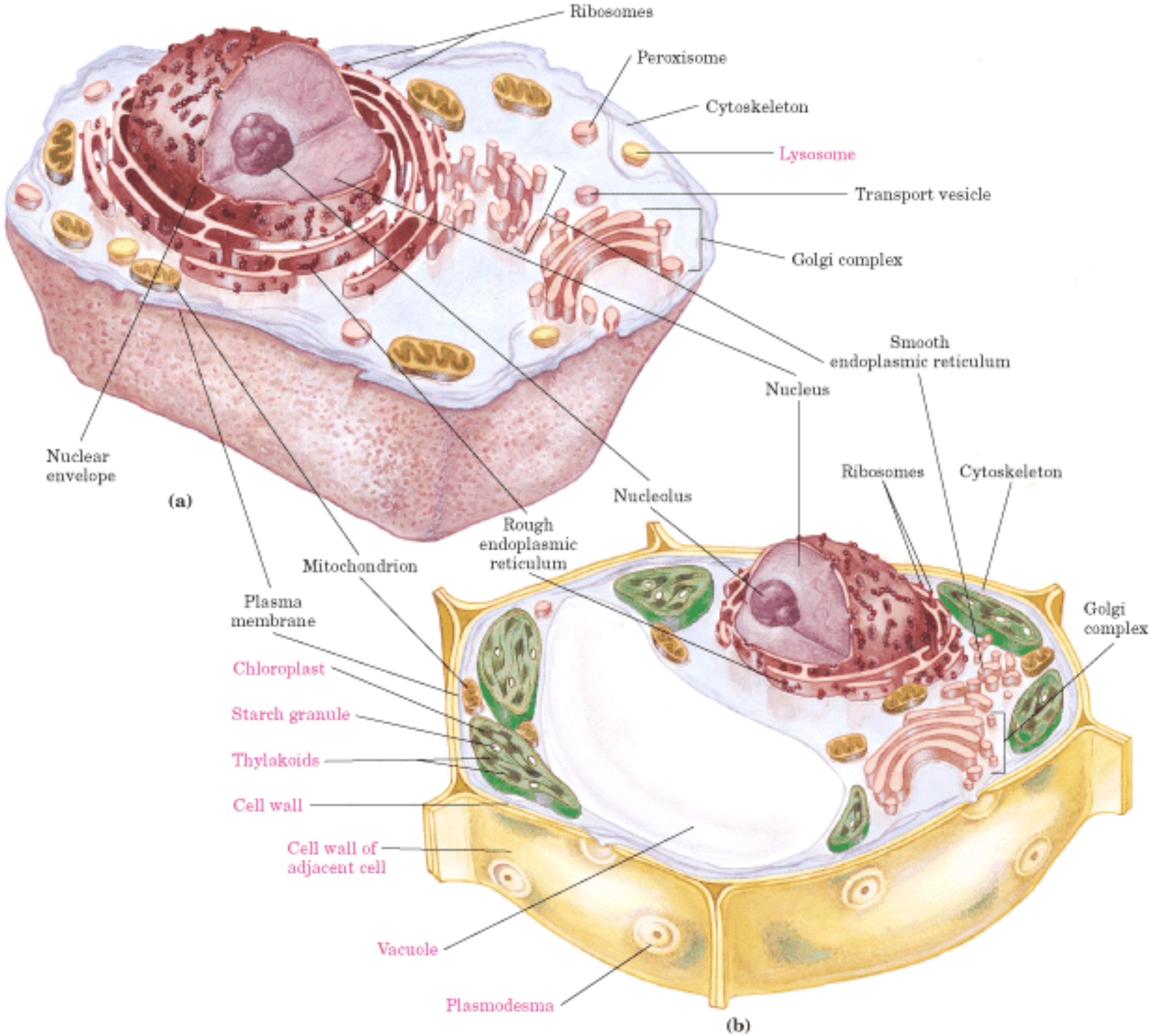
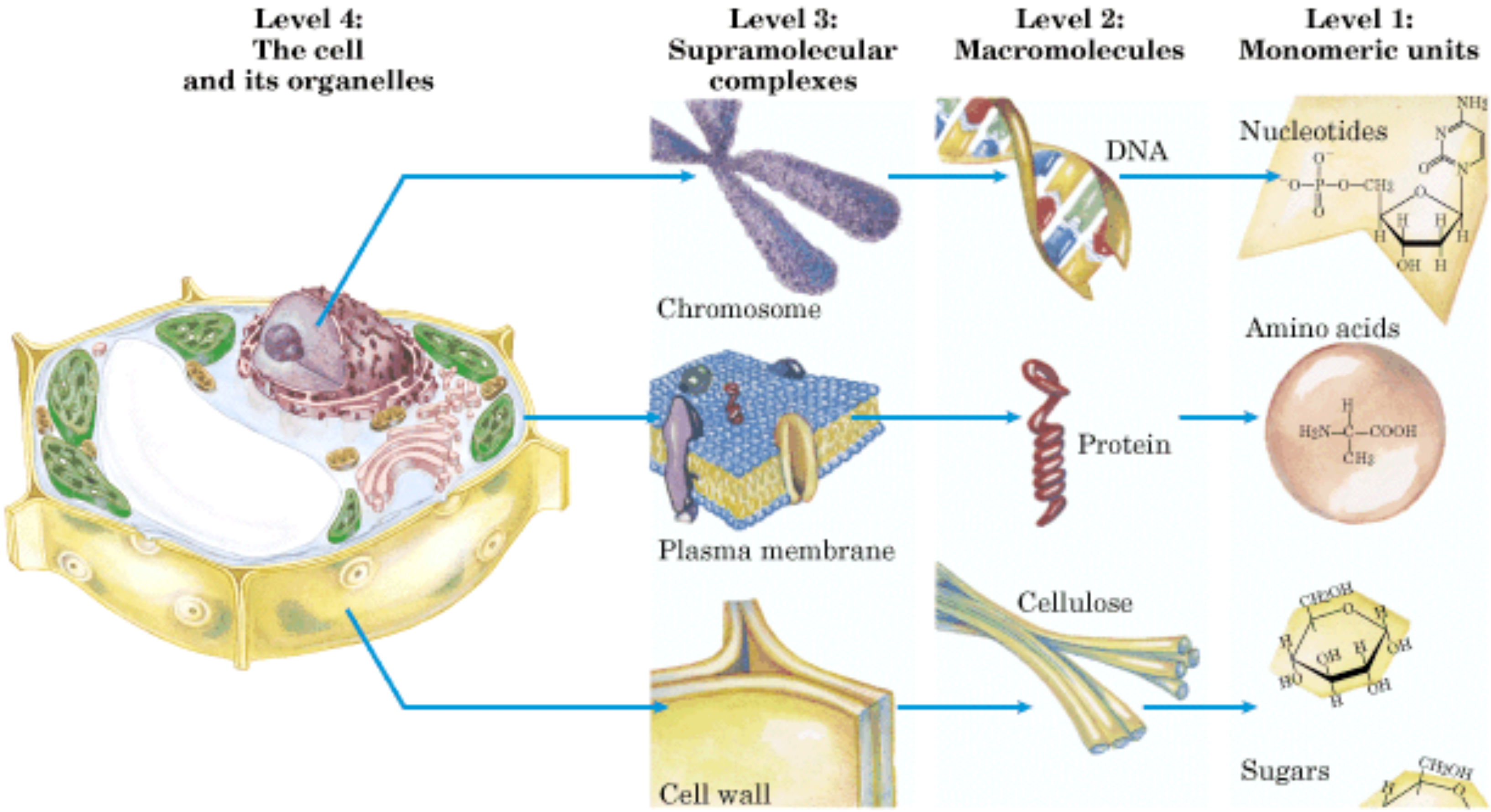

Amino acids
Proteins
Peptide hormones
Neurotransmitters
Toxic alkaloids
Adenine
Nucleic acids
ATP
Coenzymes
Neurotransmitters
Palmitic acid
Membrane lipids
Fats
Waxes
Glucose
Cellulose
Starch
Fructose
Mannose
Sucrose
Lactose

Figure 1-18b *Molecular Biology of the Cell*, Fifth Edition (© Garland Science 2008)



Ribosomes
Peroxisome
Cytoskeleton
Lysosome
Transport vesicle
Golgi complex
Smooth endoplasmic reticulum
Nucleus
Nuclear envelope
(a)
Nucleolus
Ribosomes
Cytoskeleton
Rough endoplasmic reticulum
Mitochondrion
Plasma membrane
Golgi complex
Chloroplast
Starch granule
Thylakoids
Cell wall
Cell wall of adjacent cell
Vacuole
Plasmodesma
(b)



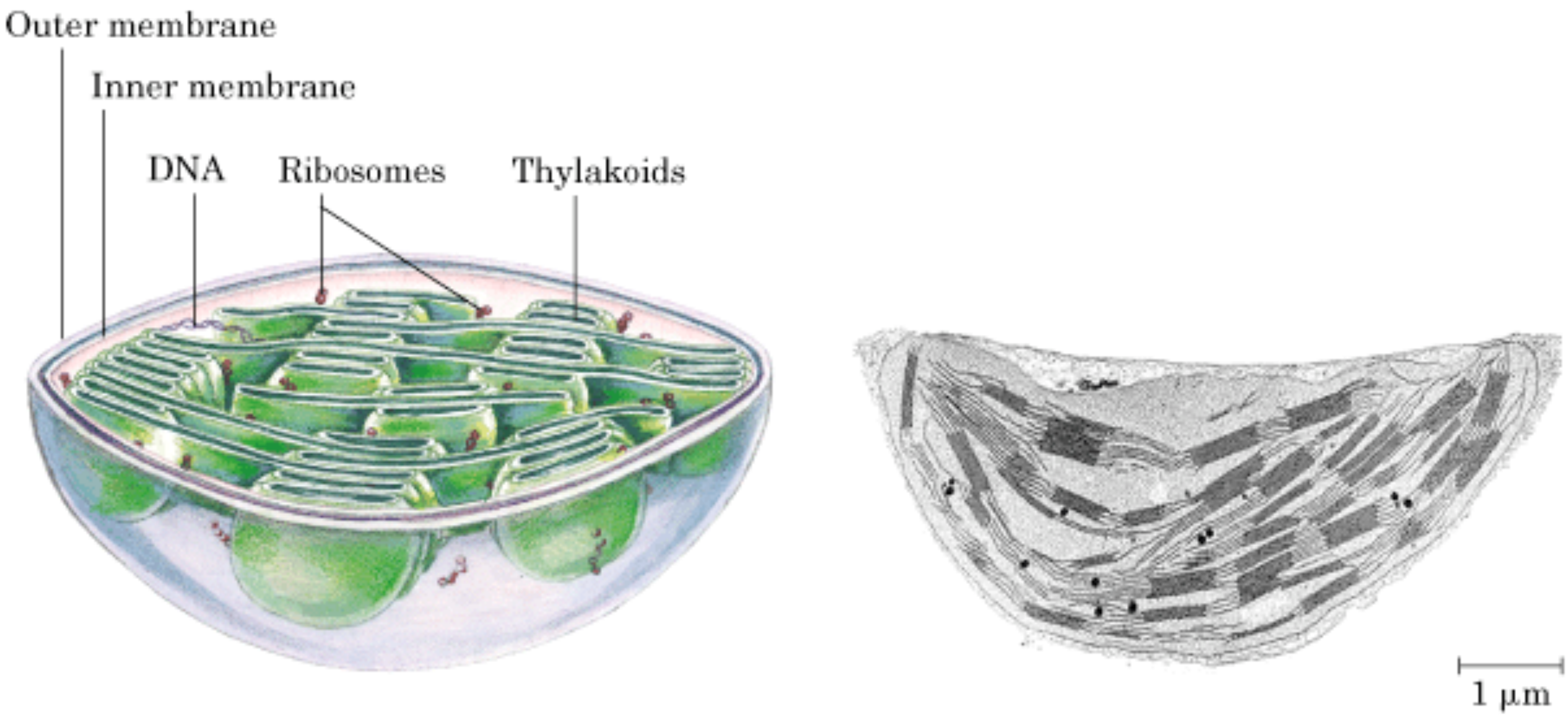
Level 4:
The cell
and its organelles
Level 3:
Supramolecular
complexes
Level 2:
Macromolecules
Level 1:
Monomeric units
Nucleotides
DNA
Chromosome
Amino acids
Protein
Plasma membrane
Cellulose
Cell wall
Sugars

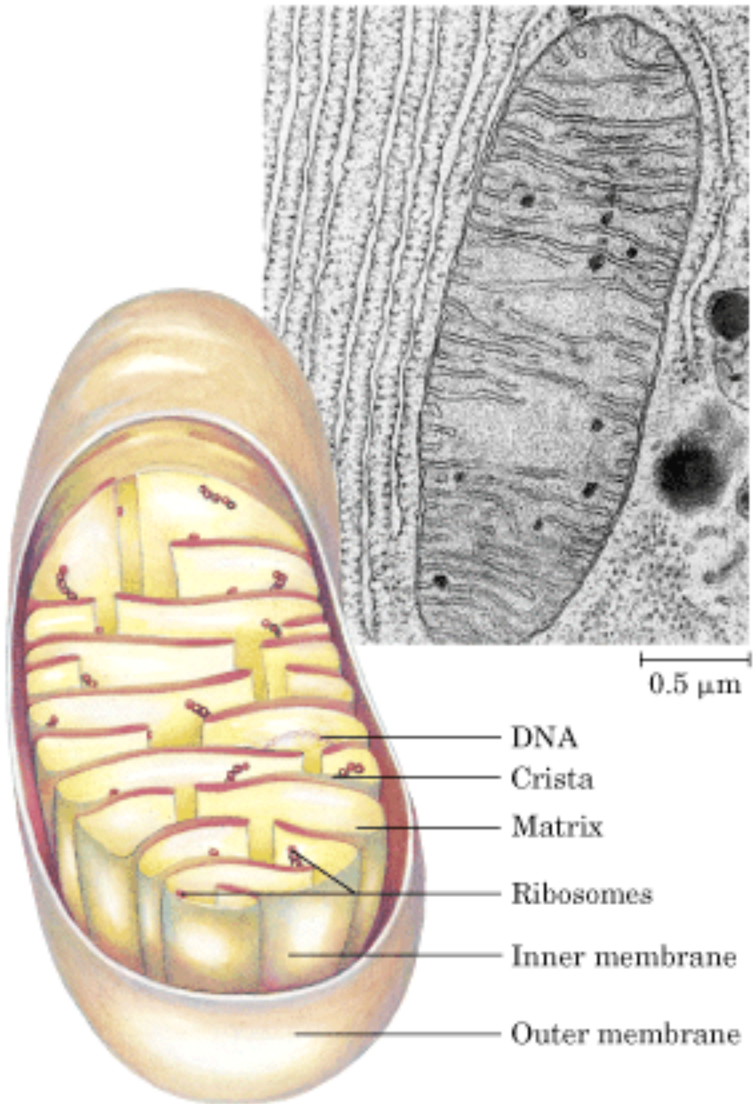
table 2–1

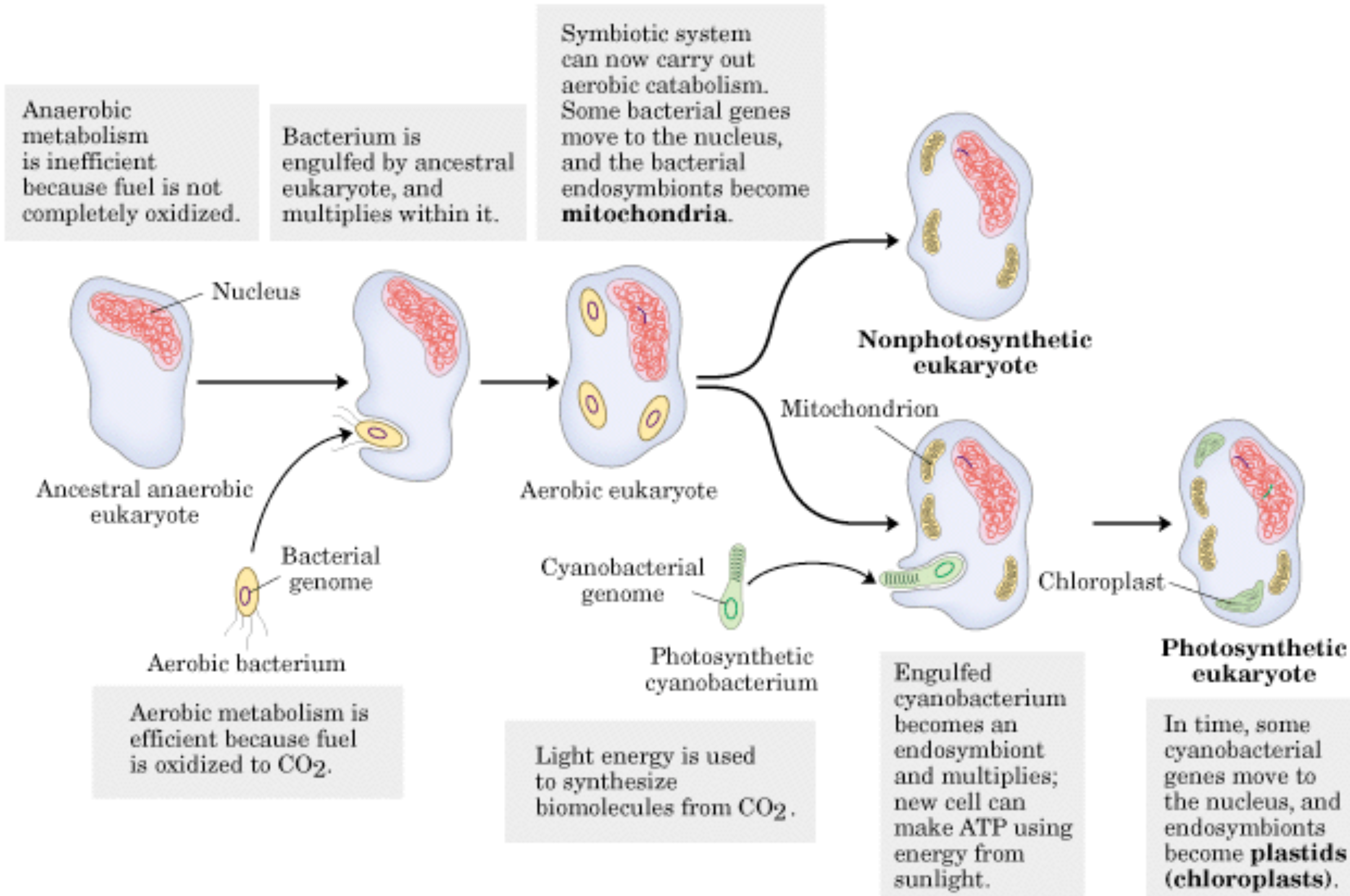
Comparison of Prokaryotic and Eukaryotic Cells

Characteristic	Prokaryotic cell	Eukaryotic cell
Size	Generally small (1–10 μm)	Generally large (5–100 μm)
Genome	DNA with nonhistone protein; genome in nucleoid, not surrounded by membrane	DNA complexed with histone and nonhistone proteins in chromosomes; chromosomes in nucleus with membranous envelope
Cell division	Fission or budding; no mitosis	Mitosis including mitotic spindle; centrioles in many species
Membrane-bounded organelles	Absent	Mitochondria, chloroplasts (in plants, some algae), endoplasmic reticulum, Golgi complexes, lysosomes (in animals), etc.
Nutrition	Absorption; some photosynthesis	Absorption, ingestion; photosynthesis in some species
Energy metabolism	No mitochondria; oxidative enzymes bound to plasma membrane; great variation in metabolic pattern	Oxidative enzymes packaged in mitochondria; more unified pattern of oxidative metabolism
Cytoskeleton	None	Complex, with microtubules, intermediate filaments, actin filaments
Intracellular movement	None	Cytoplasmic streaming, endocytosis, phagocytosis, mitosis, vesicle transport

Source: Modified from Hickman, C.P., Roberts, L.S., & Hickman, F.M. (1990) *Biology of Animals*, 5th edn, p. 30, Mosby–Yearbook, Inc., St. Louis, MO.


Outer membrane
Inner membrane
DNA
Ribosomes
Thylakoids
1 μm


0.5 μm
DNA
Crista
Matrix
Ribosomes
Inner membrane
Outer membrane


Anaerobic metabolism is inefficient because fuel is not completely oxidized.
Bacterium is engulfed by ancestral eukaryote, and multiplies within it.
Symbiotic system can now carry out aerobic catabolism. Some bacterial genes move to the nucleus, and the bacterial endosymbionts become **mitochondria**.
Nucleus
Nonphotosynthetic eukaryote
Ancestral anaerobic eukaryote
Aerobic eukaryote
Mitochondrion
Bacterial genome
Cyanobacterial genome
Chloroplast
Aerobic bacterium
Photosynthetic cyanobacterium
Photosynthetic eukaryote
Aerobic metabolism is efficient because fuel is oxidized to CO_2.
Light energy is used to synthesize biomolecules from CO_2.
Engulfed cyanobacterium becomes an endosymbiont and multiplies; new cell can make ATP using energy from sunlight.
In time, some cyanobacterial genes move to the nucleus, and endosymbionts become **plastids (chloroplasts)**.

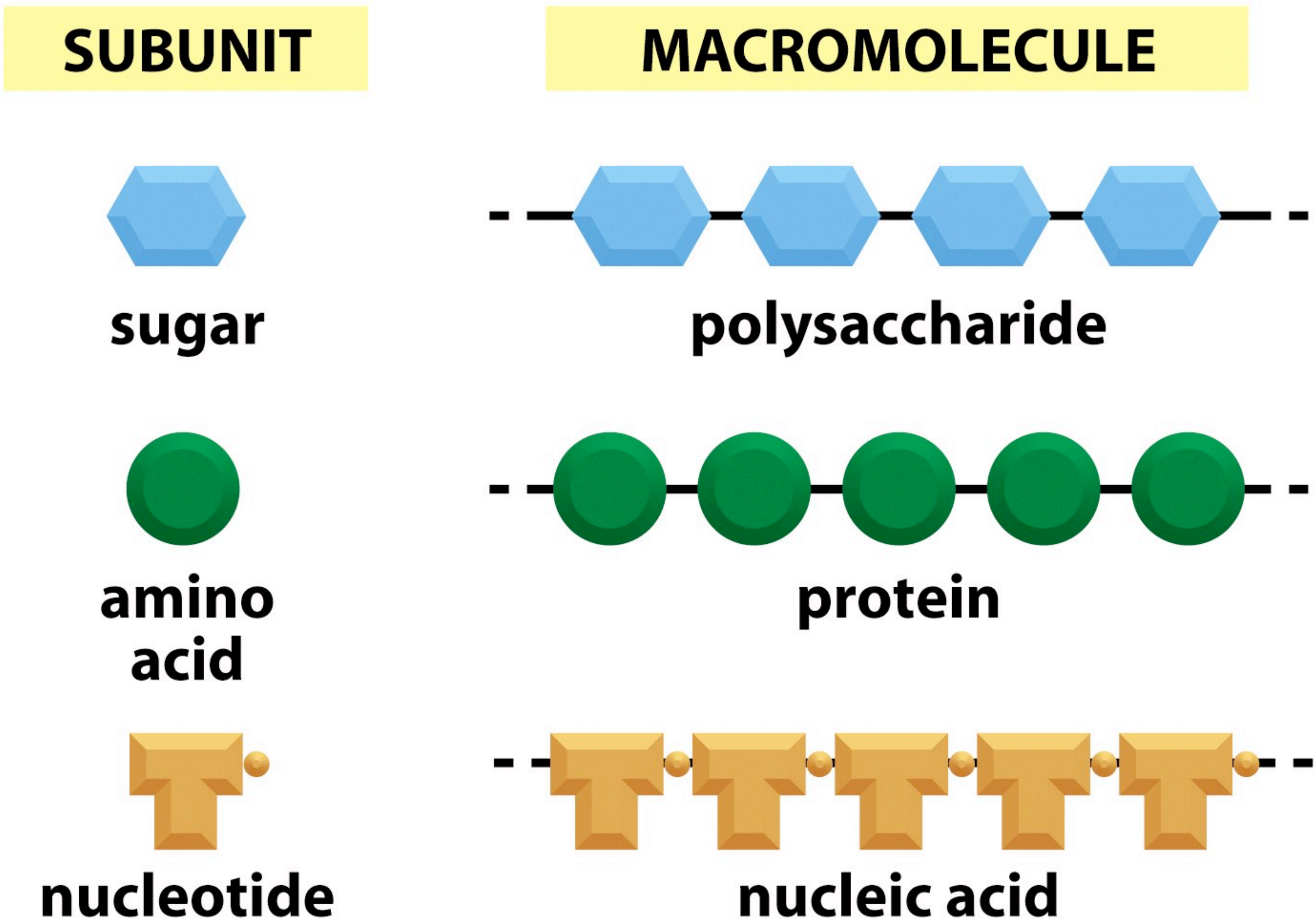


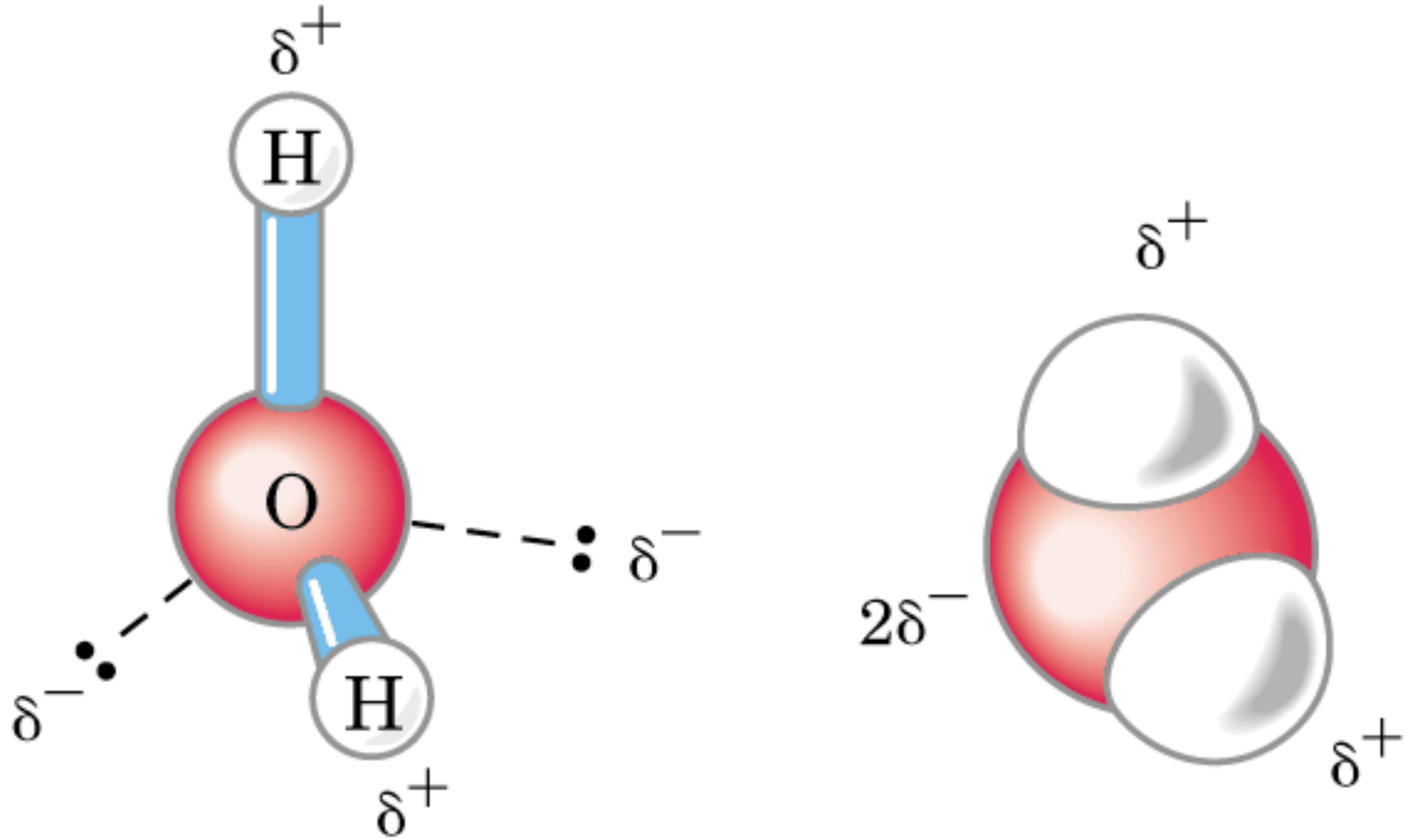
Figure 2-30 *Molecular Biology of the Cell* (© Garland Science 2008)

Table 2–3 Approximate Chemical Compositions of a Typical Bacterium and a Typical Mammalian Cell

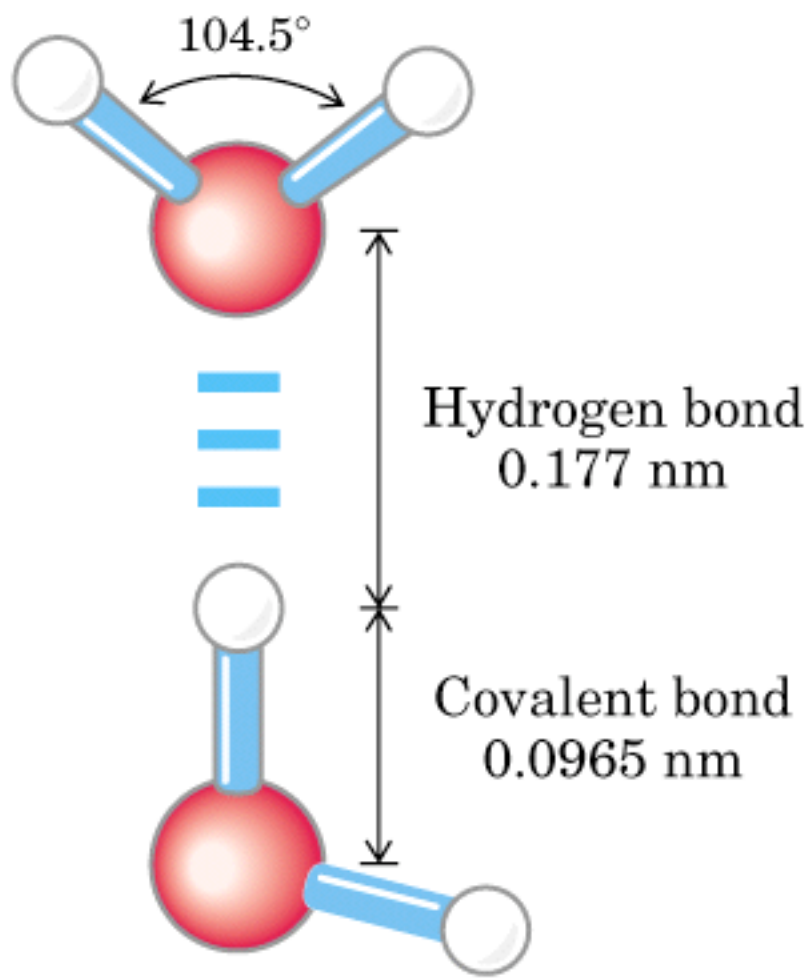
COMPONENT	PERCENT OF TOTAL CELL WEIGHT *E. COLI* BACTERIUM	MAMMALIAN CELL
H_2O	70	70
Inorganic ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, etc.)	1	1
Miscellaneous small metabolites	3	3
Proteins	15	18
RNA	6	1.1
DNA	1	0.25
Phospholipids	2	3
Other lipids	–	2
Polysaccharides	2	2
Total cell volume	2×10^{-12} cm^3	4×10^{-9} cm^3
Relative cell volume	1	2000

Proteins, polysaccharides, DNA, and RNA are macromolecules. Lipids are not generally classed as macromolecules even though they share some of their features; for example, most are synthesized as linear polymers of a smaller molecule (the acetyl group on acetyl CoA), and they self-assemble into larger structures (membranes). Note that water and protein comprise most of the mass of both mammalian and bacterial cells.

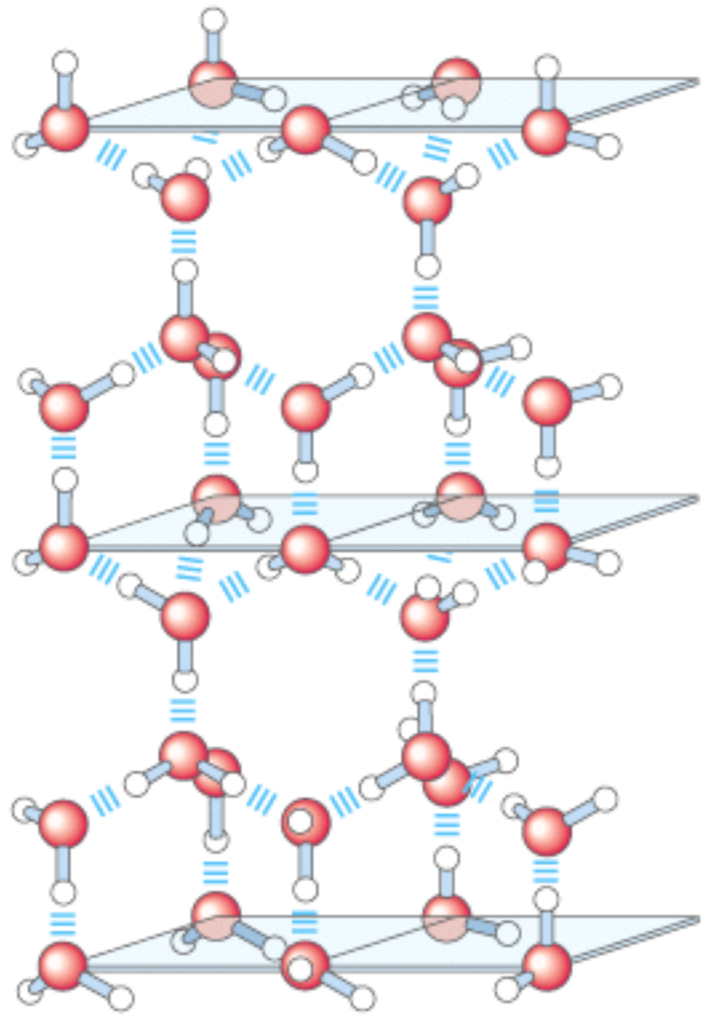
Table 2-3 *Molecular Biology of the Cell* (© Garland Science 2008)

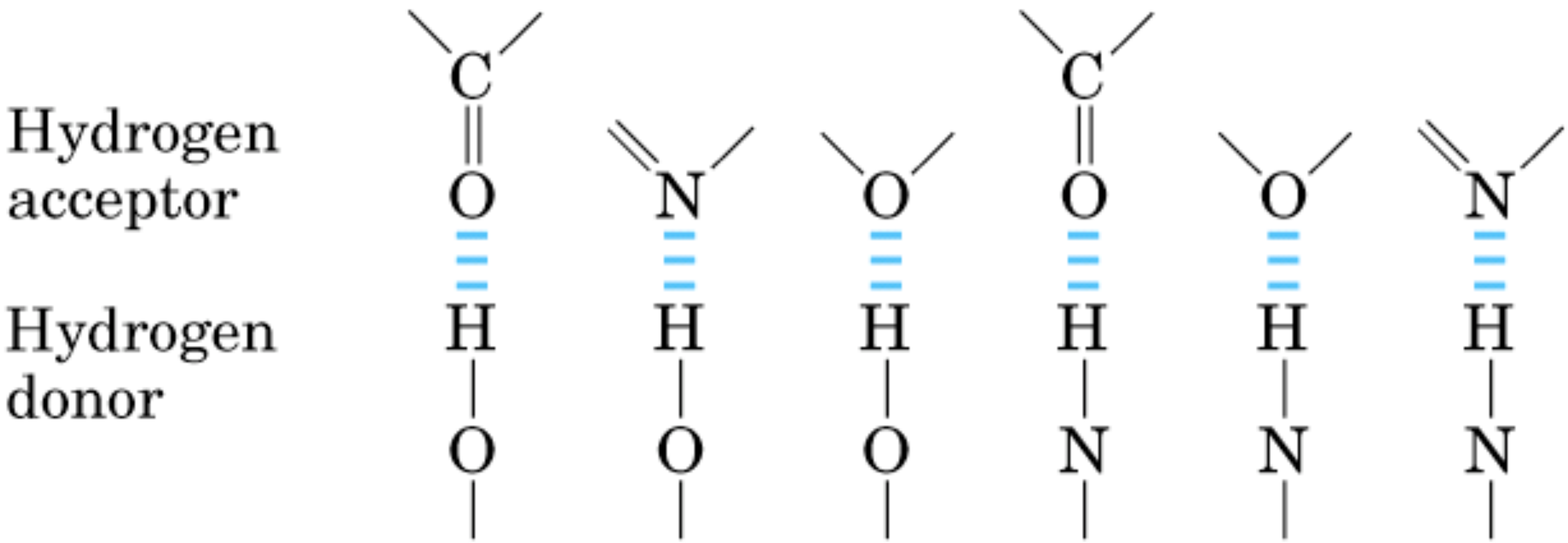


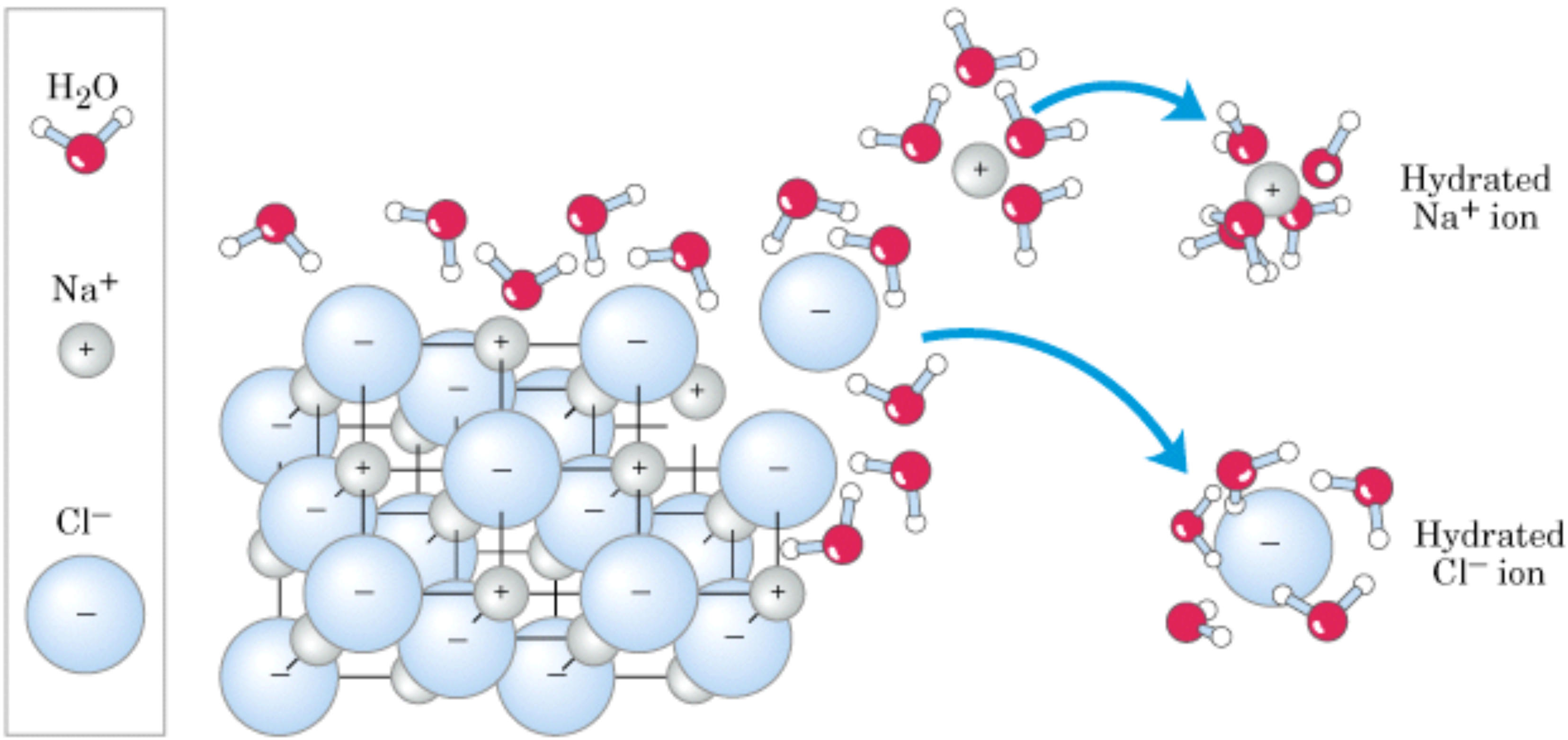
(a) **(b)**



(c)



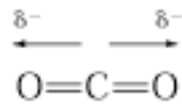
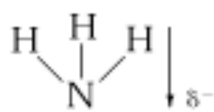
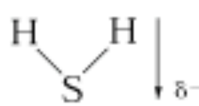

Hydrogen acceptor
Hydrogen donor



H_2O
Na^+
Cl^-
Hydrated Na^+ ion
Hydrated Cl^- ion

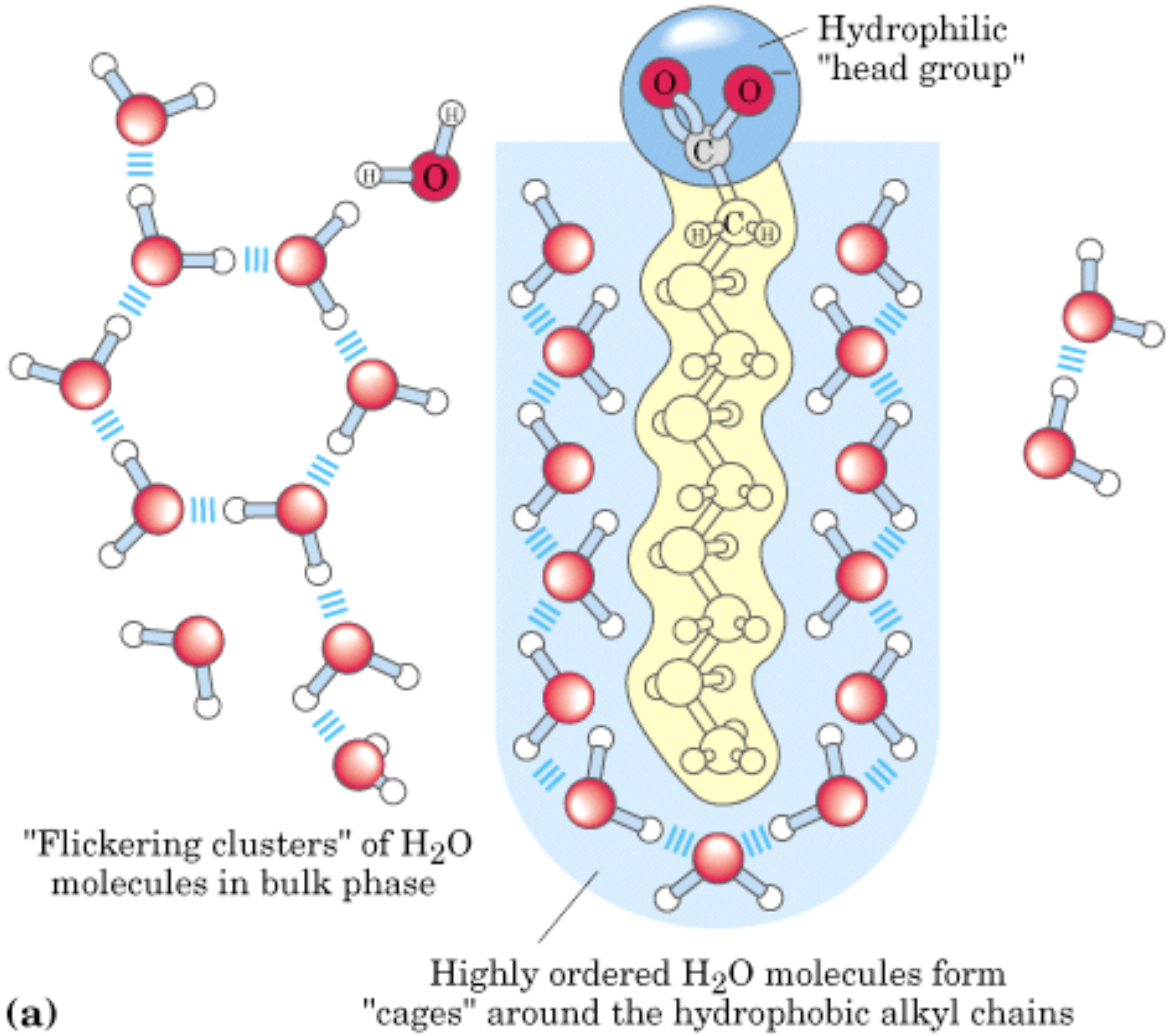
table 4–3

Solubilities of Some Gases in Water

Gas	Structure*	Polarity	Solubility in water (g/L)†
Nitrogen	N≡N	Nonpolar	0.018 (40 °C)
Oxygen	O=O	Nonpolar	0.035 (50 °C)
Carbon dioxide		Nonpolar	0.97 (45 °C)
Ammonia		Polar	900 (10 °C)
Hydrogen sulfide		Polar	1,860 (40 °C)

*The arrows represent electric dipoles; there is a partial negative charge (δ^-) at the head of the arrow, a partial positive charge (δ^+; not shown here) at the tail.

†Note that polar molecules dissolve far better even at low temperatures than do nonpolar molecules at relatively high temperatures.


Hydrophilic
"head group"
"Flickering clusters" of H_2O
molecules in bulk phase
Highly ordered H_2O molecules form
"cages" around the hydrophobic alkyl chains

(a)

table 4–4

Four Types of Noncovalent ("Weak") Interactions among Biomolecules in Aqueous Solvent

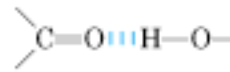
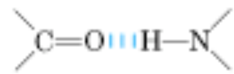
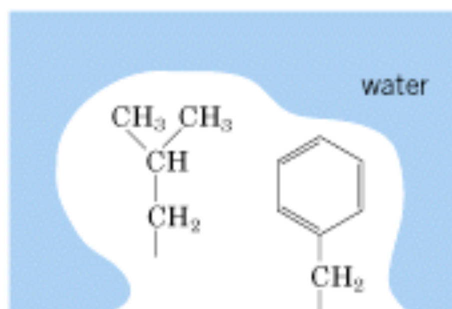
Hydrogen bonds	
Between neutral groups	
Between peptide bonds	
Ionic interactions	
Attraction	
Repulsion	
Hydrophobic interactions	
Van der Waals interactions	Any two atoms in close proximity

Table 2–1 Covalent and Noncovalent Chemical Bonds

BOND TYPE	LENGTH (nm)	STRENGTH (kcal/mole) IN VACUUM	STRENGTH (kcal/mole) IN WATER
Covalent	0.15	90	90
Noncovalent: ionic*	0.25	80	3
hydrogen	0.30	4	1
van der Waals attraction (per atom)	0.35	0.1	0.1

*An ionic bond is an electrostatic attraction between two fully charged atoms.

Table 2-1 *Molecular Biology of the Cell* (© Garland Science 2008)

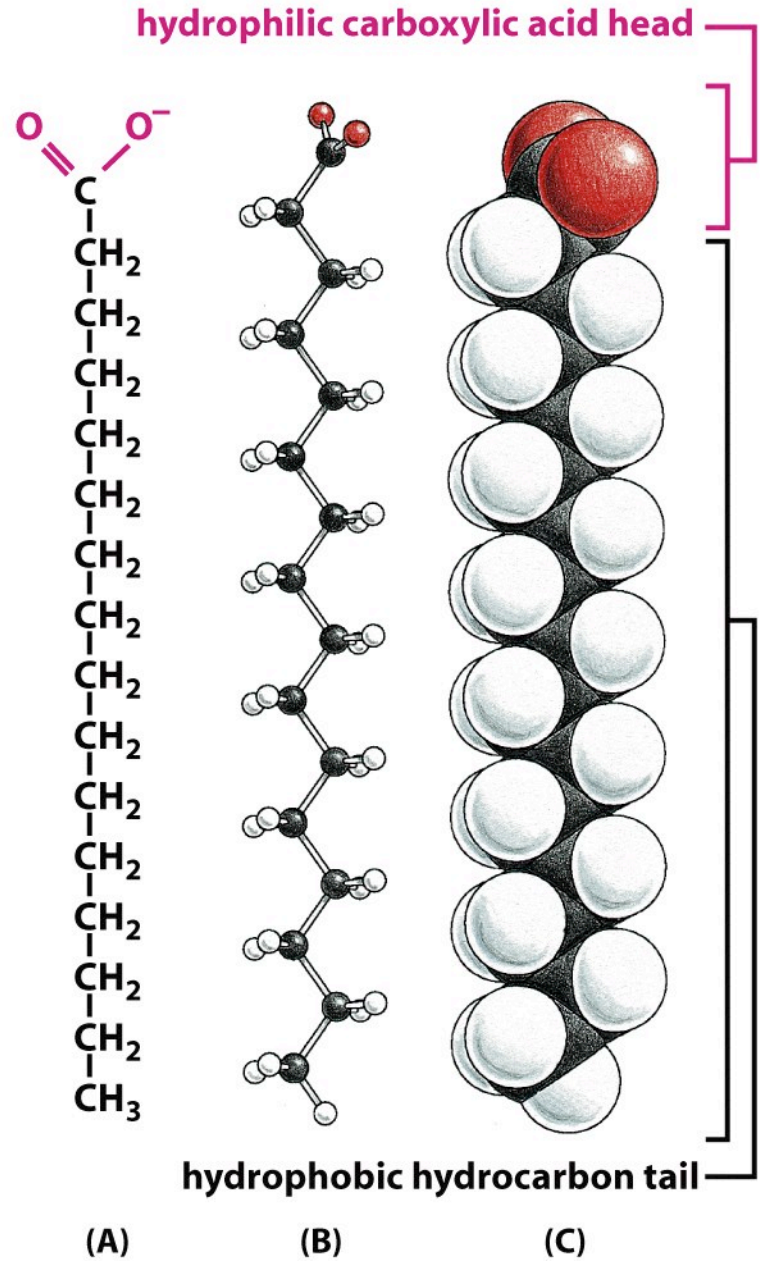


Figure 2-21 *Molecular Biology of the Cell* (© Garland Science 2008)

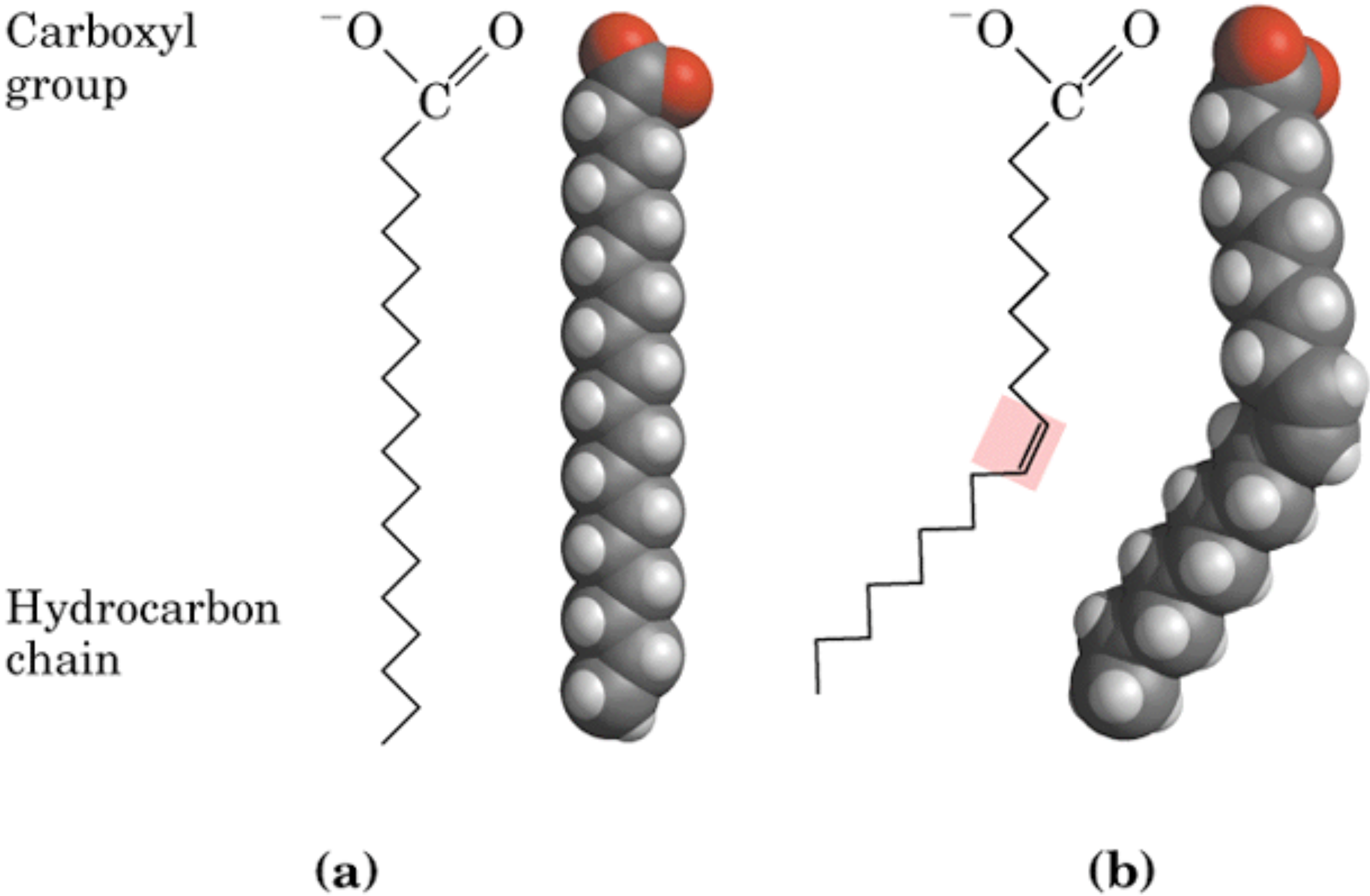

Carboxyl
group
Hydrocarbon
chain
⁻O
C
O
(a)
(b)

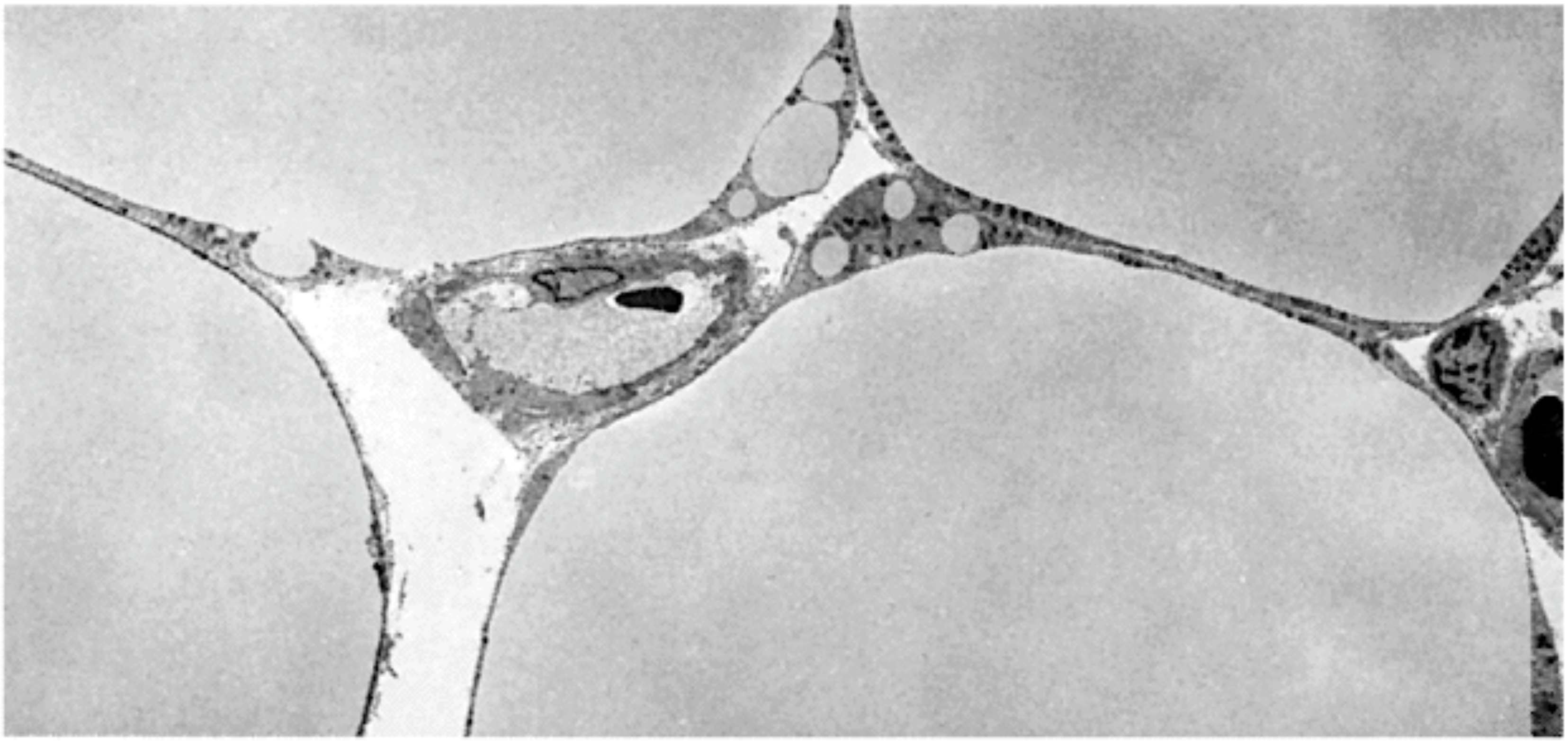
table 11–1

Some Naturally Occurring Fatty Acids

Carbon skeleton	Structure*	Systematic name[†]	Common name (derivation)	Melting point (°C)	Solubility at 30 °C (mg/g solvent) Water	Benzene
12:0	$CH_3(CH_2)_{10}COOH$	*n*-Dodecanoic acid	Lauric acid (Latin *laurus*, "laurel plant")	44.2	0.063	2,600
14:0	$CH_3(CH_2)_{12}COOH$	*n*-Tetradecanoic acid	Myristic acid (Latin *Myristica*, nutmeg genus)	53.9	0.024	874
16:0	$CH_3(CH_2)_{14}COOH$	*n*-Hexadecanoic acid	Palmitic acid (Latin *palma*, "palm tree")	63.1	0.0083	348
18:0	$CH_3(CH_2)_{16}COOH$	*n*-Octadecanoic acid	Stearic acid (Greek *stear*, "hard fat")	69.6	0.0034	124
20:0	$CH_3(CH_2)_{18}COOH$	*n*-Eicosanoic acid	Arachidic acid (Latin *Arachis*, legume genus)	76.5		
24:0	$CH_3(CH_2)_{22}COOH$	*n*-Tetracosanoic acid	Lignoceric acid (Latin *lignum*, "wood" + *cera*, "wax")	86.0		
16:1(Δ^9)	$CH_3(CH_2)_5CH{=}CH(CH_2)_7COOH$	*cis*-9-Hexadecenoic acid	Palmitoleic acid	−0.5		
18:1(Δ^9)	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$	*cis*-9-Octadecenoic acid	Oleic acid (Latin *oleum*, "oil")	13.4		
18:2($\Delta^{9,12}$)	$CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$	*cis*-,*cis*-9,12-Octadecadienoic acid	Linoleic acid (Greek *linon*, "flax")	−5		
18:3($\Delta^{9,12,15}$)	$CH_3CH_2CH{=}CHCH_2CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$	*cis*-,*cis*-,*cis*-9,12,15-Octadecatrienoic acid	α-Linolenic acid	−11		
20:4($\Delta^{5,8,11,14}$)	$CH_3(CH_2)_4CH{=}CHCH_2CH{=}CHCH_2CH{=}CHCH_2CH{=}CH(CH_2)_3COOH$	*cis*-,*cis*-,*cis*-,*cis*-5,8,11,14-Icosatetraenoic acid	Arachidonic acid	−49.5		

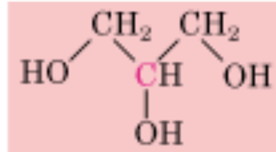
*All acids are shown in their nonionized form. At pH 7, all free fatty acids have an ionized carboxylate. Note that numbering of carbon atoms begins at the carboxyl carbon.

[†]The prefix *n*- indicates the "normal" unbranched structure. For instance, "dodecanoic" simply indicates 12 carbon atoms, which could be arranged in a variety of branched forms; "*n*-dodecanoic" specifies the linear, unbranched form. For unsaturated fatty acids, the configuration of each double bond is indicated; in biological fatty acids the configuration is almost always cis.

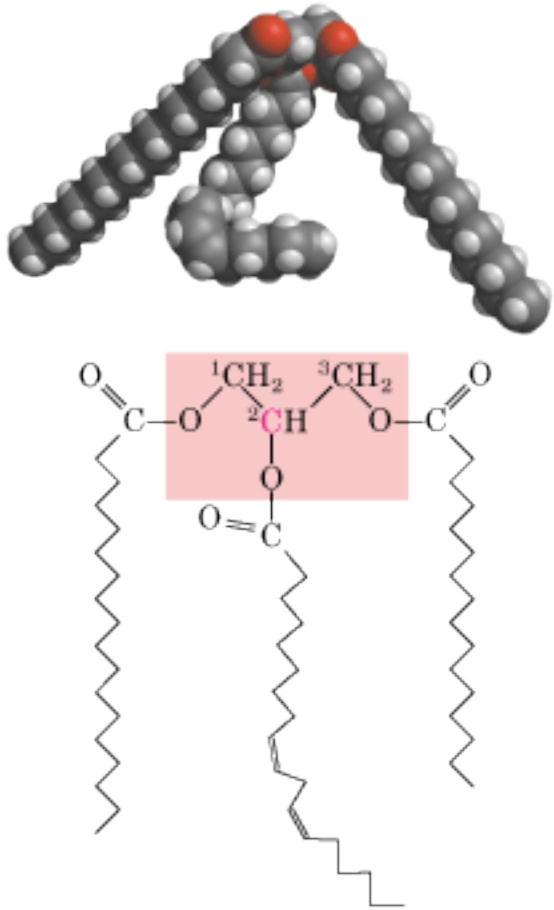


8 μm

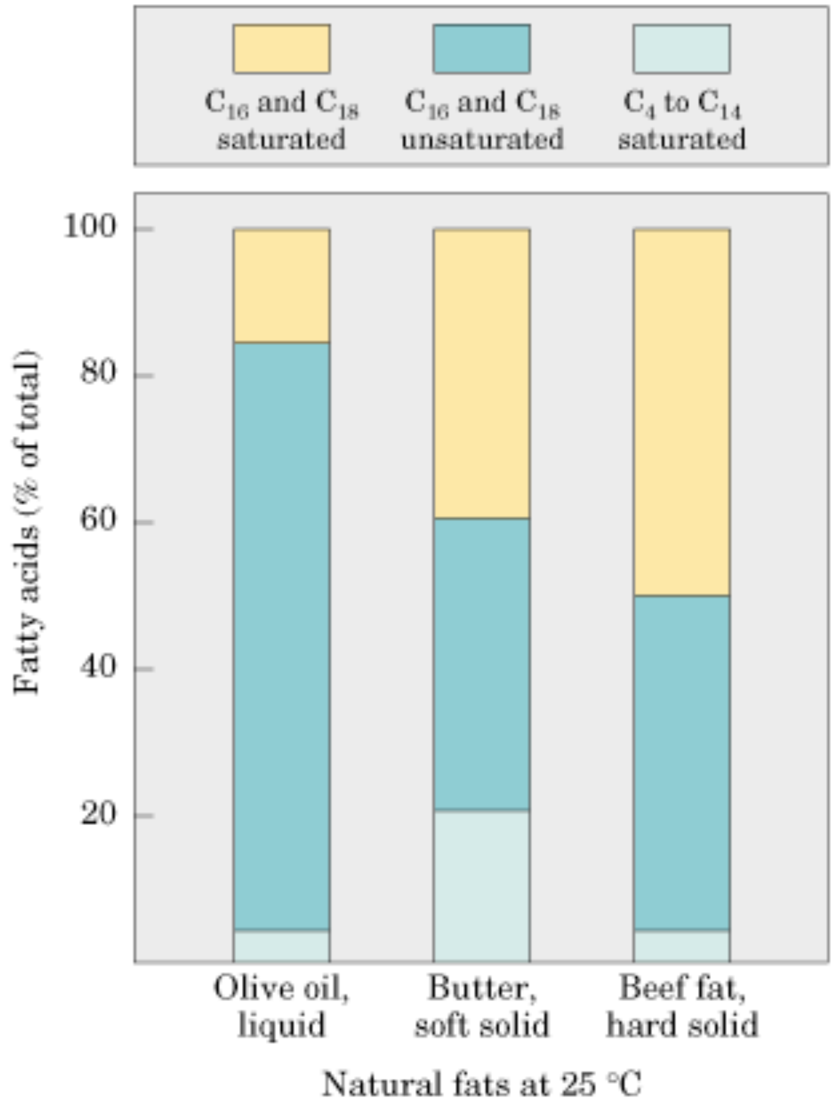
(a)



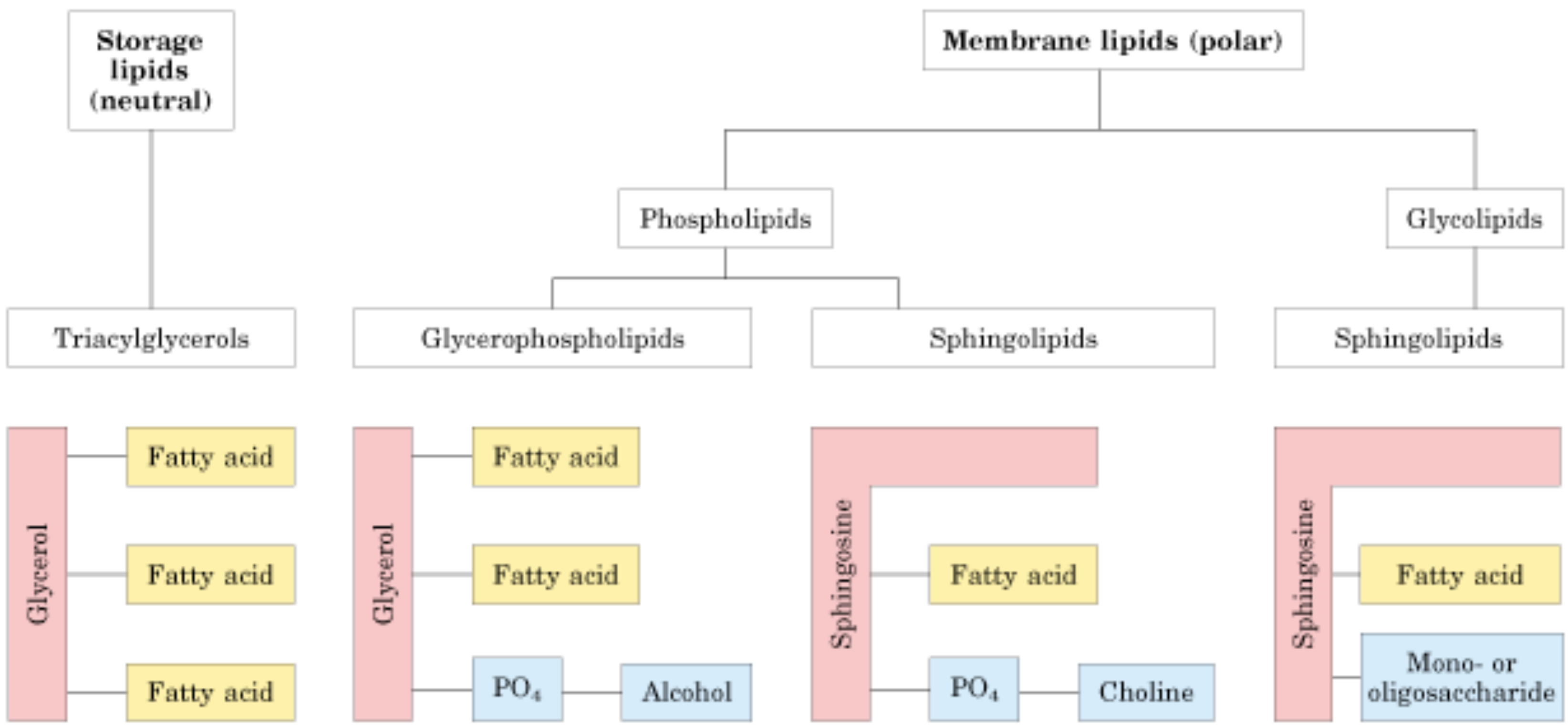
Glycerol

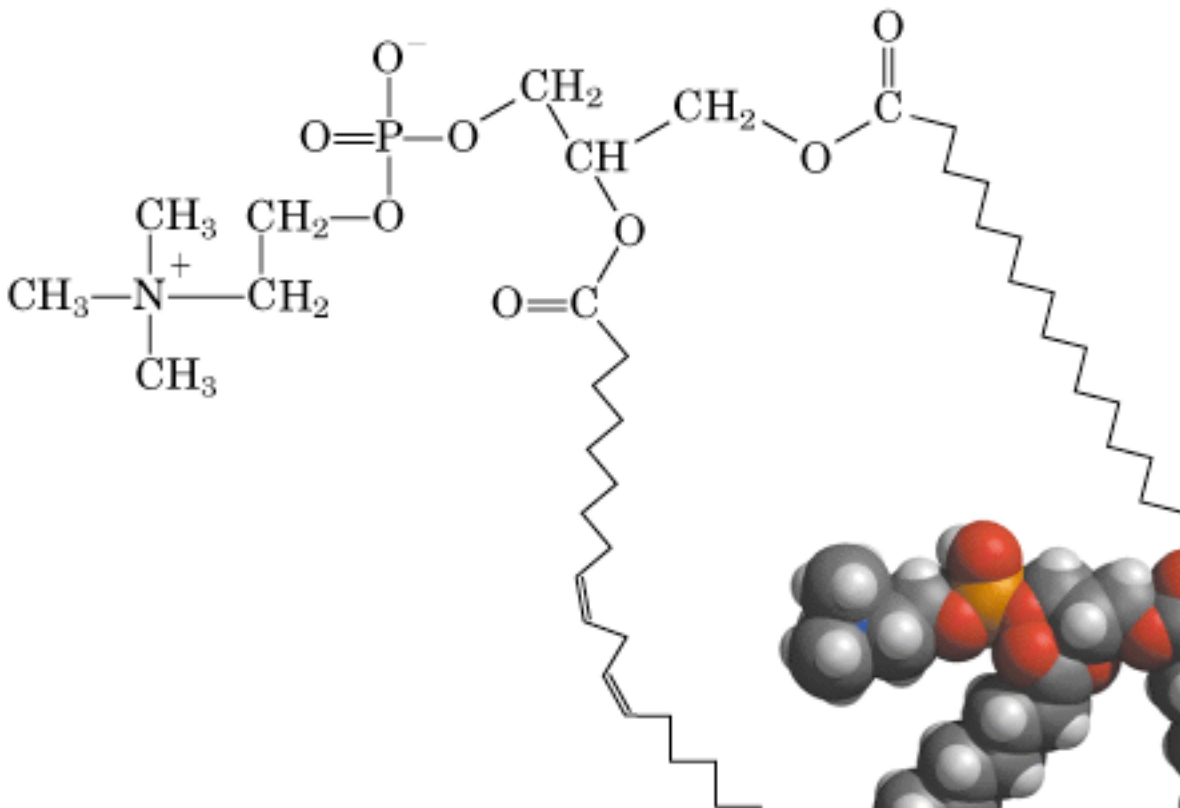


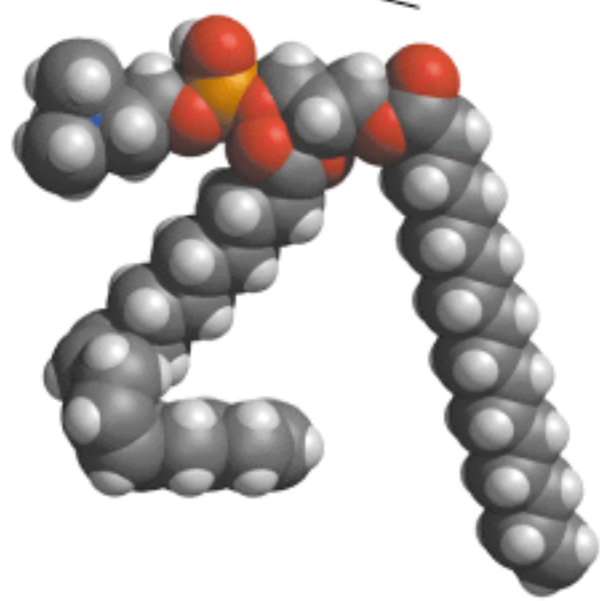
1-Stearoyl, 2-linoleoyl, 3-palmitoyl glycerol,
a mixed triacylglycerol



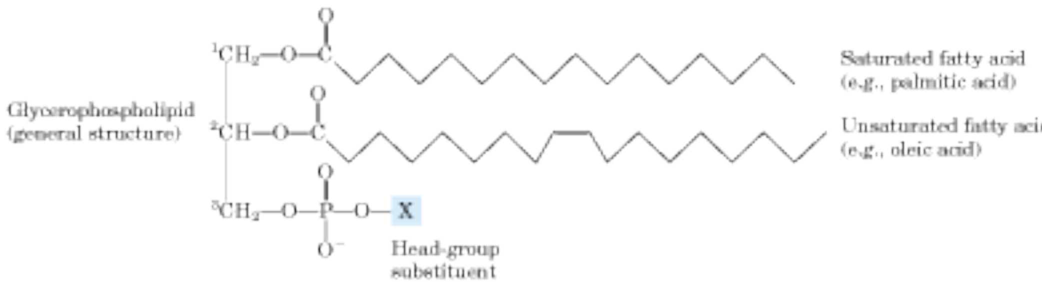
C_{16} and C_{18} saturated
C_{16} and C_{18} unsaturated
C_4 to C_{14} saturated
100
80
60
40
20
Fatty acids (% of total)
Olive oil, liquid
Butter, soft solid
Beef fat, hard solid
Natural fats at 25 °C

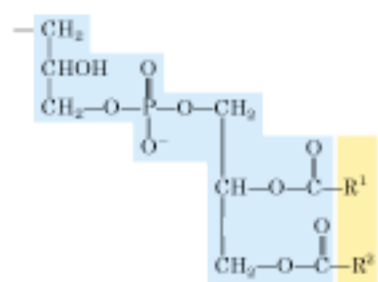

Storage lipids (neutral)
Membrane lipids (polar)
Phospholipids
Glycolipids
Triacylglycerols
Glycerophospholipids
Sphingolipids
Sphingolipids
Glycerol
Fatty acid
Fatty acid
Fatty acid
Glycerol
Fatty acid
Fatty acid
PO_4
Alcohol
Sphingosine
Fatty acid
PO_4
Choline
Sphingosine
Fatty acid
Mono- or oligosaccharide

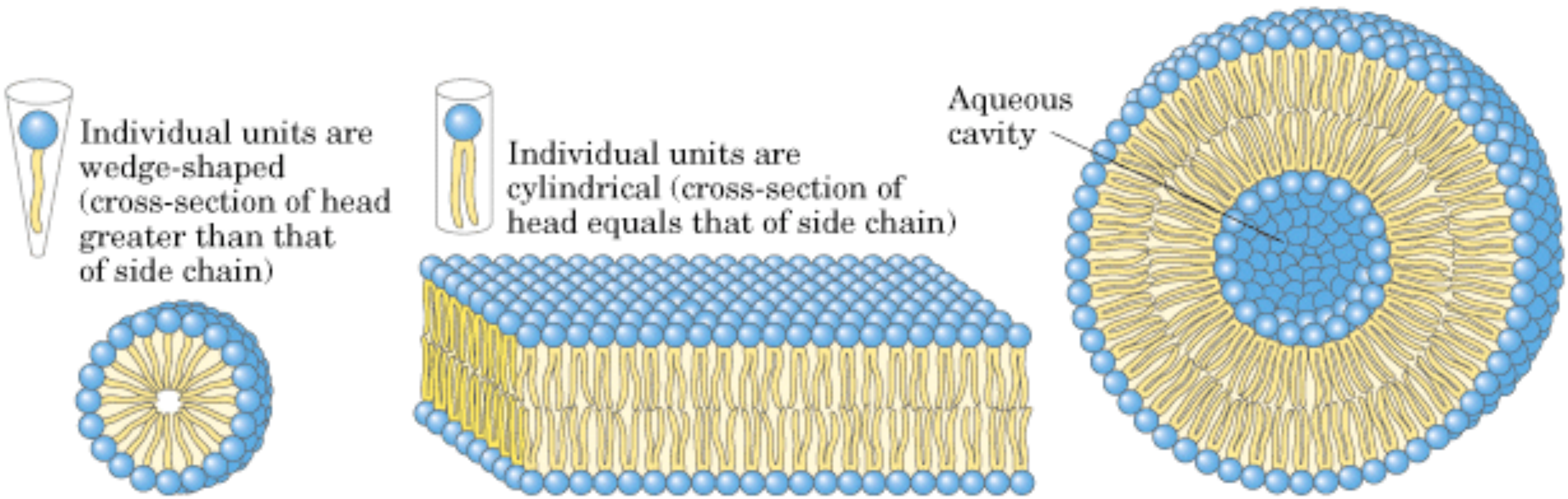




Phosphatidylcholine



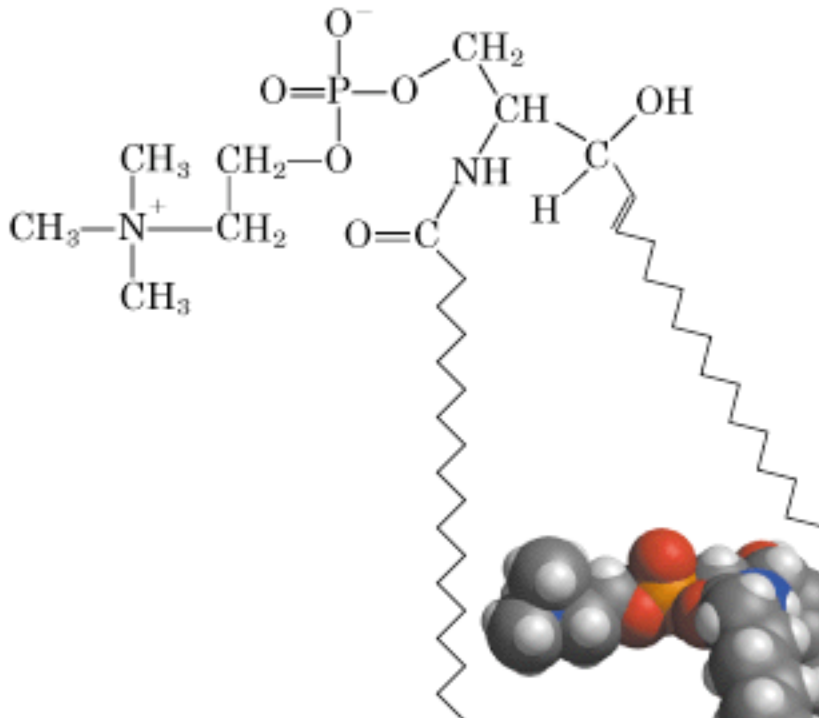
Name of glycerophospholipid	Name of X	Formula of X	Net charge (at pH 7)
Phosphatidic acid	—	$—H$	−1
Phosphatidylethanolamine	Ethanolamine	$—CH_2—CH_2—\overset{+}{N}H_3$	0
Phosphatidylcholine	Choline	$—CH_2—CH_2—\overset{+}{N}(CH_3)_3$	0
Phosphatidylserine	Serine	$—CH_2—CH(COO^-)—\overset{+}{N}H_3$	−1
Phosphatidylglycerol	Glycerol	$—CH_2—CH(OH)—CH_2—OH$	−1
Phosphatidylinositol 4,5-bisphosphate	*myo*-Inositol 4,5-bisphosphate		−4
Cardiolipin	Phosphatidyl-glycerol		−2



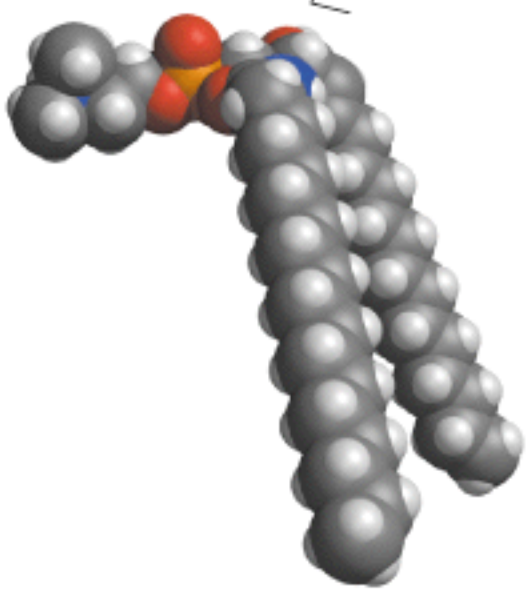
Micelle
(a)

Bilayer
(b)

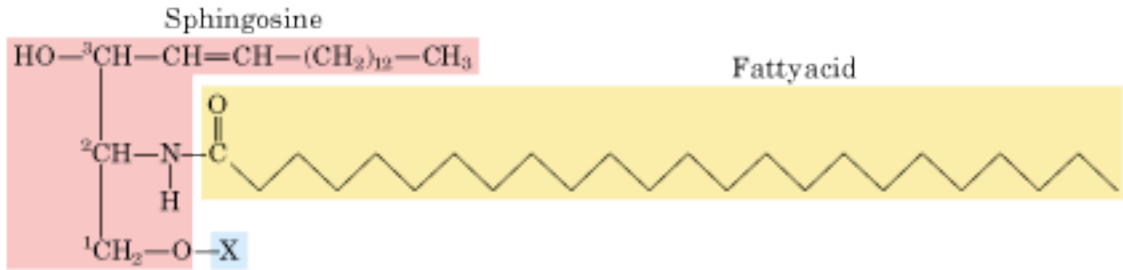
Liposome
(c)

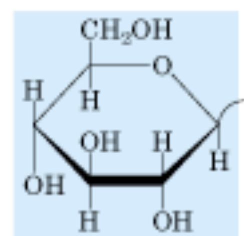
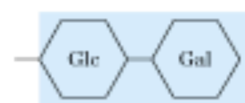
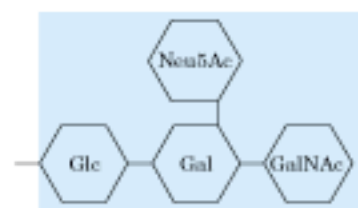


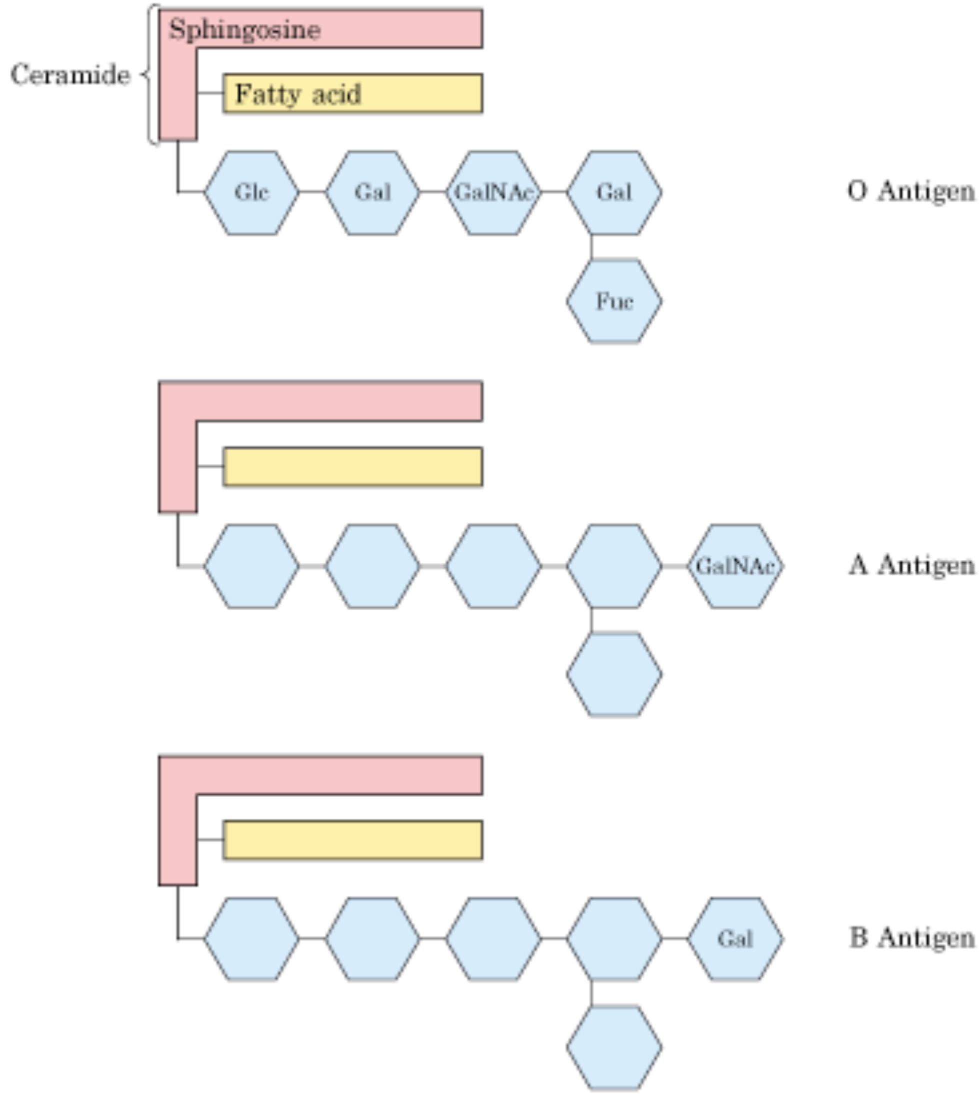
Sphingomyelin

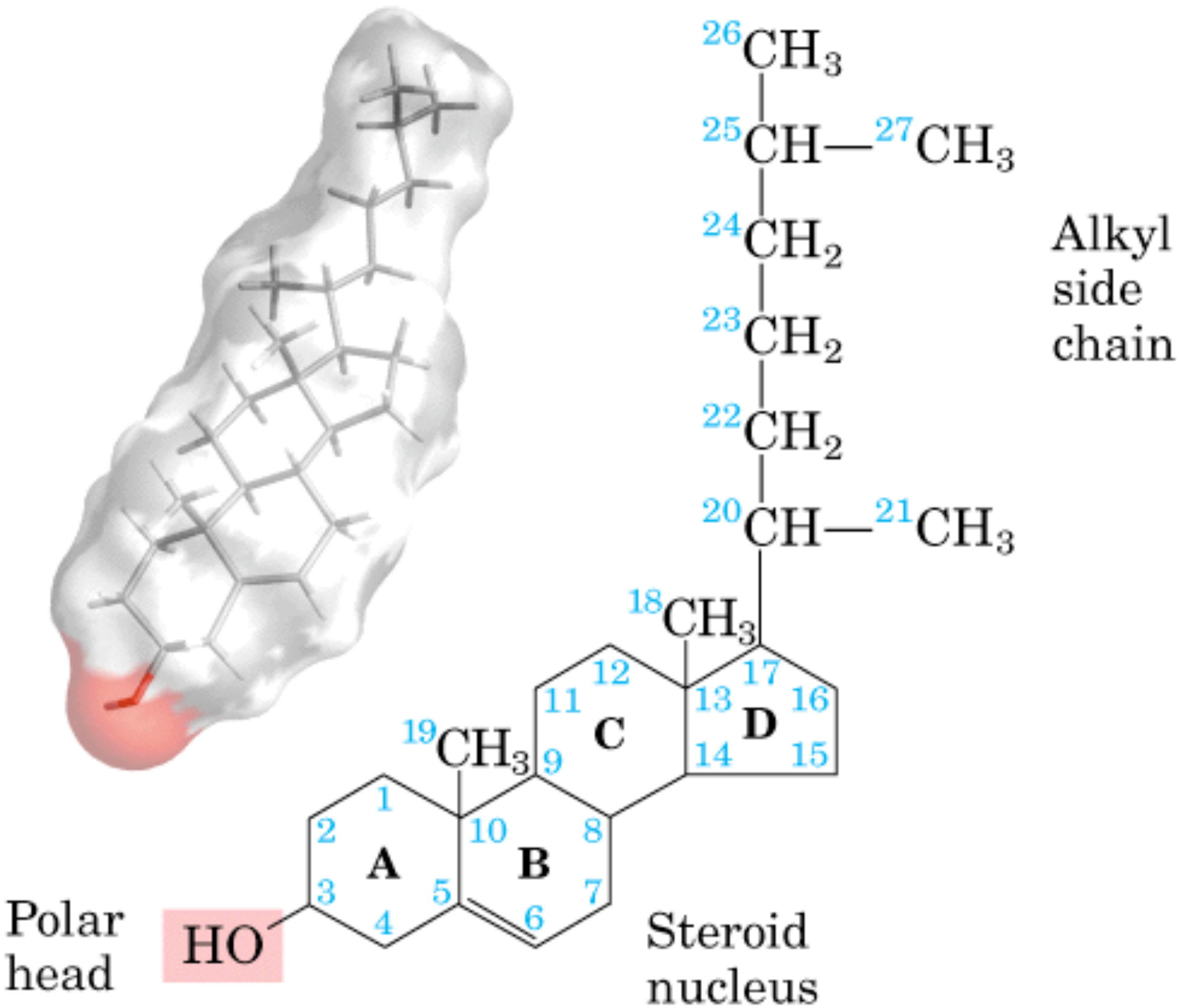


Sphingolipid (general structure)



Name of sphingolipid	Name of X	Formula of X
Ceramide	—	—H
Sphingomyelin	Phosphocholine	$-\overset{\displaystyle O}{\overset{\|}{\underset{\underset{\displaystyle O^-}{\|}}{P}}}-O-CH_2-CH_2-\overset{+}{N}(CH_3)_3$
Neutral glycolipids Glucosylcerebroside	Glucose	
Lactosylceramide (a globoside)	Di-, tri-, or tetrasaccharide	
Ganglioside GM2	Complex oligosaccharide	


Ceramide
Sphingosine
Fatty acid
Glc
Gal
GalNAc
Gal
Fuc
O Antigen
GalNAc
A Antigen
Gal
B Antigen



26CH3
25CH—27CH3
24CH2
23CH2
22CH2
20CH—21CH3
18CH3
Alkyl
side
chain
19CH3
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
A
B
C
D
Polar
head
HO
Steroid
nucleus

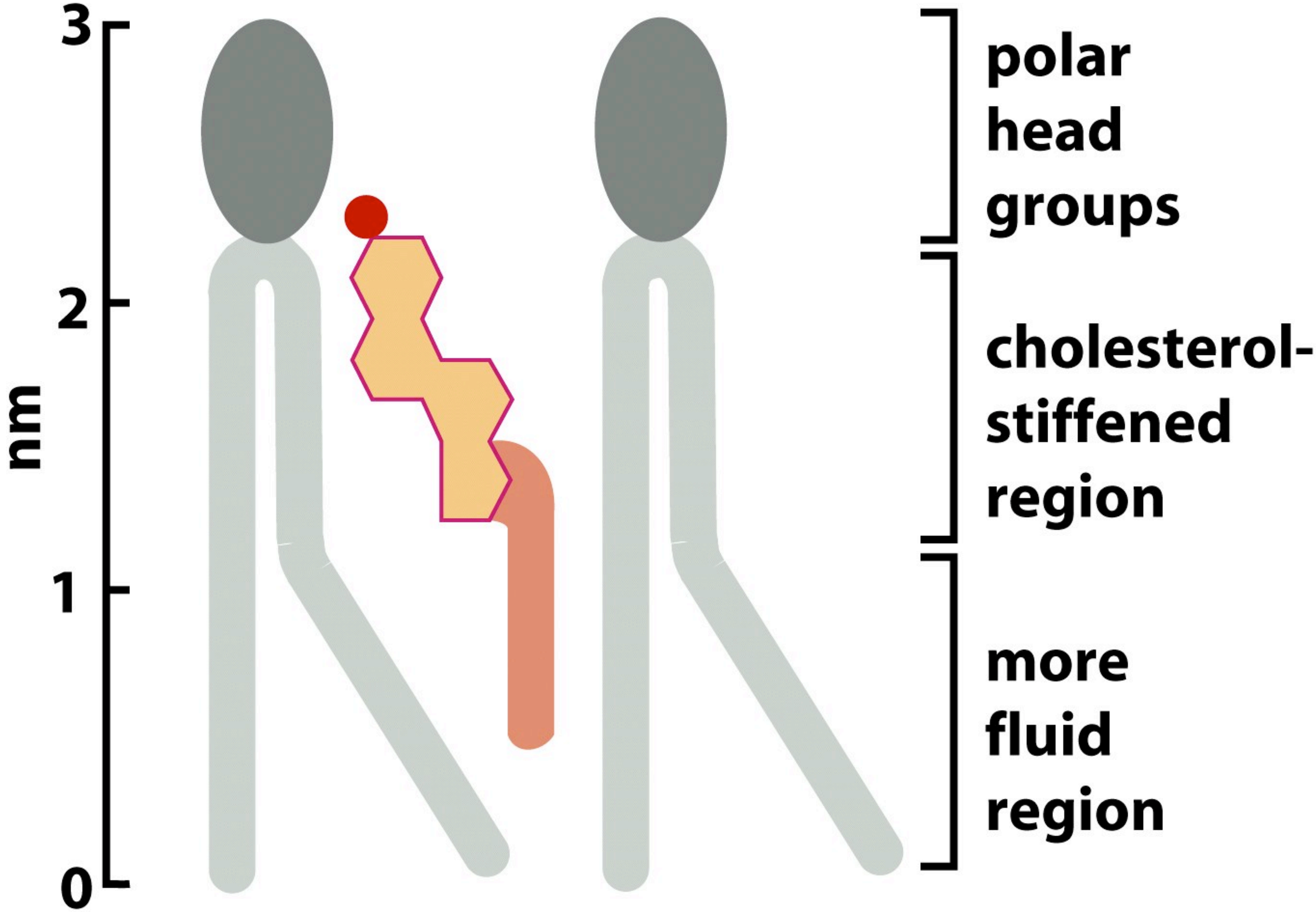
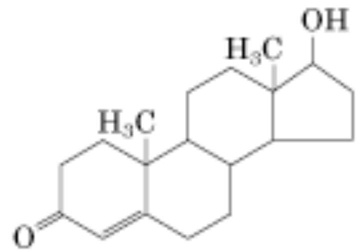
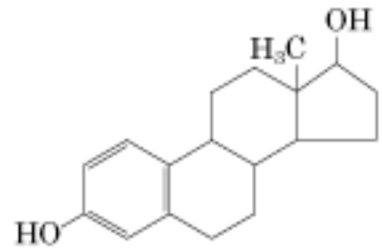


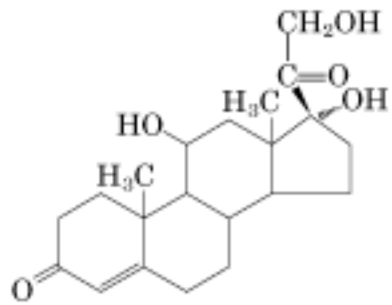
Figure 10-5 *Molecular Biology of the Cell* (© Garland Science 2008)



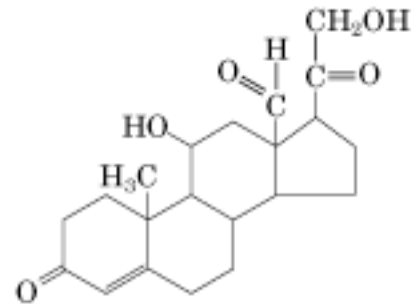
Testosterone



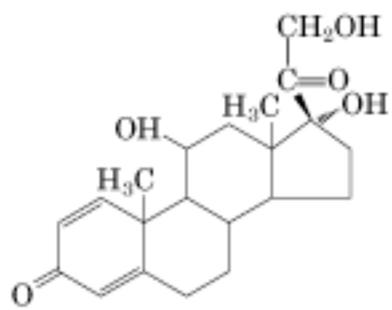
Estradiol



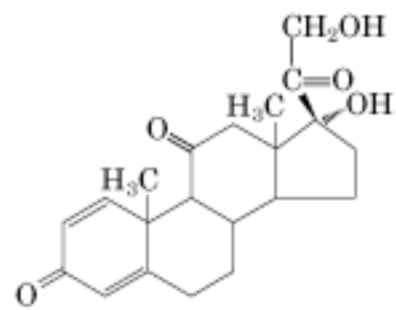
Cortisol



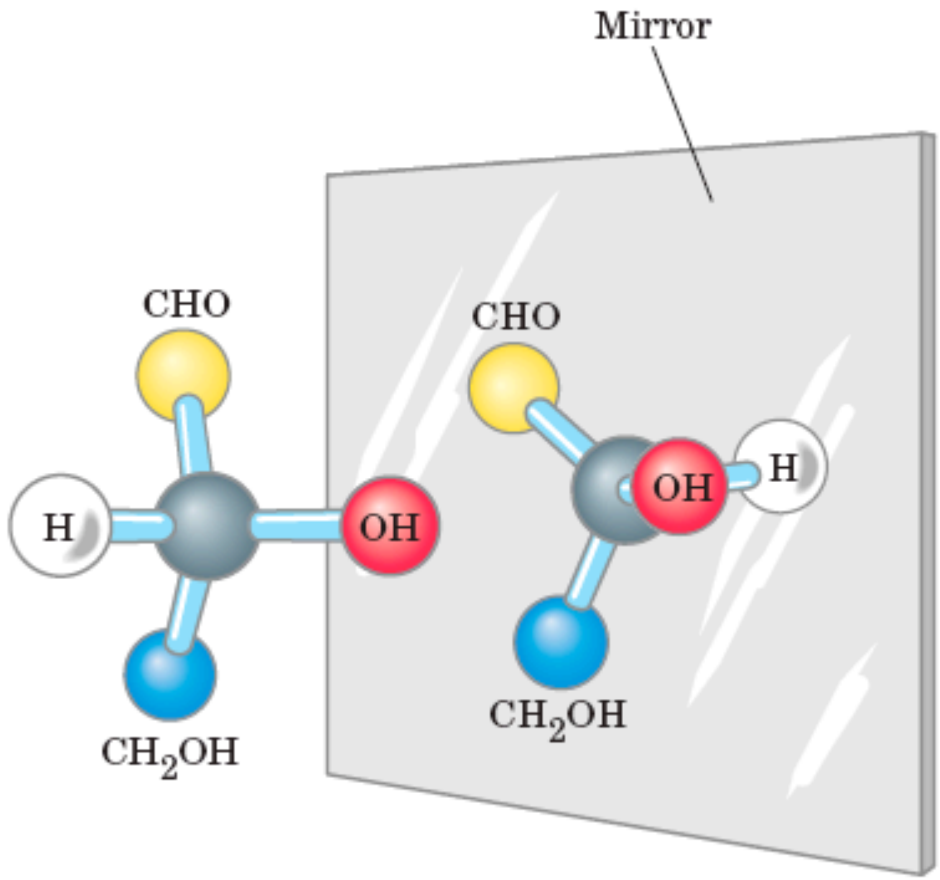
Aldosterone



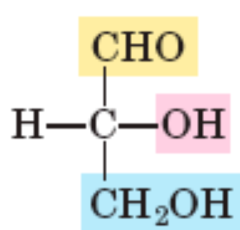
Prednisolone

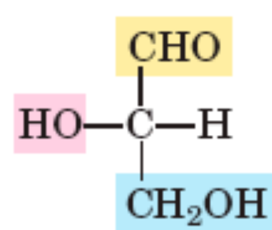


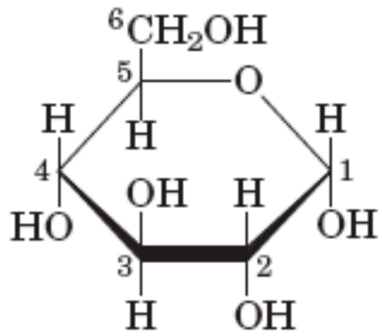
Prednisone



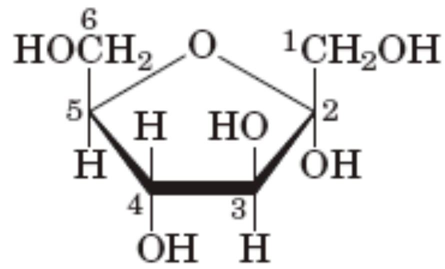
Ball-and-stick models


D-Glyceraldehyde

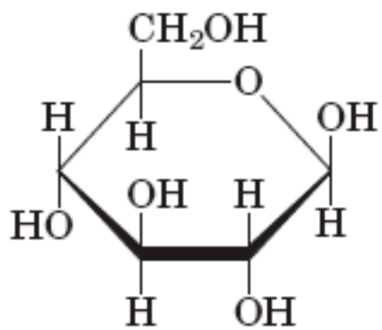

L-Glyceraldehyde



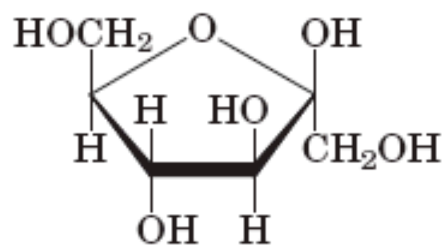
α-D-Glucopyranose



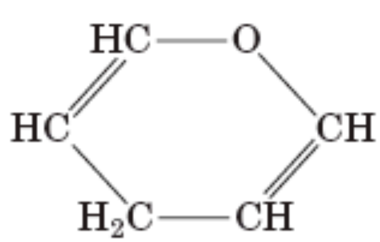
α-D-Fructofuranose



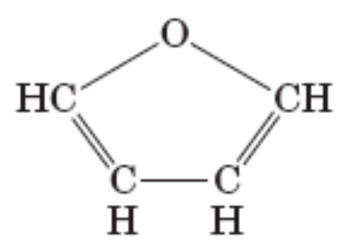
β-D-Glucopyranose



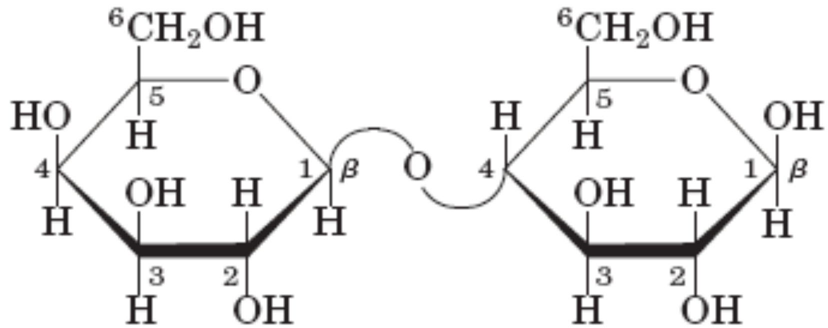
β-D-Fructofuranose



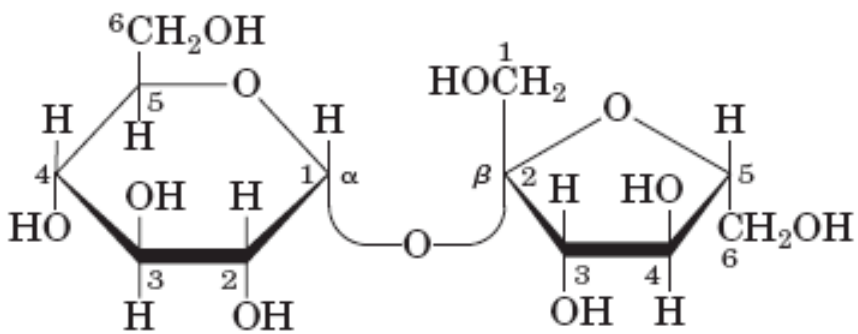
Pyran



Furan



Lactose (β form)
β-D-galactopyranosyl-(1→4)-β-D-glucopyranose
Gal(β1→4)Glc



Sucrose
α-D-glucopyranosyl β-D-fructofuranoside
Glc(α1↔2β)Fru

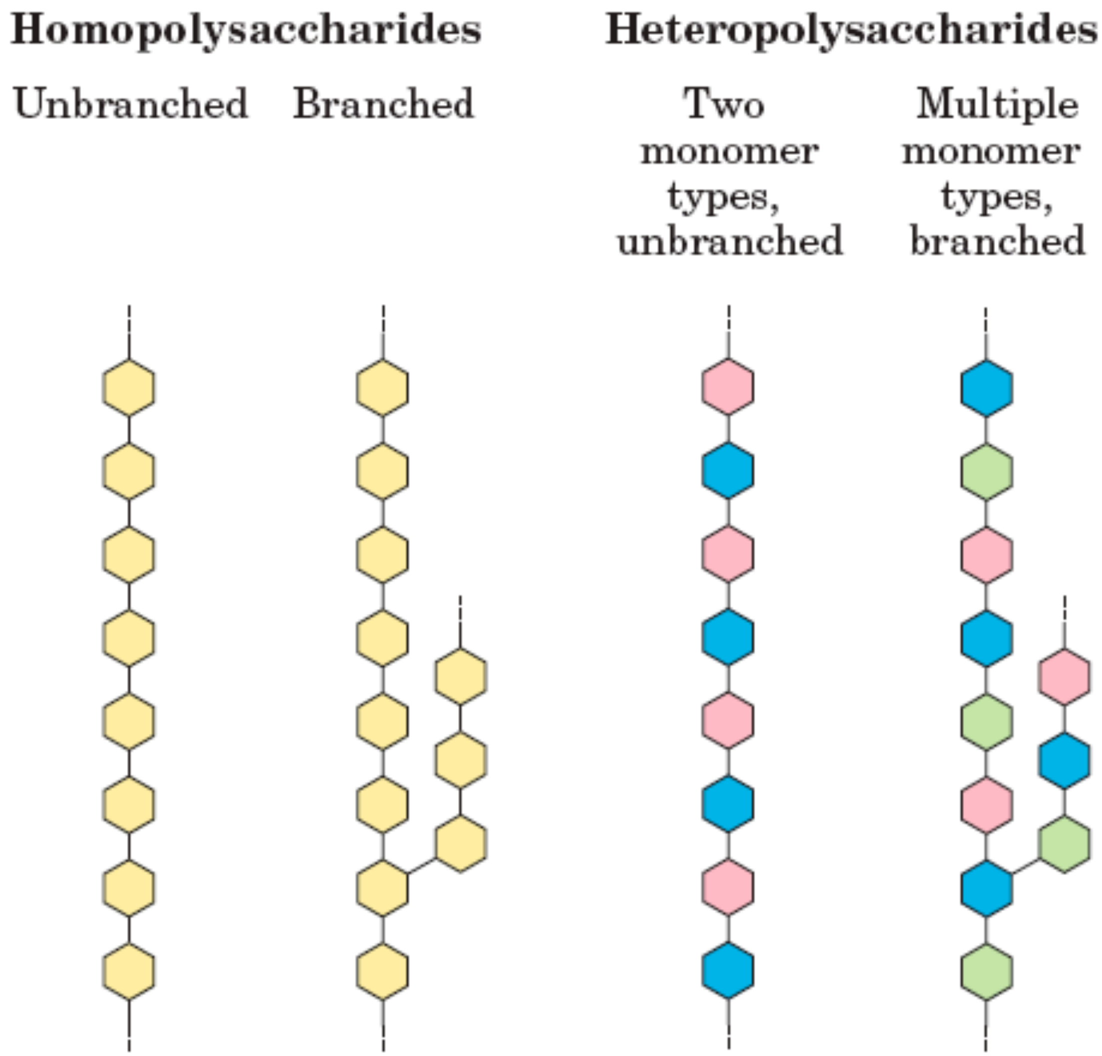
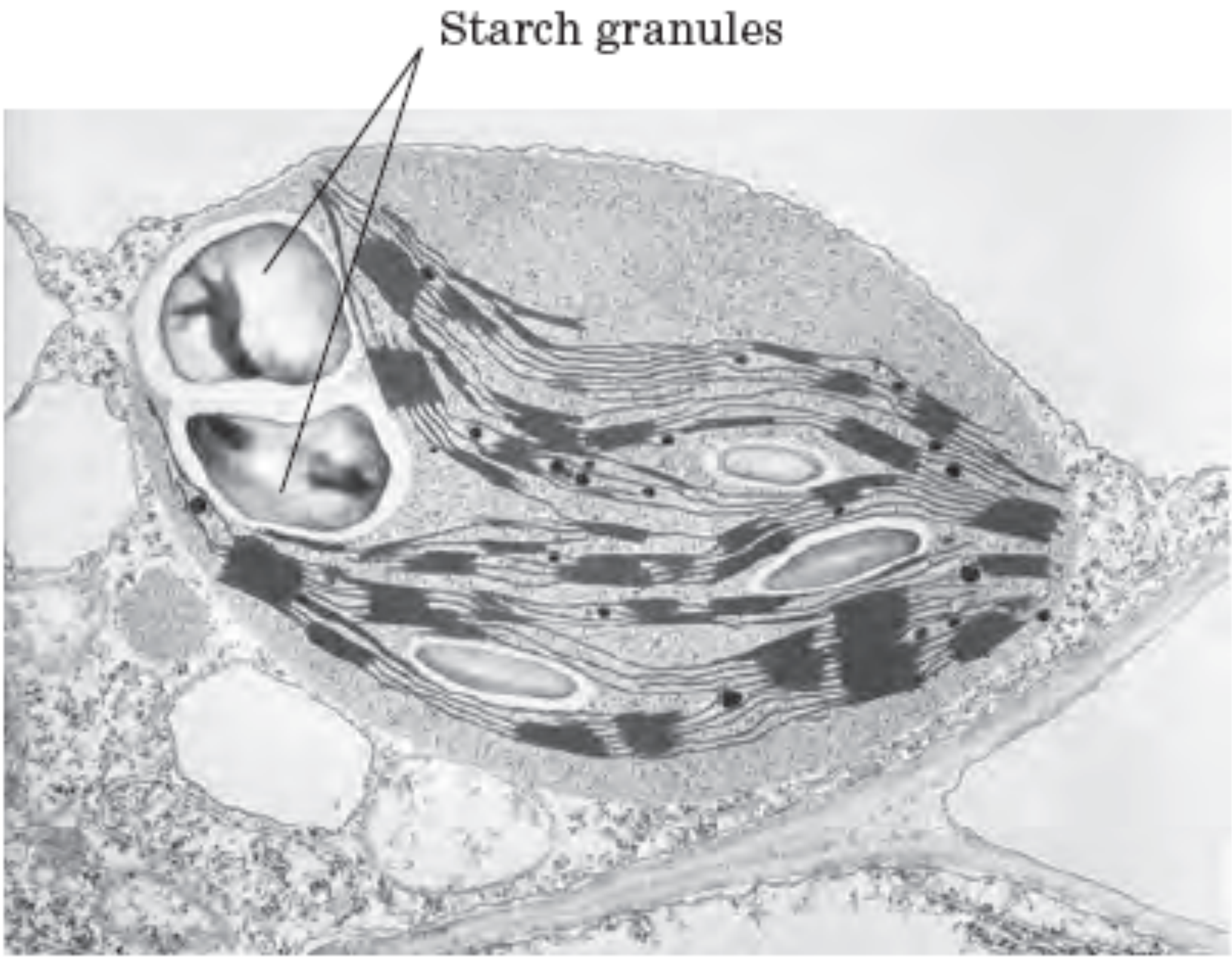


FIGURE 7–13 **Homo- and heteropolysaccharides.** Polysaccharides may be composed of one, two, or several different monosaccharides, in straight or branched chains of varying length.

TABLE 7–2 Structures and Roles of Some Polysaccharides

Polymer	*Type**	*Repeating unit†*	*Size (number of monosaccharide units)*	*Roles/significance*
Starch				Energy storage: in plants
Amylose	Homo-	(α1→4)Glc, linear	50–5,000	
Amylopectin	Homo-	(α1→4)Glc, with (α1→6)Glc branches every 24–30 residues	Up to 10^6	
Glycogen	Homo-	(α1→4)Glc, with (α1→6)Glc branches every 8–12 residues	Up to 50,000	Energy storage: in bacteria and animal cells
Cellulose	Homo-	(β1→4)Glc	Up to 15,000	Structural: in plants, gives rigidity and strength to cell walls
Chitin	Homo-	(β1→4)GlcNAc	Very large	Structural: in insects, spiders, crustaceans, gives rigidity and strength to exoskeletons
Dextran	Homo-	(α1→6)Glc, with (α1→3) branches	Wide range	Structural: in bacteria, extracellular adhesive
Peptidoglycan	Hetero-; peptides attached	4)Mur2Ac(β1→4) GlcNAc(β1	Very large	Structural: in bacteria, gives rigidity and strength to cell envelope
Agarose	Hetero-	3)D-Gal(β1→4)3,6-anhydro-L-Gal(α1	1,000	Structural: in algae, cell wall material
Hyaluronate (a glycosamino-glycan)	Hetero-; acidic	4)GlcA(β1→3) GlcNAc(β1	Up to 100,000	Structural: in vertebrates, extracellular matrix of skin and connective tissue; viscosity and lubrication in joints


Starch granules

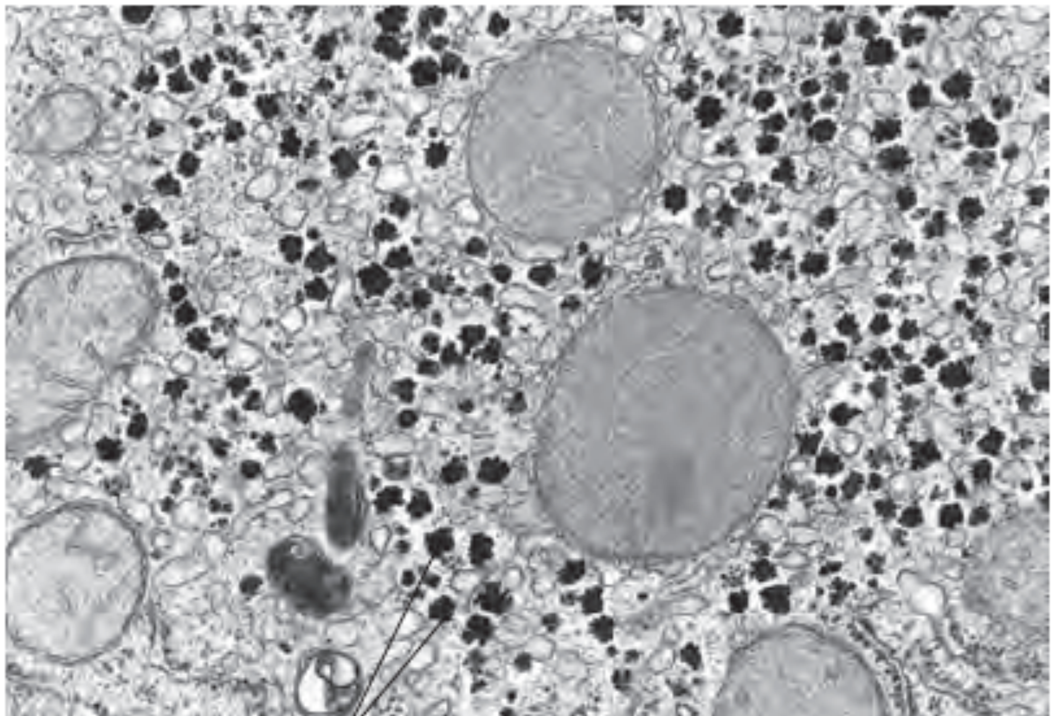
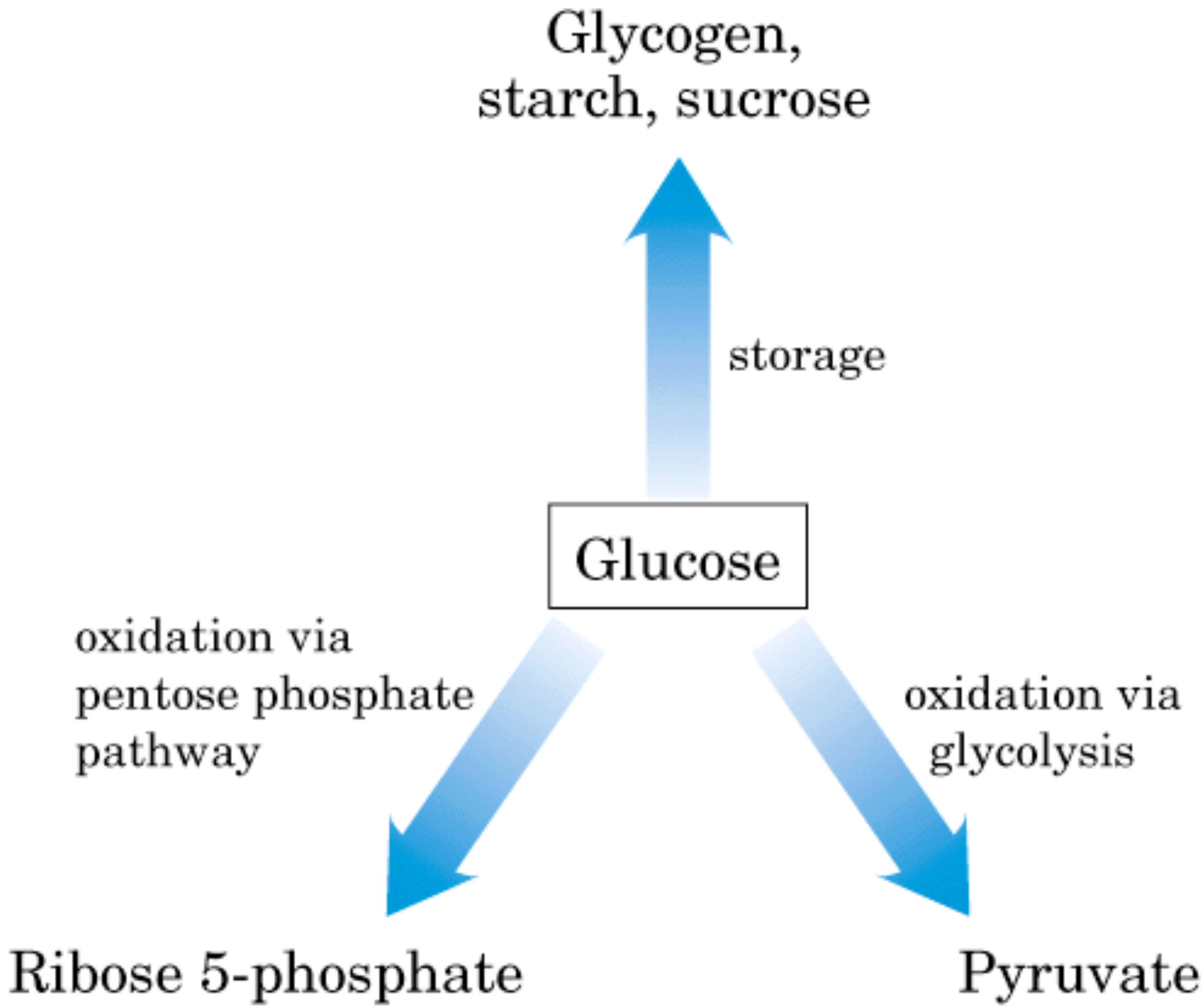
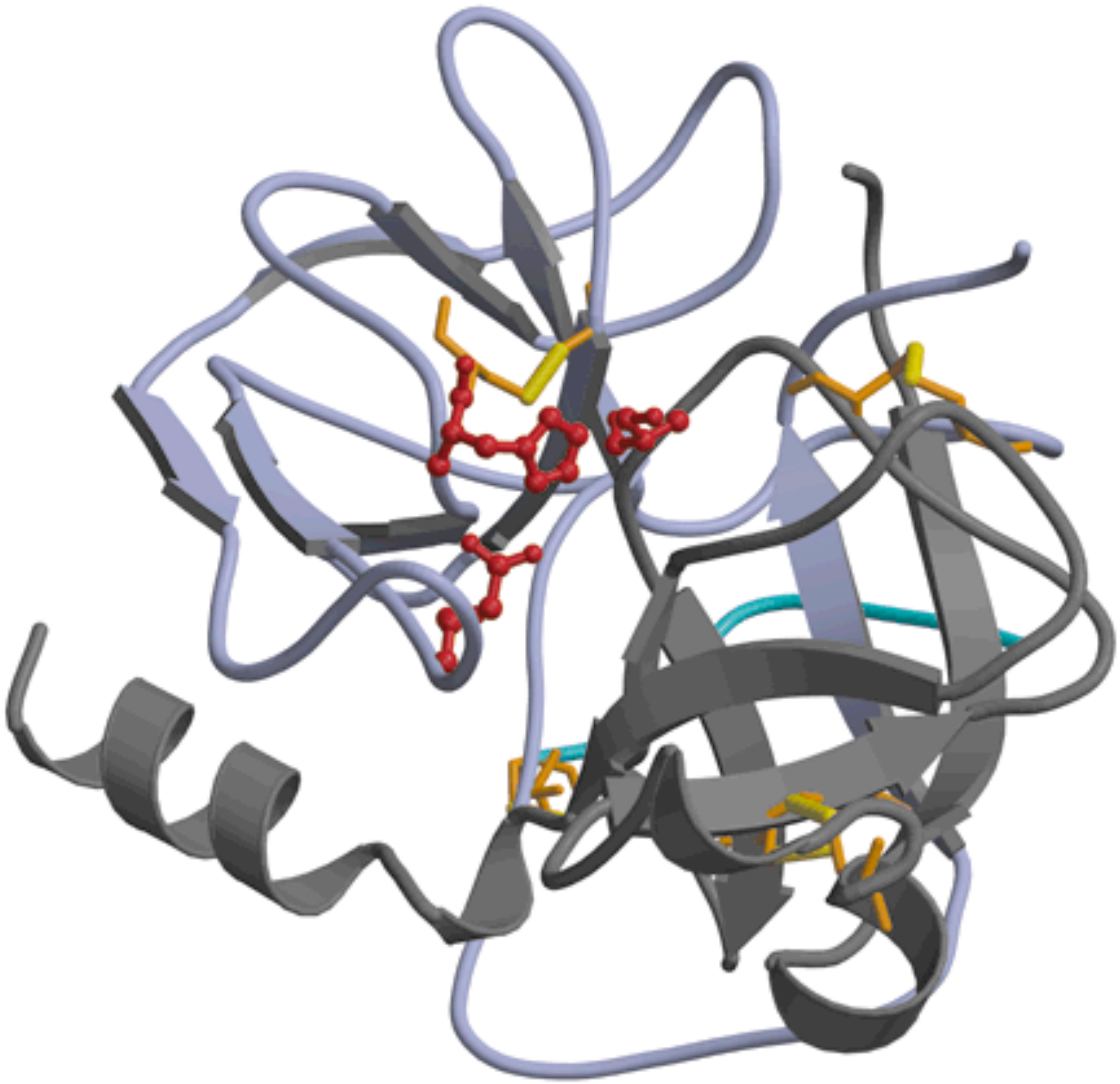
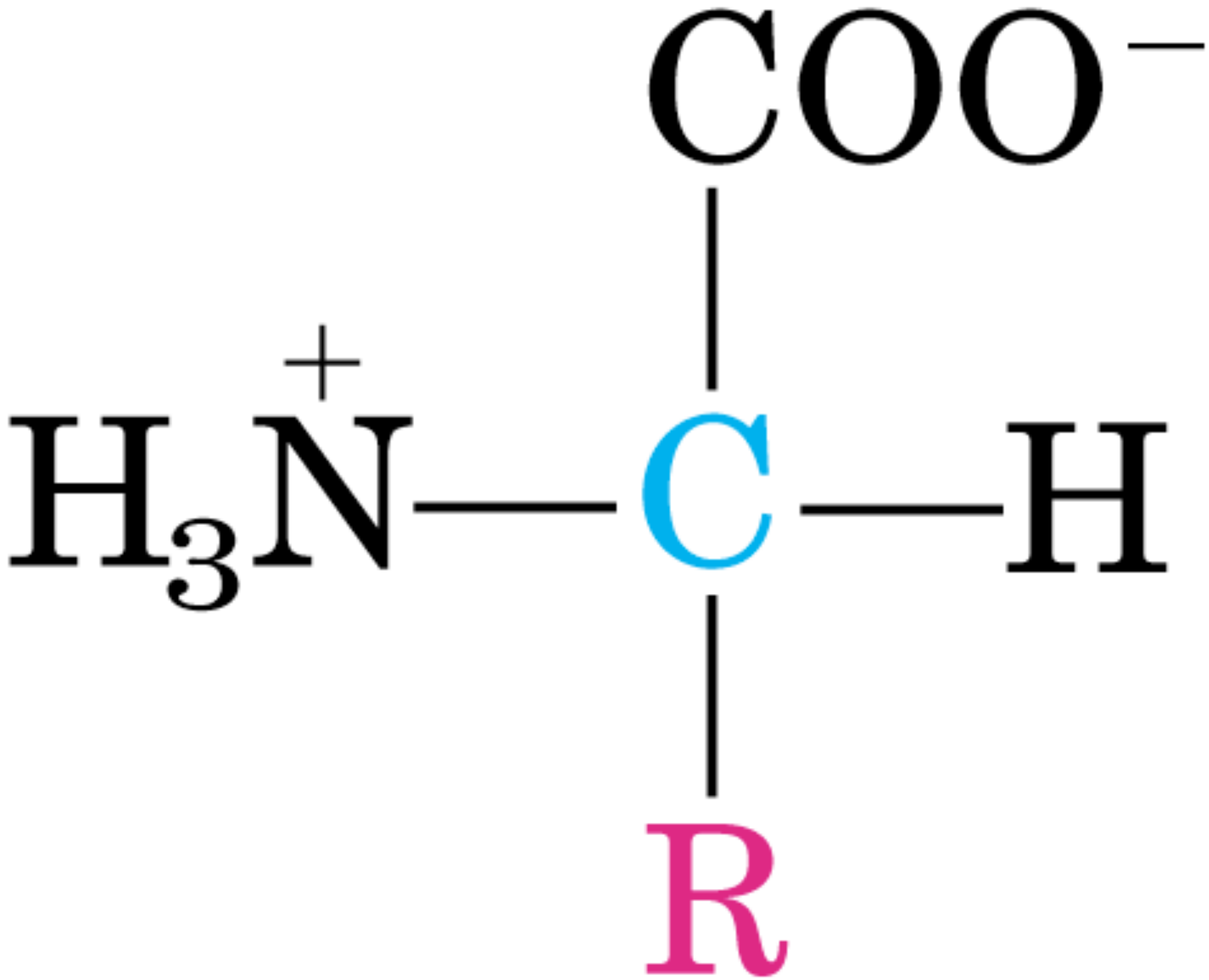

Glycogen granules

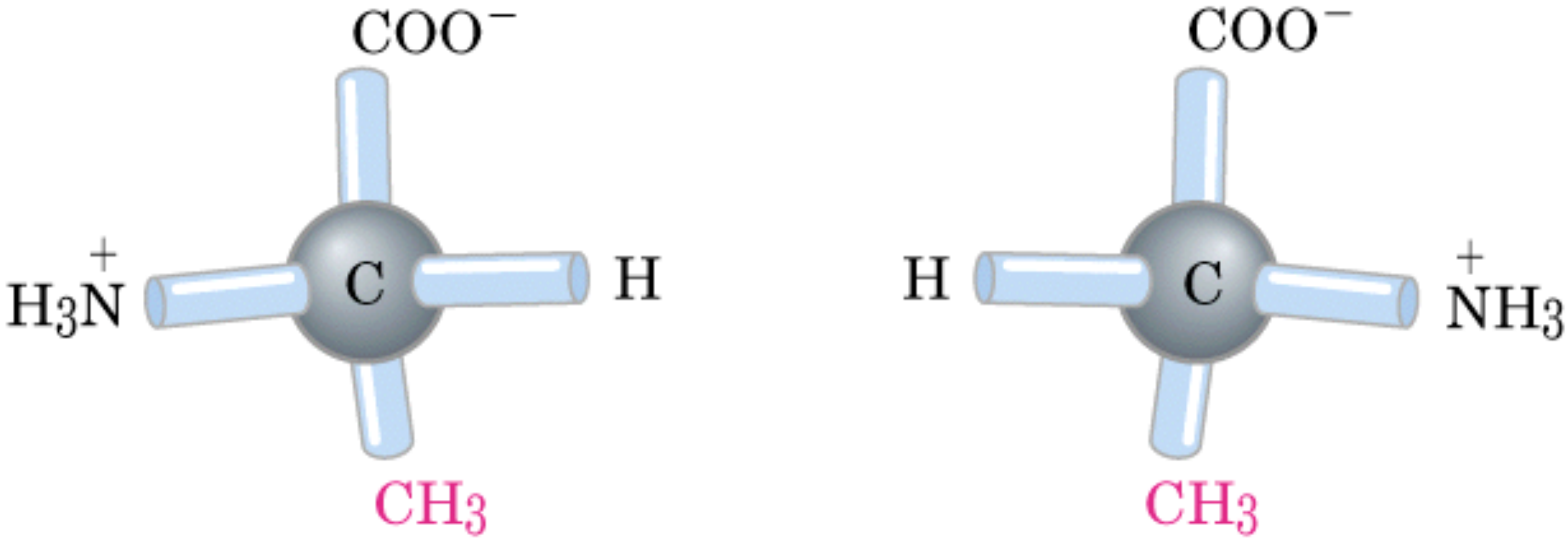
FIGURE 7–17 **Cellulose breakdown by wood fungi.** A wood fungus growing on an oak log. All wood fungi have the enzyme cellulase, which breaks the ($\beta 1 \rightarrow 4$) glycosidic bonds in cellulose, such that wood is a source of metabolizable sugar (glucose) for the fungus. The only vertebrates able to use cellulose as food are cattle and other ruminants (sheep, goats, camels, giraffes). The extra stomach compartment (rumen) of a ruminant teems with bacteria and protists that secrete cellulase.



Glycogen,
starch, sucrose
storage
Glucose
oxidation via
pentose phosphate
pathway
oxidation via
glycolysis
Ribose 5-phosphate
Pyruvate

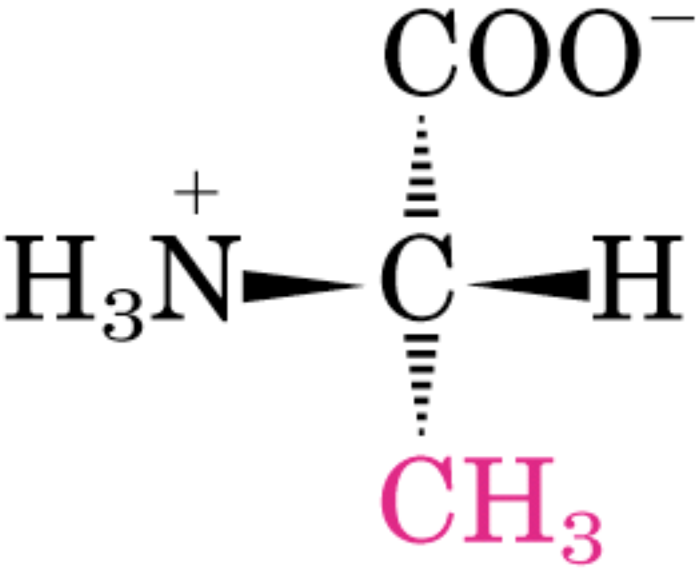



COO⁻
H₃N⁺
C
H
R

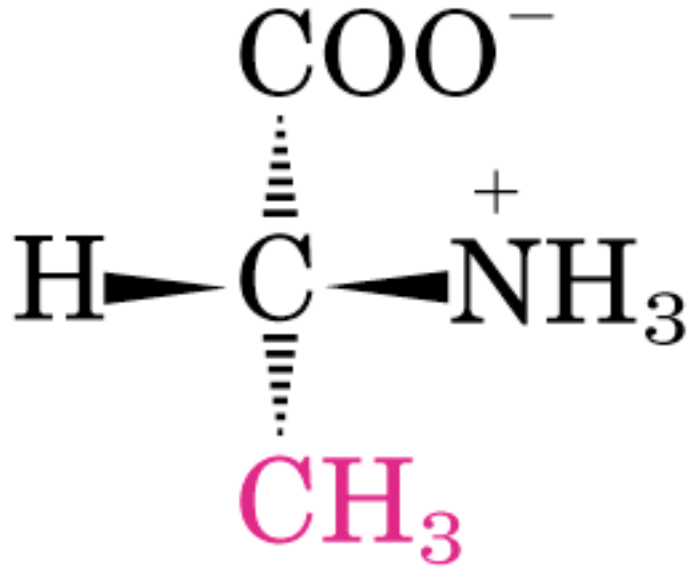


L-Alanine D-Alanine

(a)

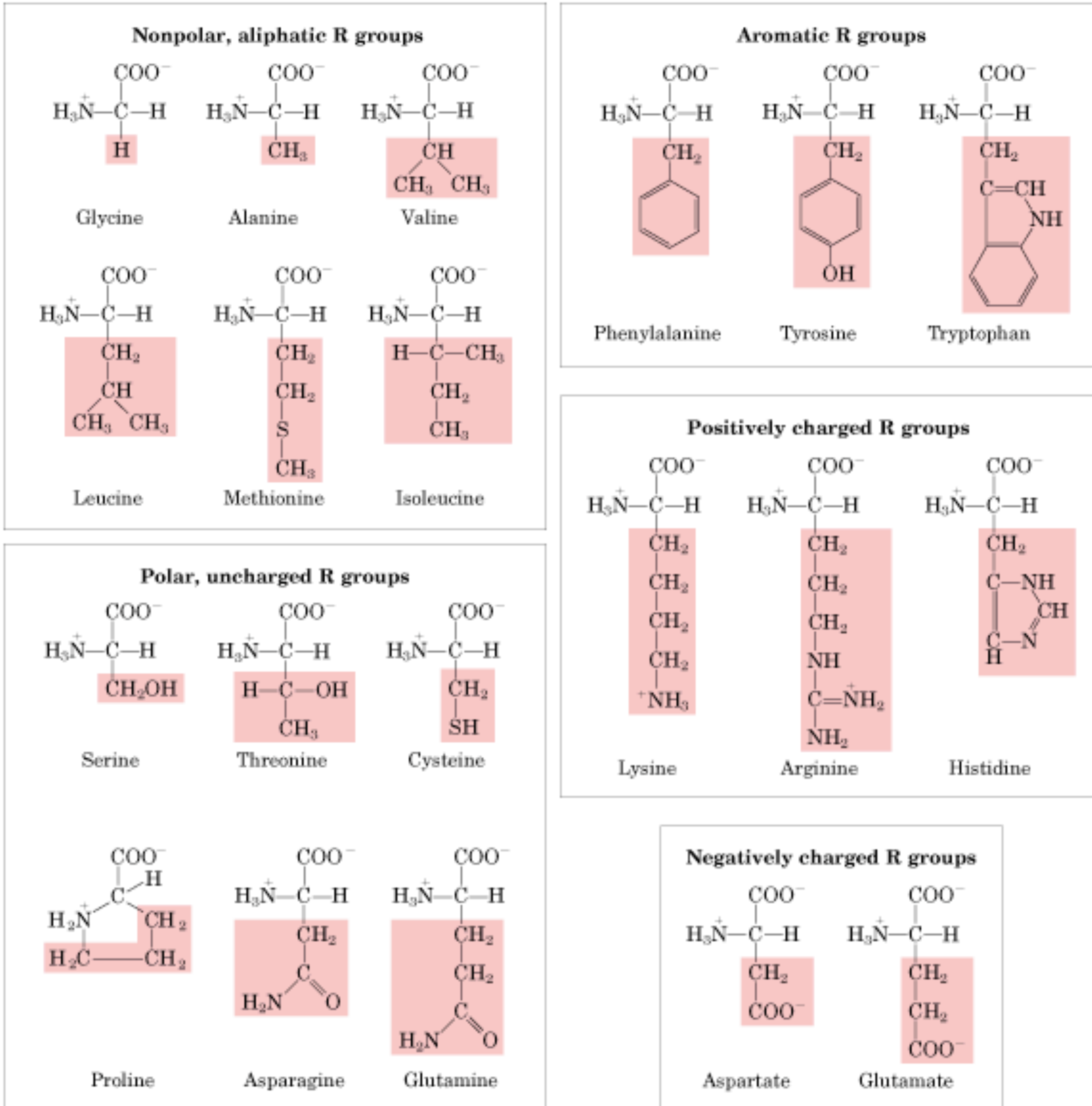


L-Alanine



D-Alanine

(b)



Nonpolar, aliphatic R groups
Glycine
Alanine
Valine
Leucine
Methionine
Isoleucine
Aromatic R groups
Phenylalanine
Tyrosine
Tryptophan
Polar, uncharged R groups
Serine
Threonine
Cysteine
Proline
Asparagine
Glutamine
Positively charged R groups
Lysine
Arginine
Histidine
Negatively charged R groups
Aspartate
Glutamate

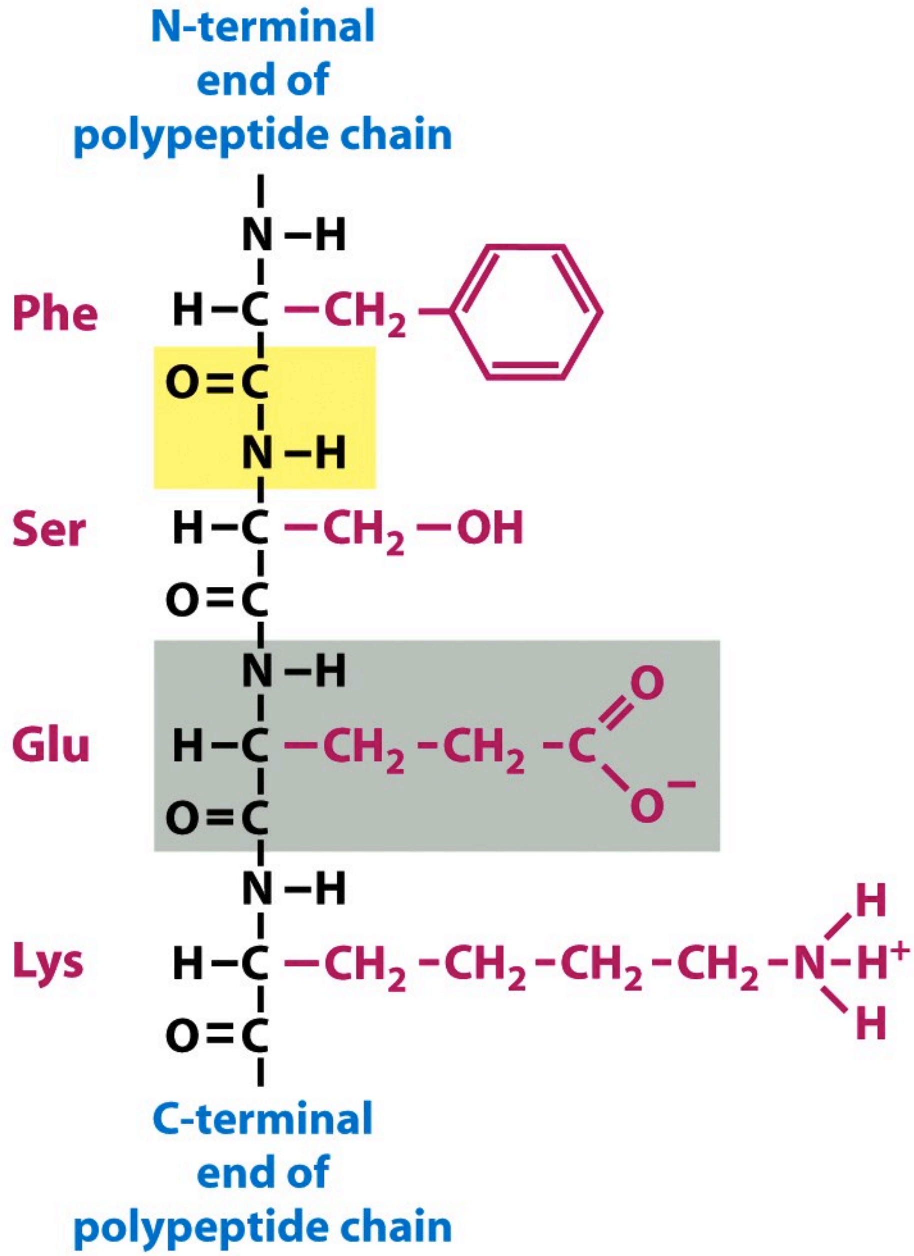
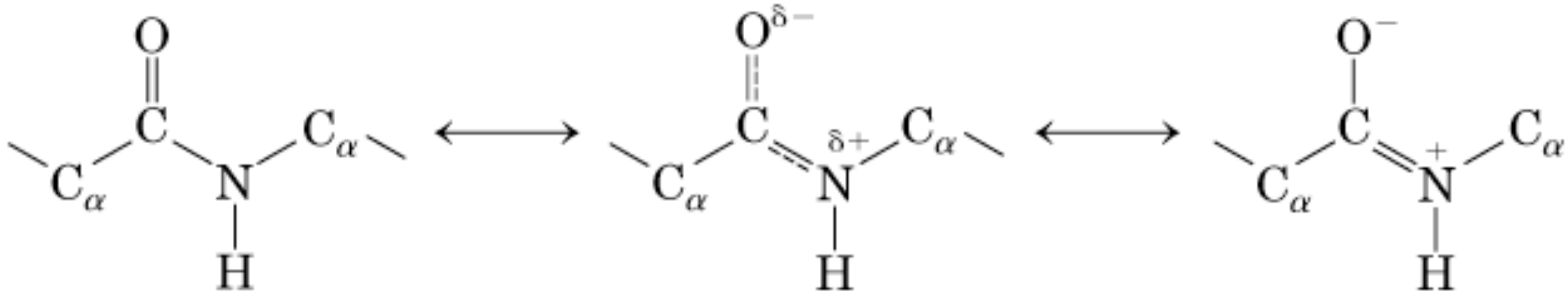
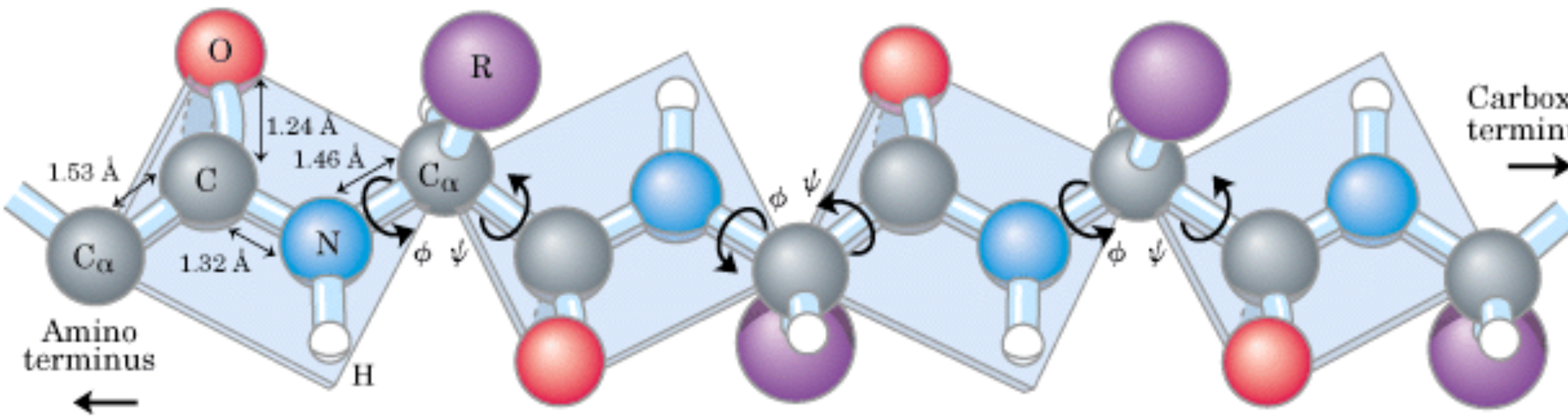


Figure 2-24 *Molecular Biology of the Cell* (© Garland Science 2008)

The carbonyl oxygen has a partial negative charge and the amide nitrogen a partial positive charge, setting up a small electric dipole. Virtually all peptide bonds in proteins occur in this trans configuration; an exception is noted in Figure 6–8b.

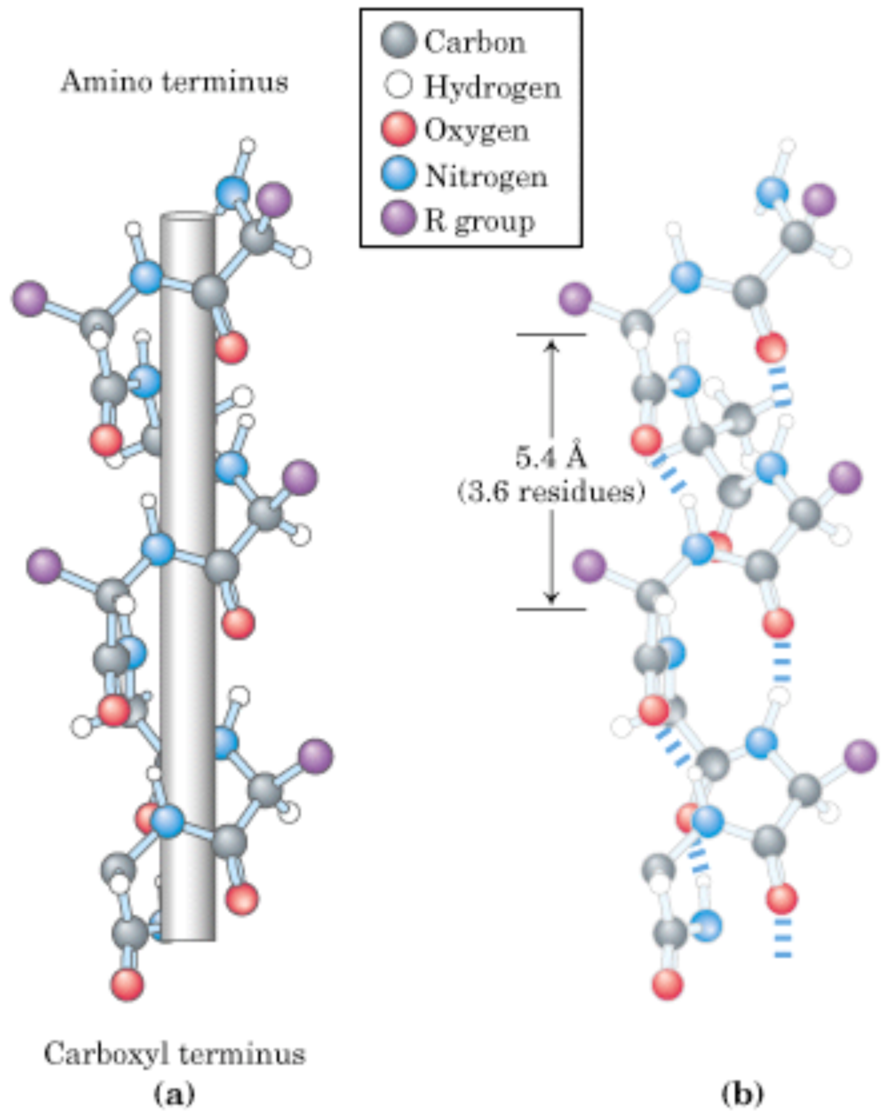


(a)

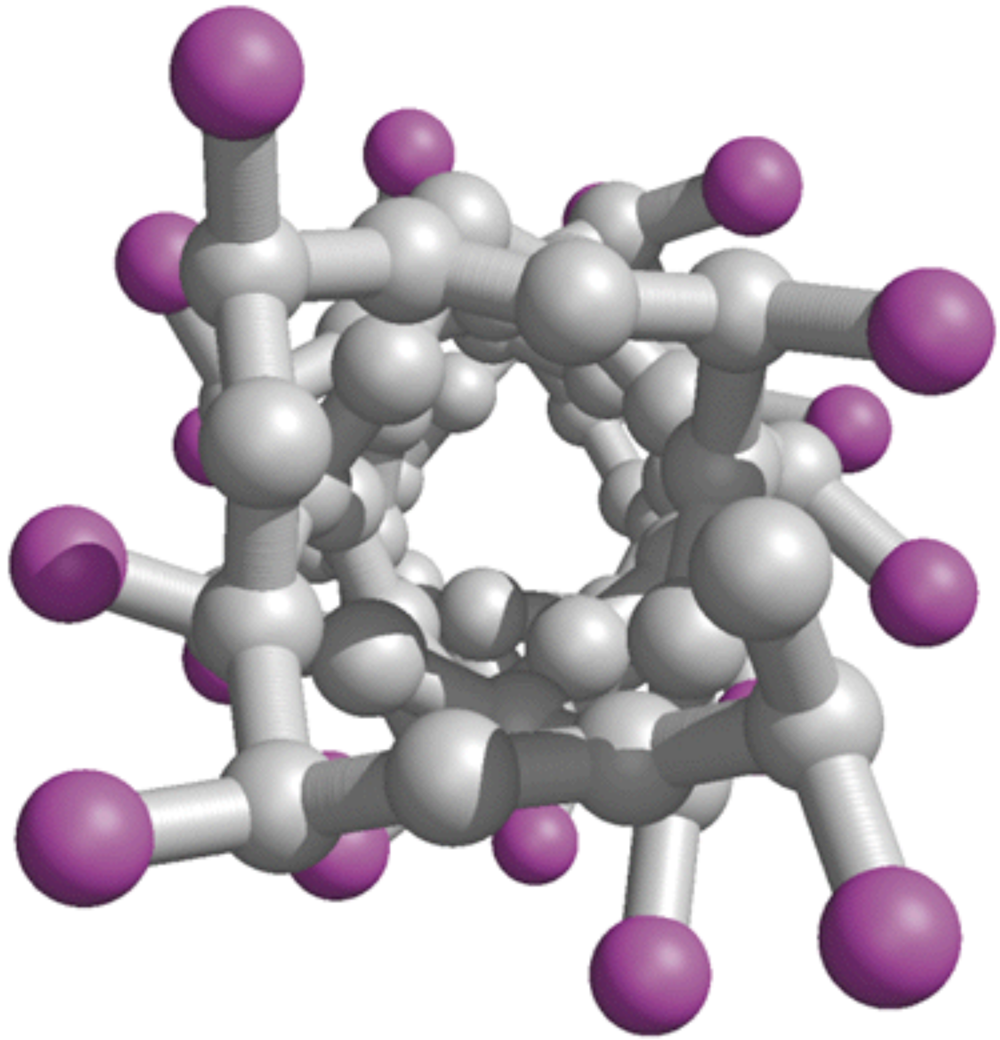


O
R
1.24 Å
1.46 Å
1.53 Å
C
C_α
C_α
N
1.32 Å
H
ϕ ψ
ϕ ψ
ϕ ψ
Carboxyl terminus
Amino terminus

(b)

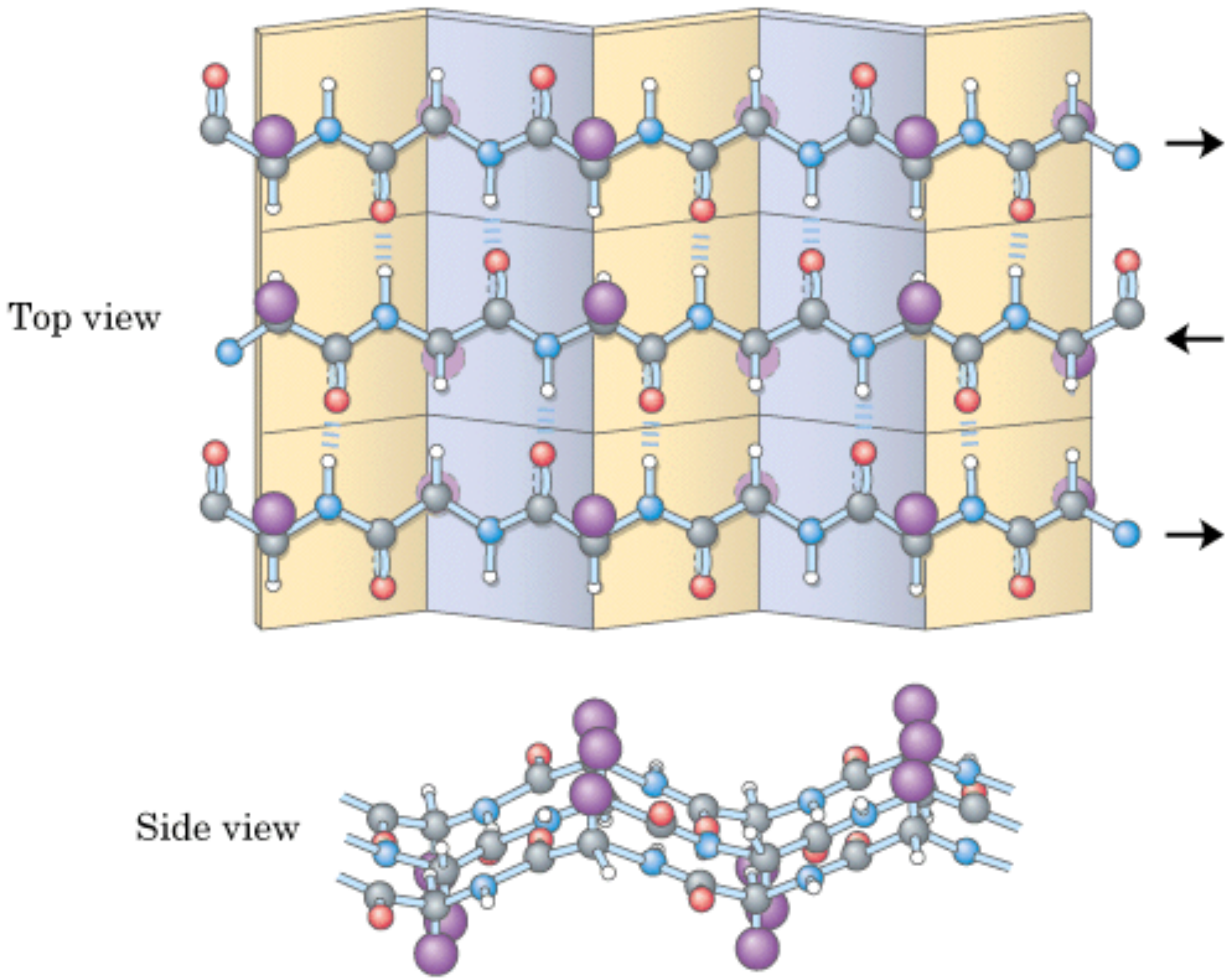


Carbon
Hydrogen
Oxygen
Nitrogen
R group
Amino terminus
Carboxyl terminus
5.4 Å
(3.6 residues)
(a)
(b)

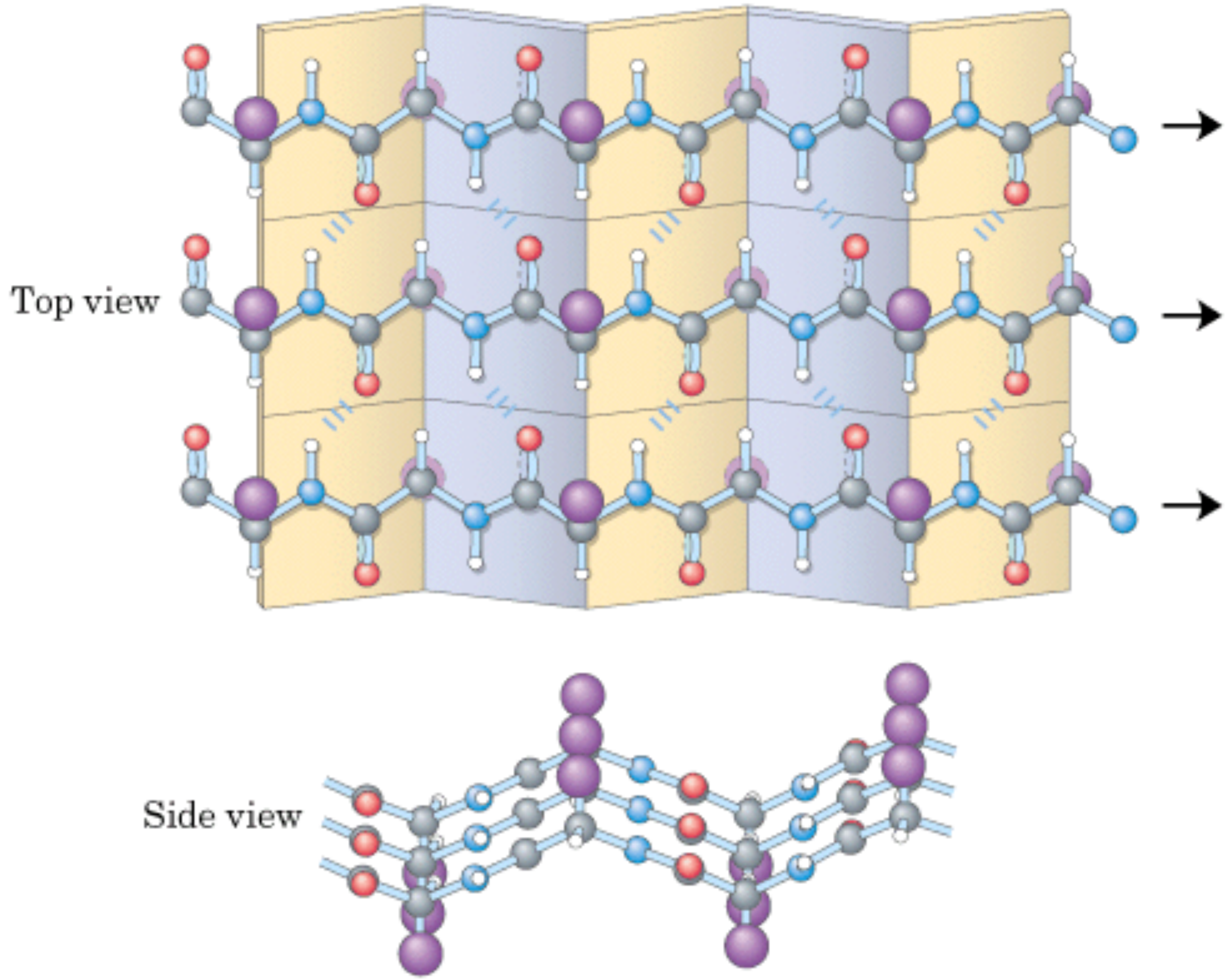


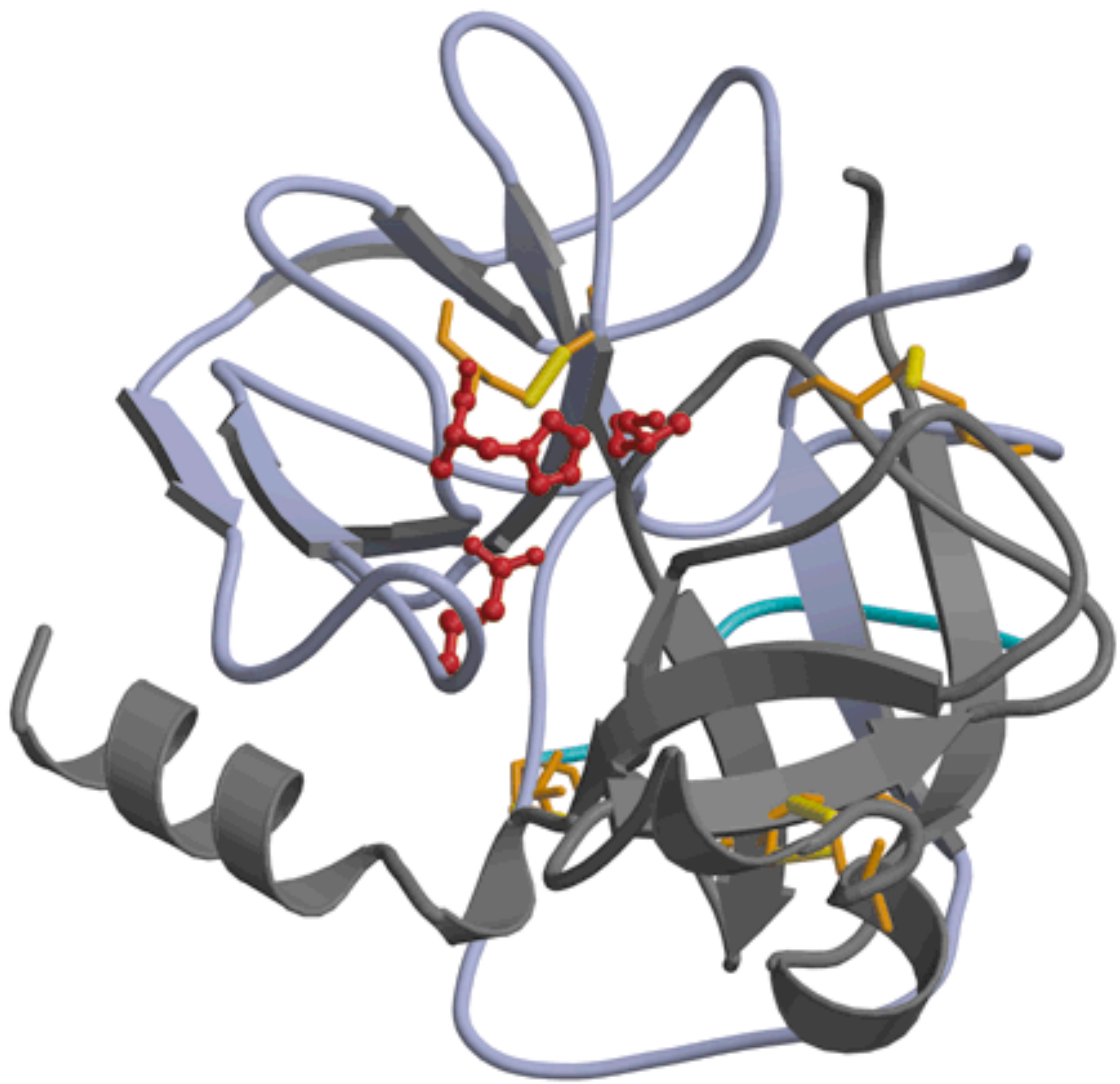
(c)

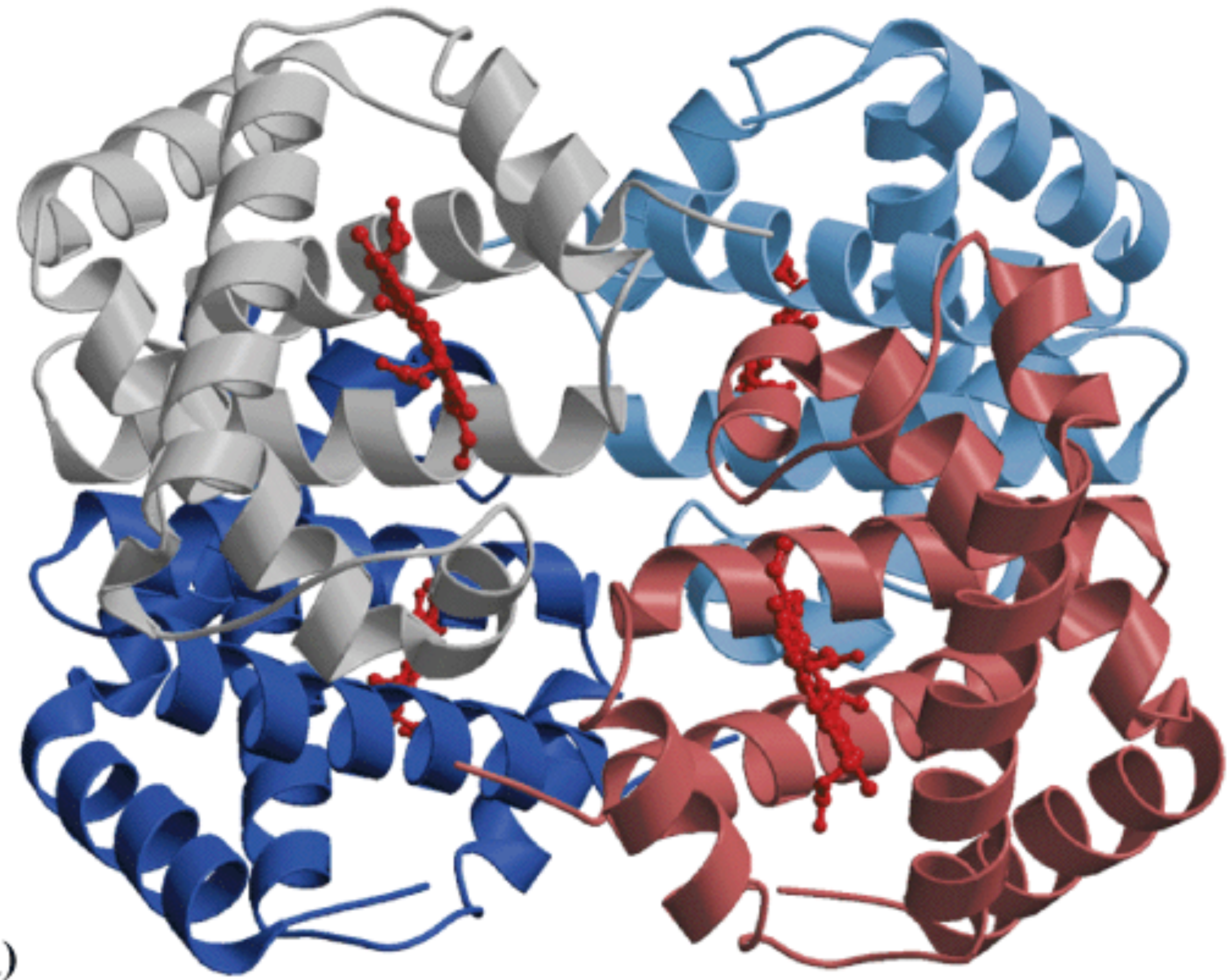
(a) Antiparallel



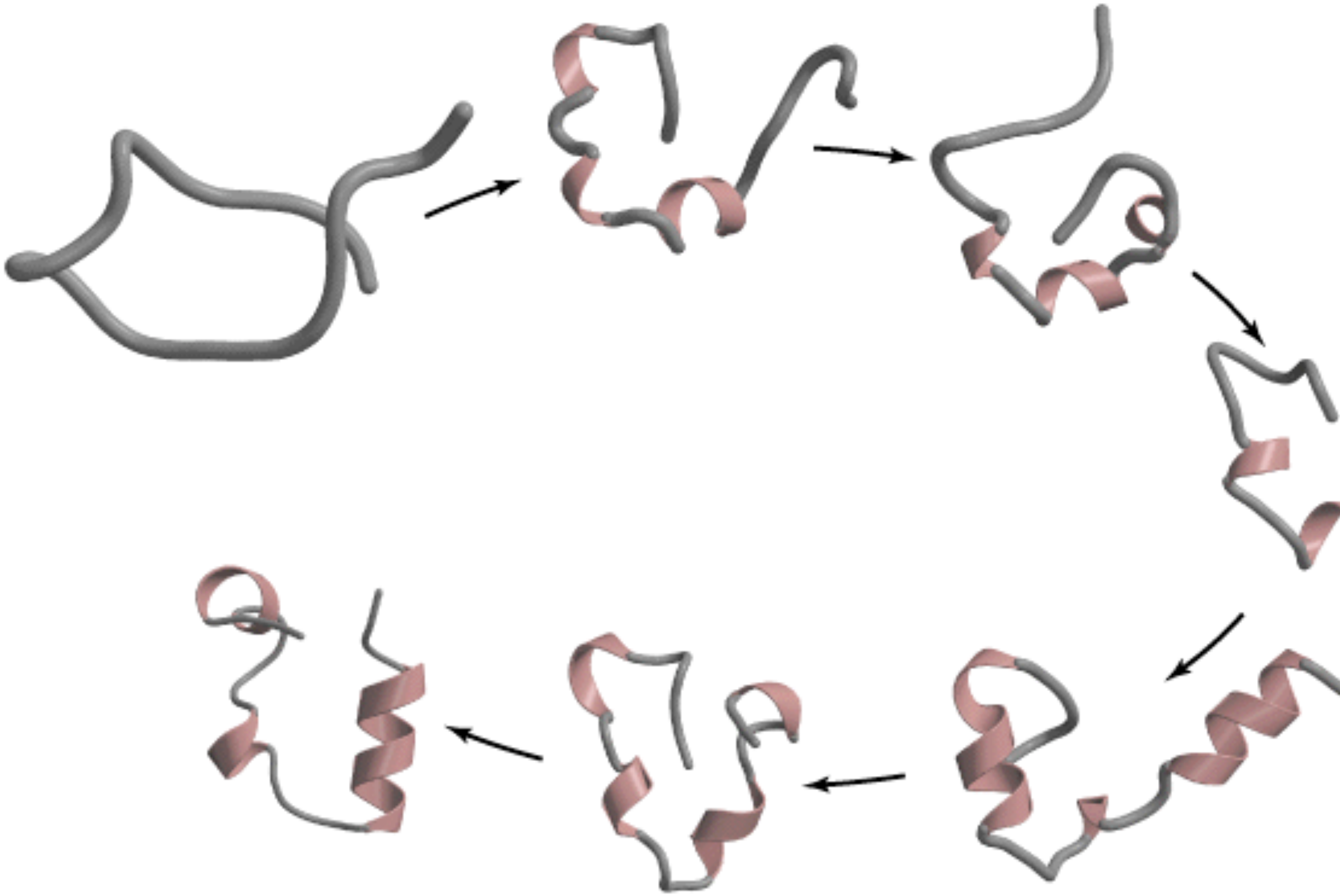
(b) Parallel

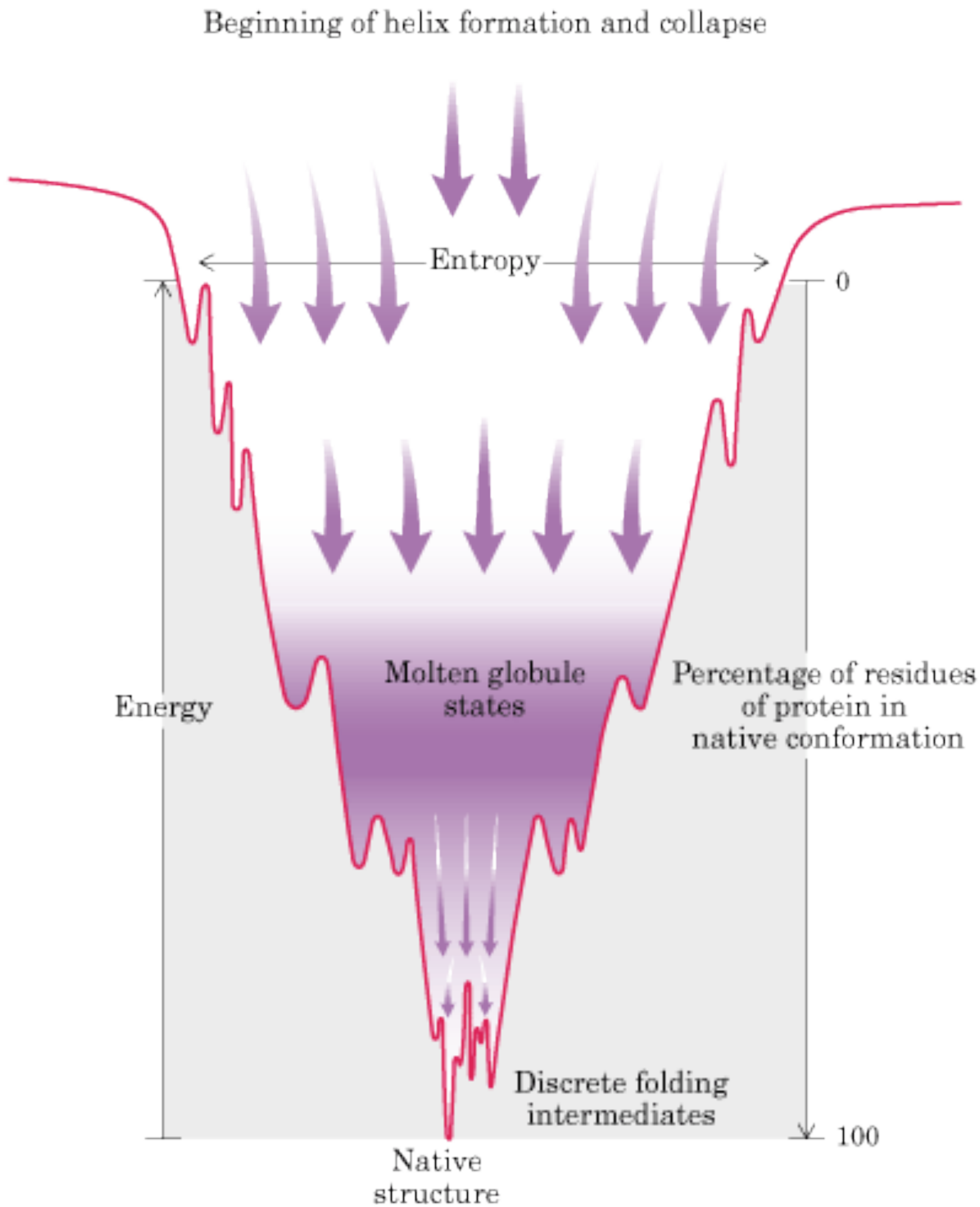


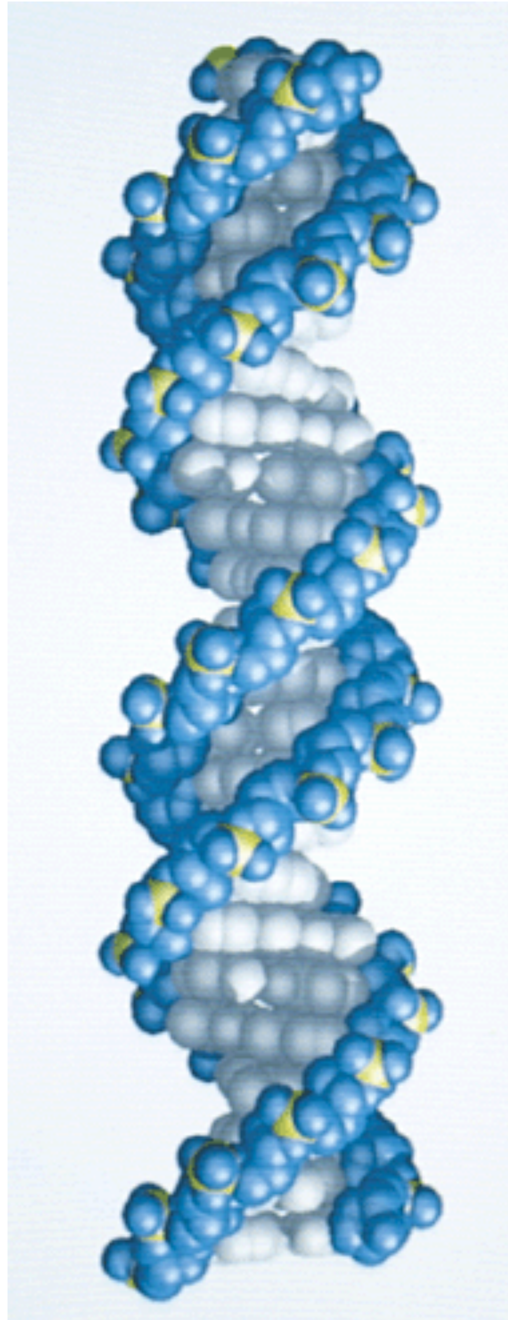


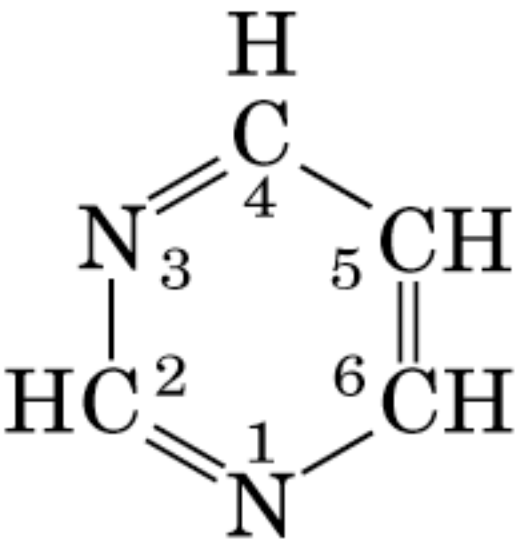


(a)

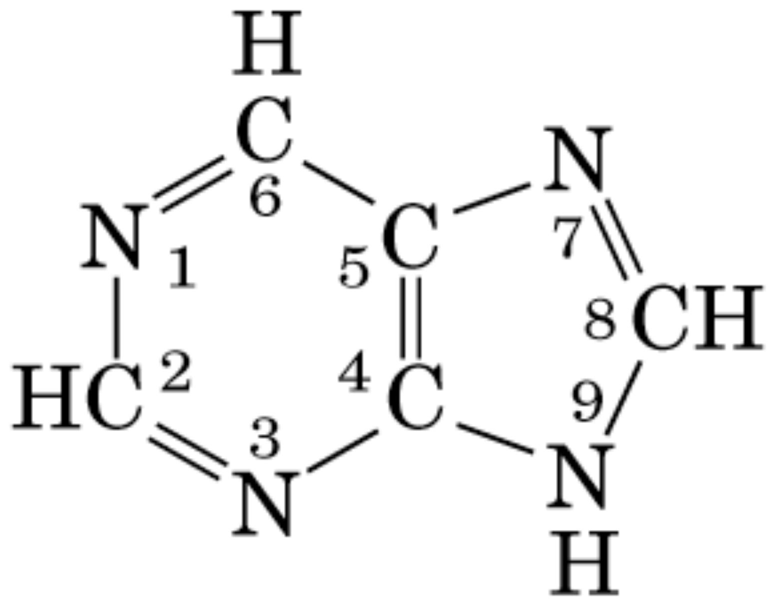



Beginning of helix formation and collapse
Entropy
0
Energy
Molten globule
states
Percentage of residues
of protein in
native conformation
Discrete folding
intermediates
100
Native
structure



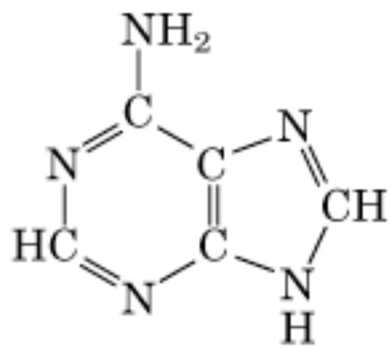


Pyrimidine

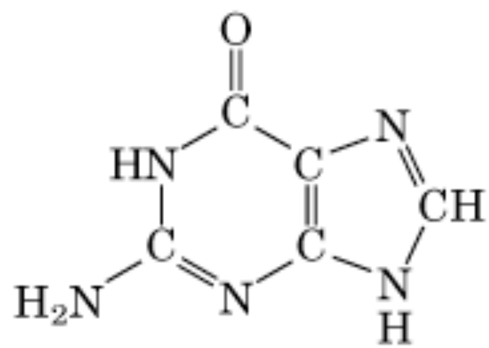


Purine

(b)

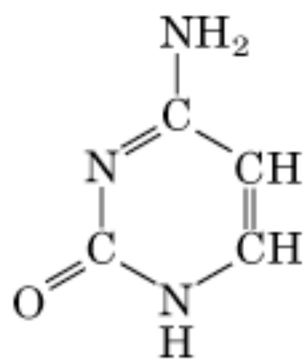


Adenine

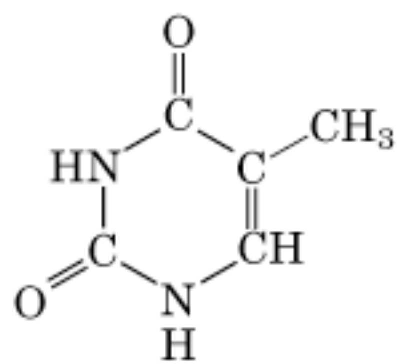


Guanine

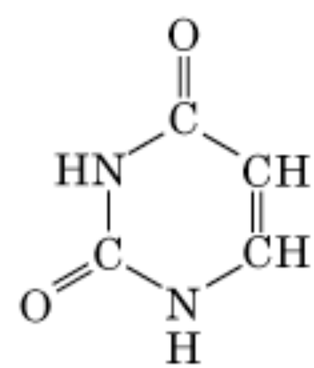
Purines



Cytosine



Thymine
(DNA)



Uracil
(RNA)

Pyrimidines

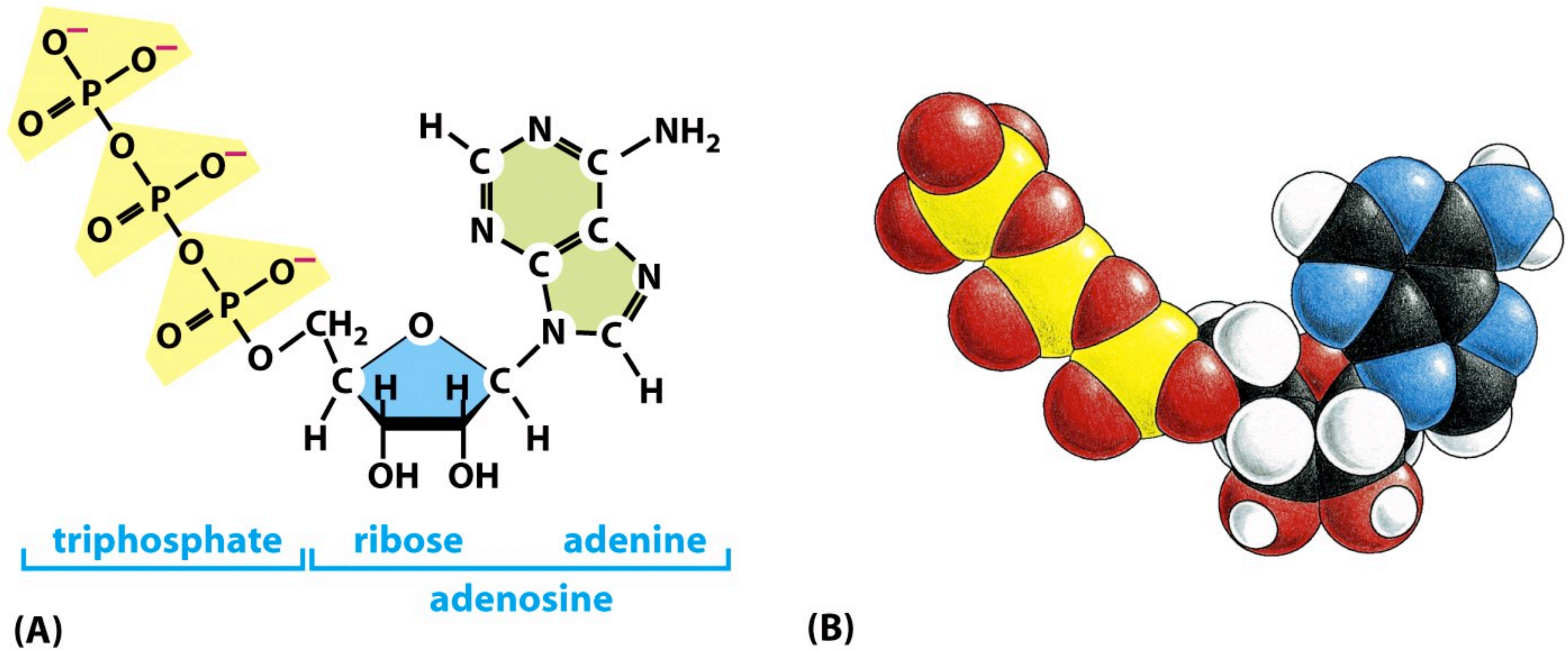
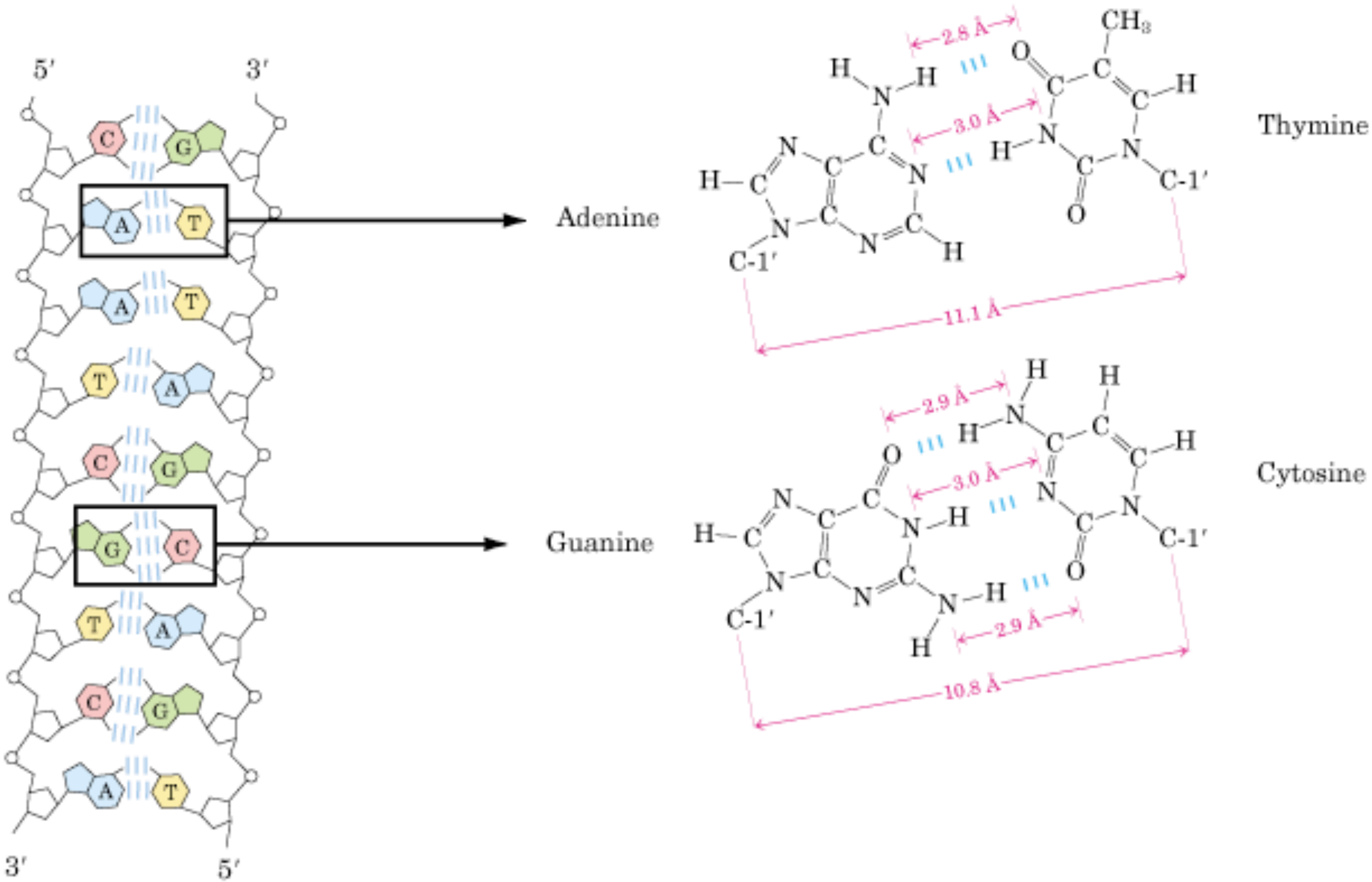
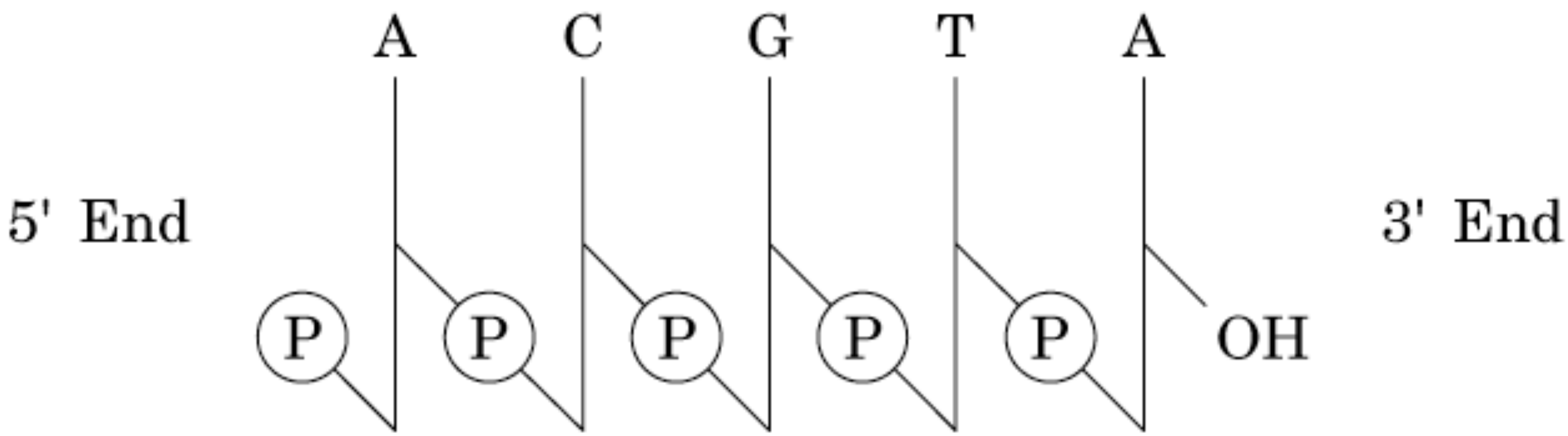
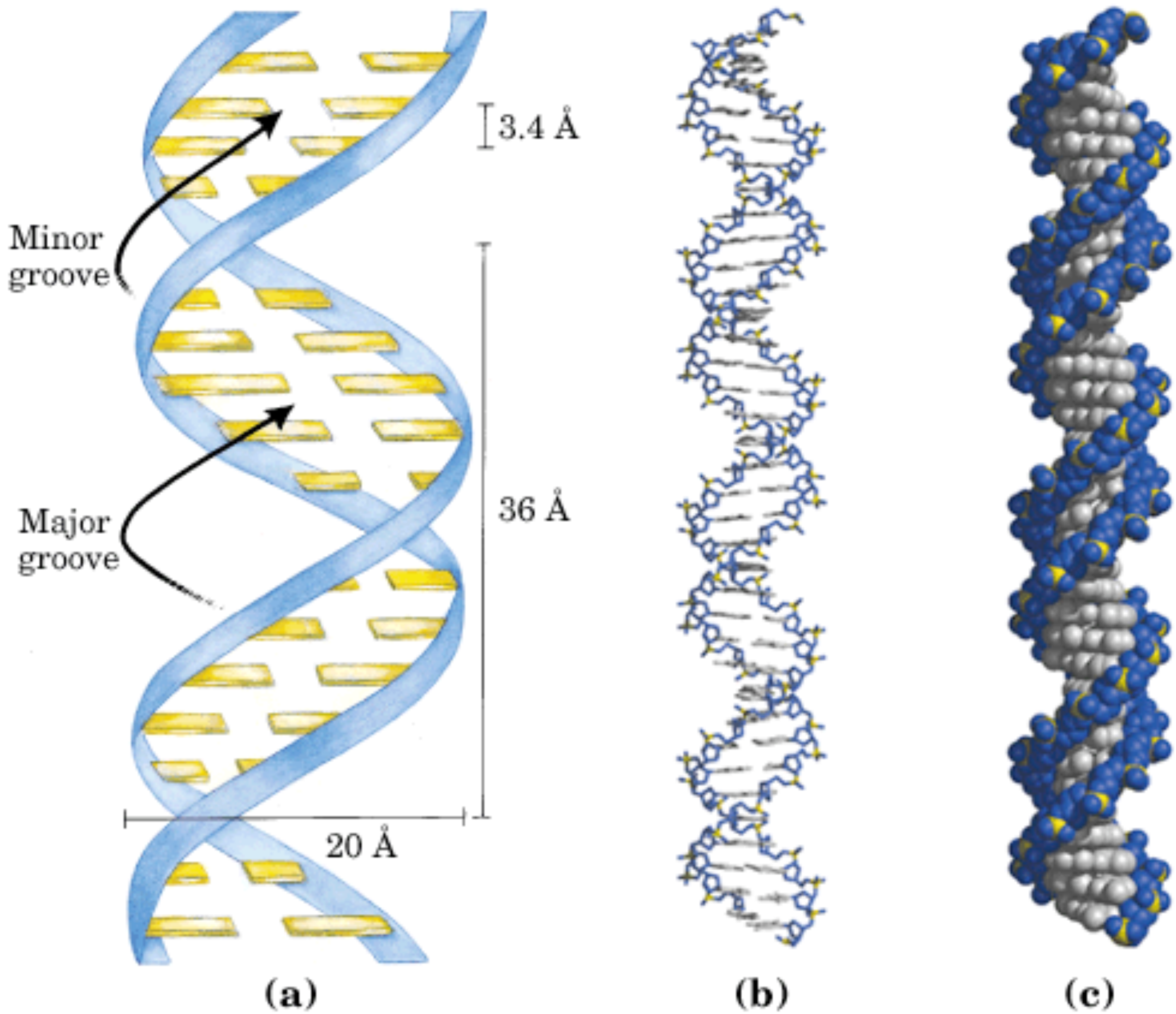


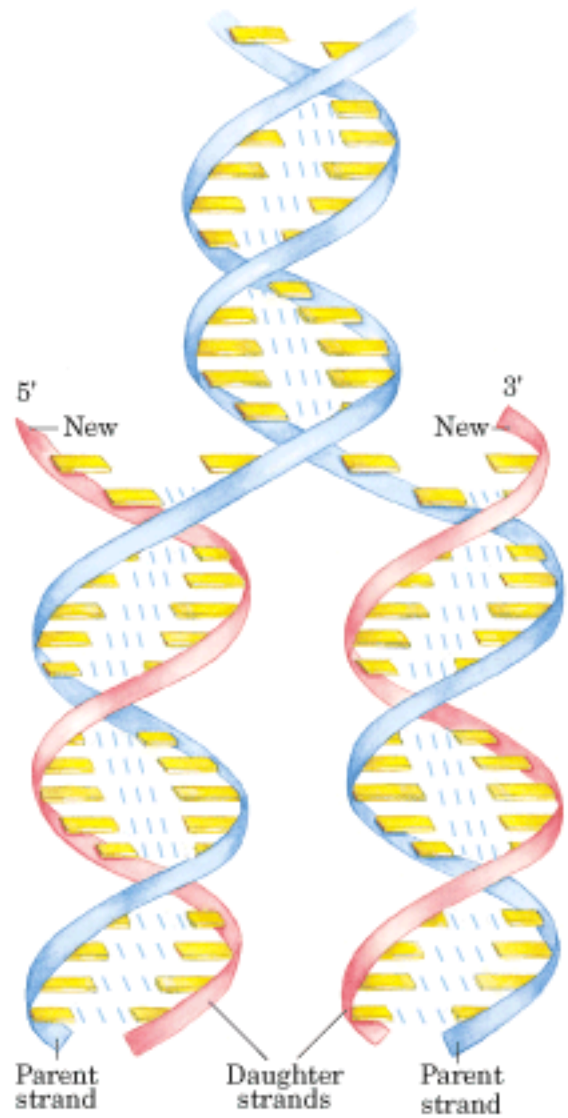
Figure 2-26 *Molecular Biology of the Cell* (© Garland Science 2008)

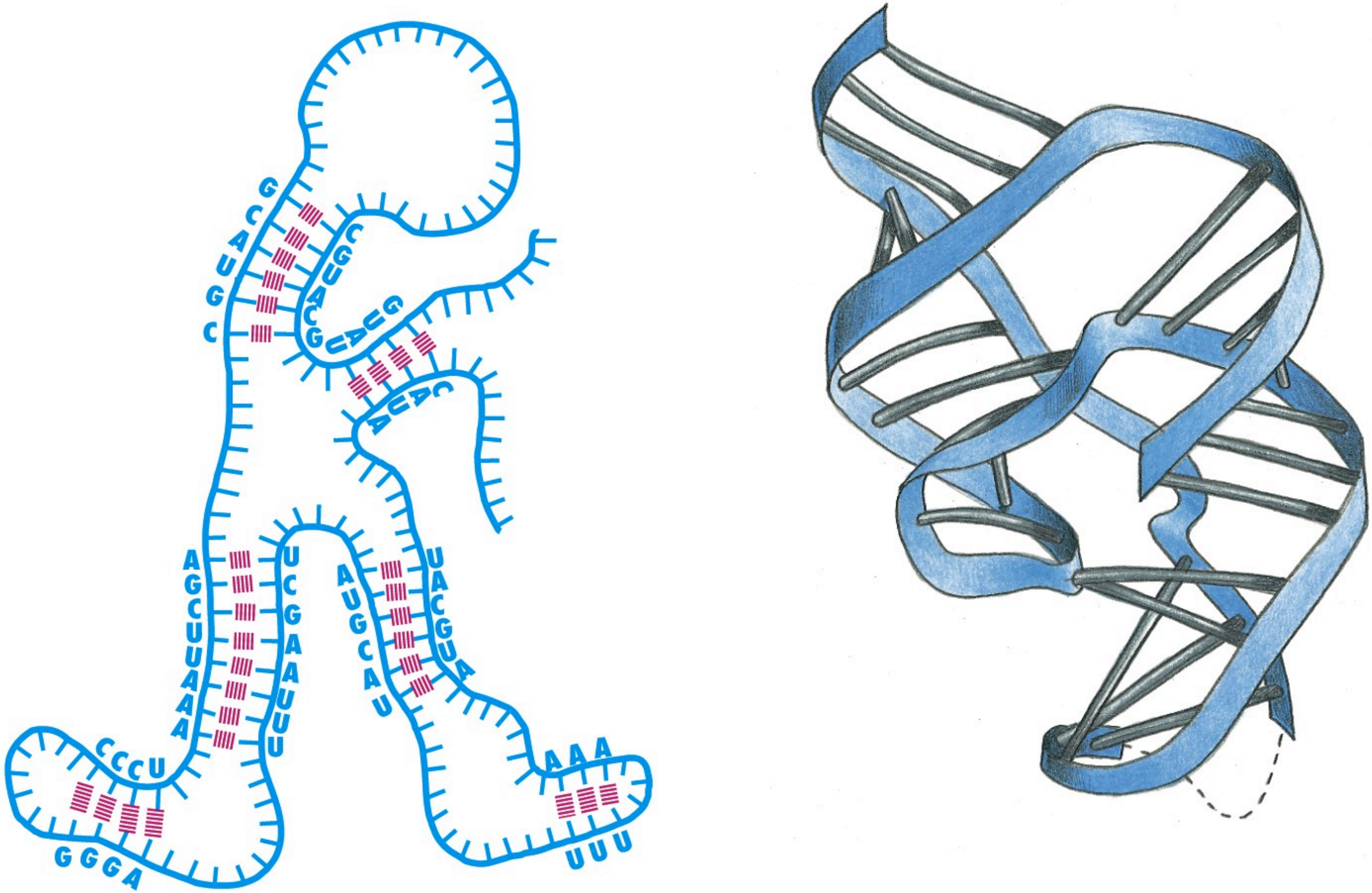


5′
3′
3′
5′
Adenine
Thymine
Guanine
Cytosine
2.8 Å
3.0 Å
11.1 Å
2.9 Å
3.0 Å
2.9 Å
10.8 Å
C-1′


5' End
A
C
G
T
A
P
P
P
P
P
OH
3' End

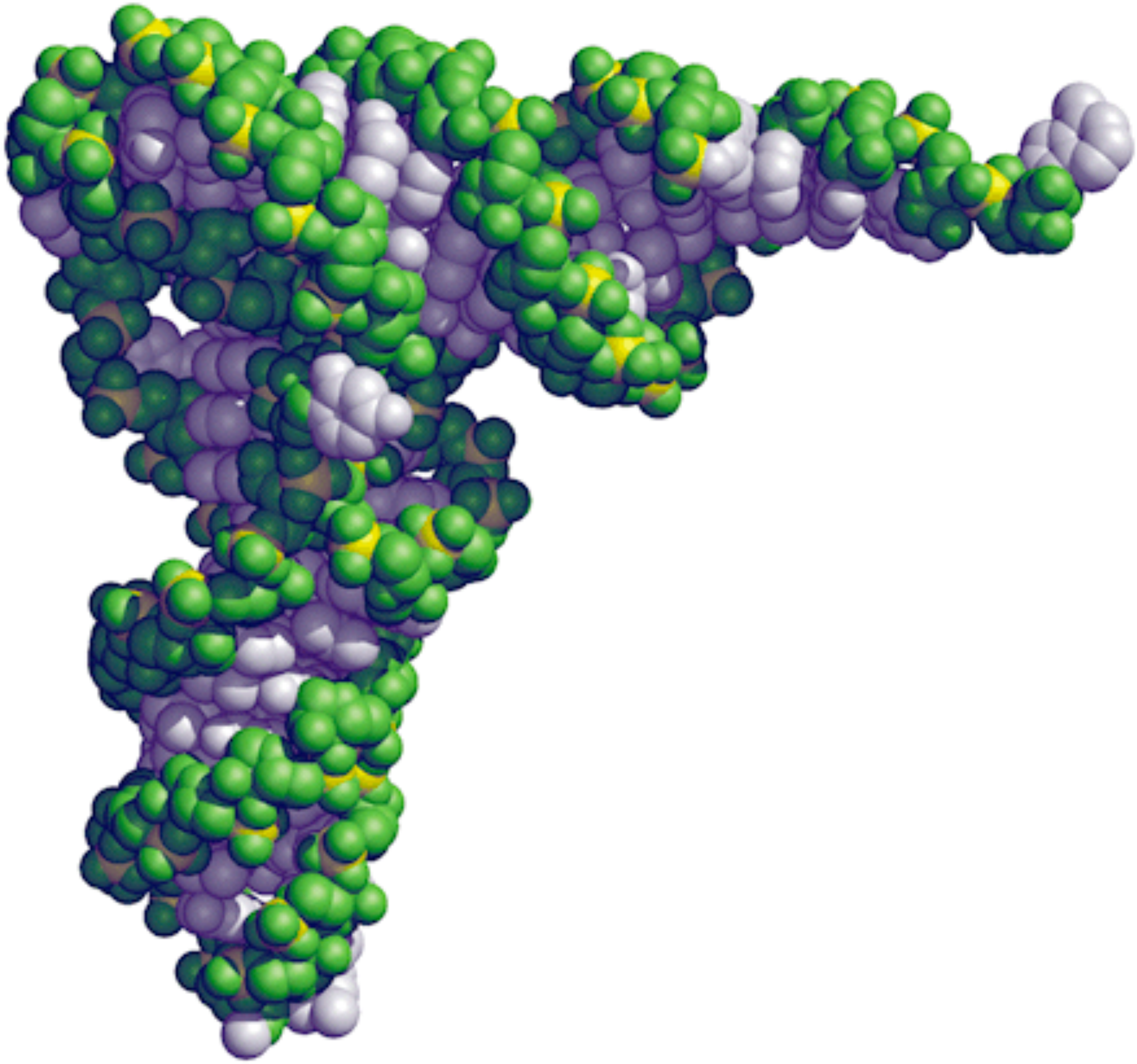

3.4 Å
Minor groove
36 Å
Major groove
20 Å
(a)
(b)
(c)

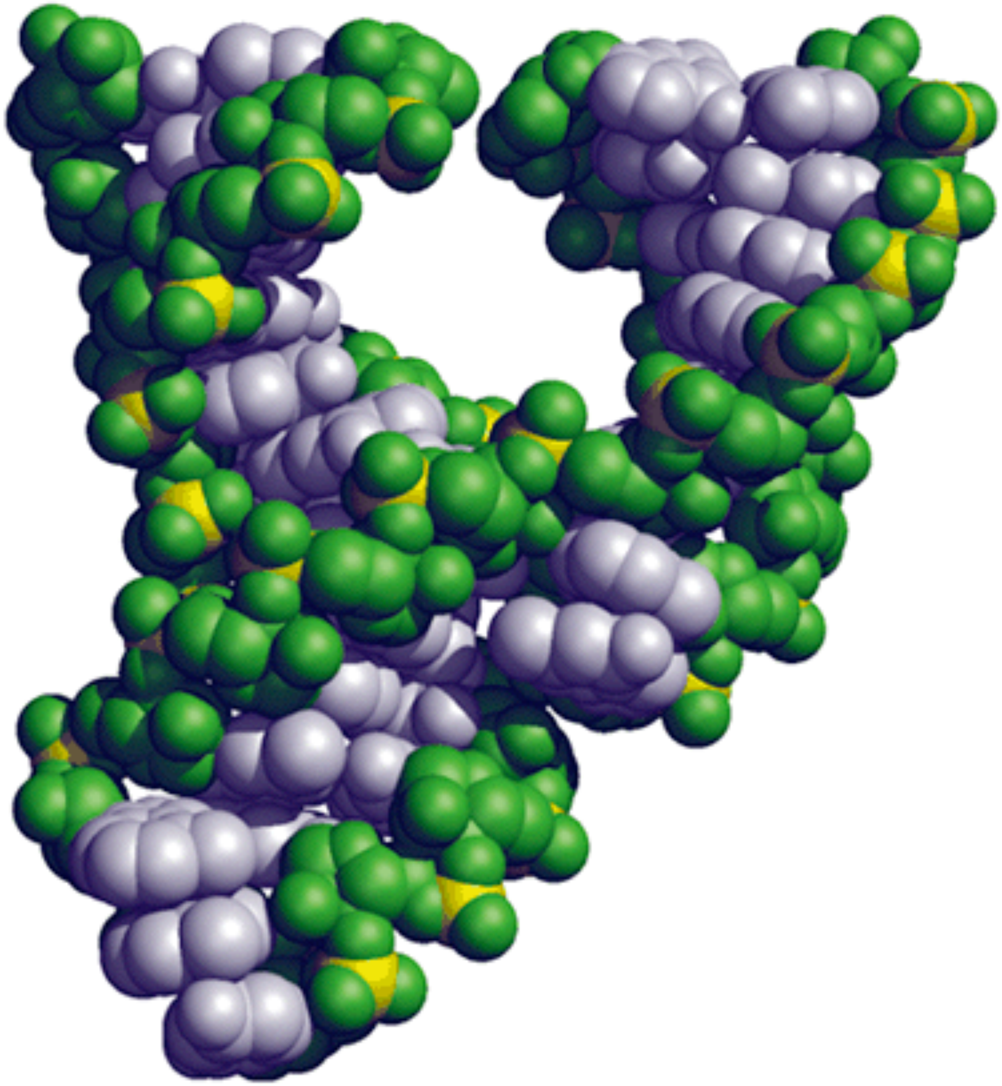

5'
New
3'
New
Parent strand
Daughter strands
Parent strand

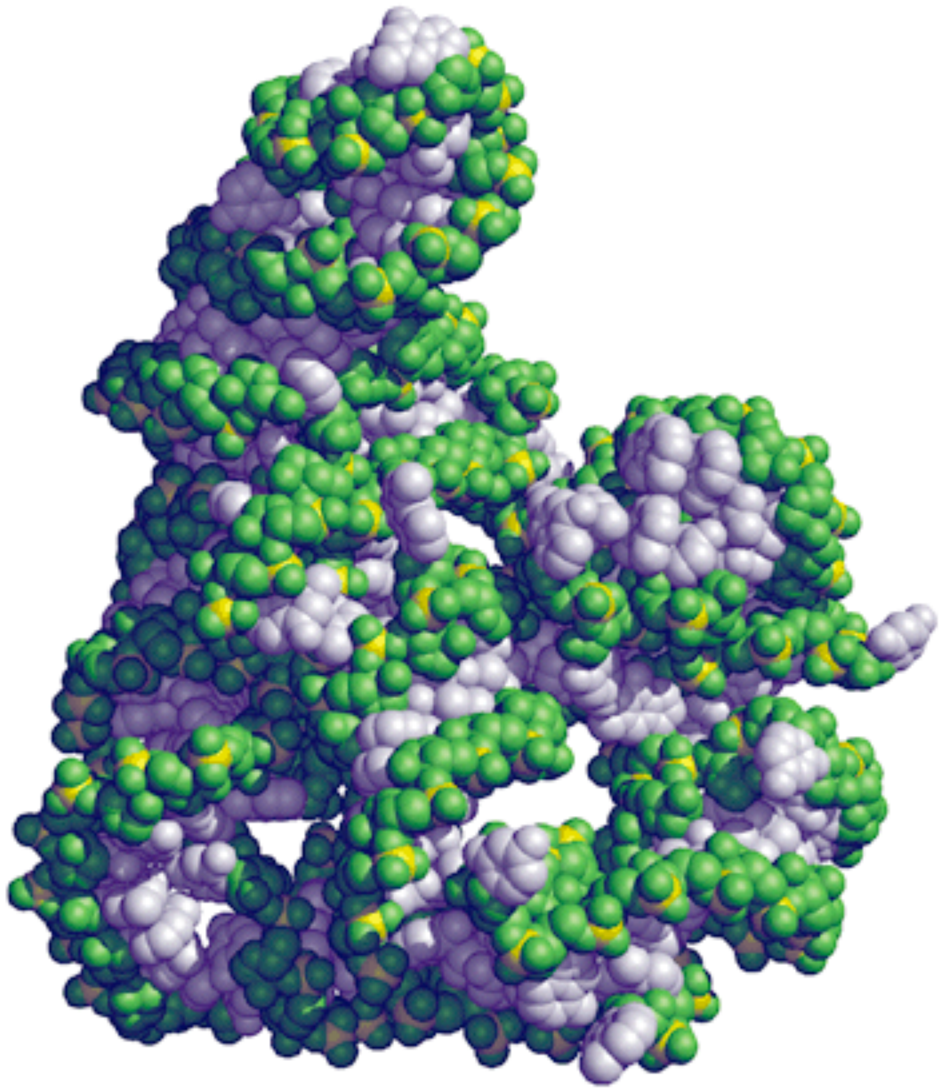


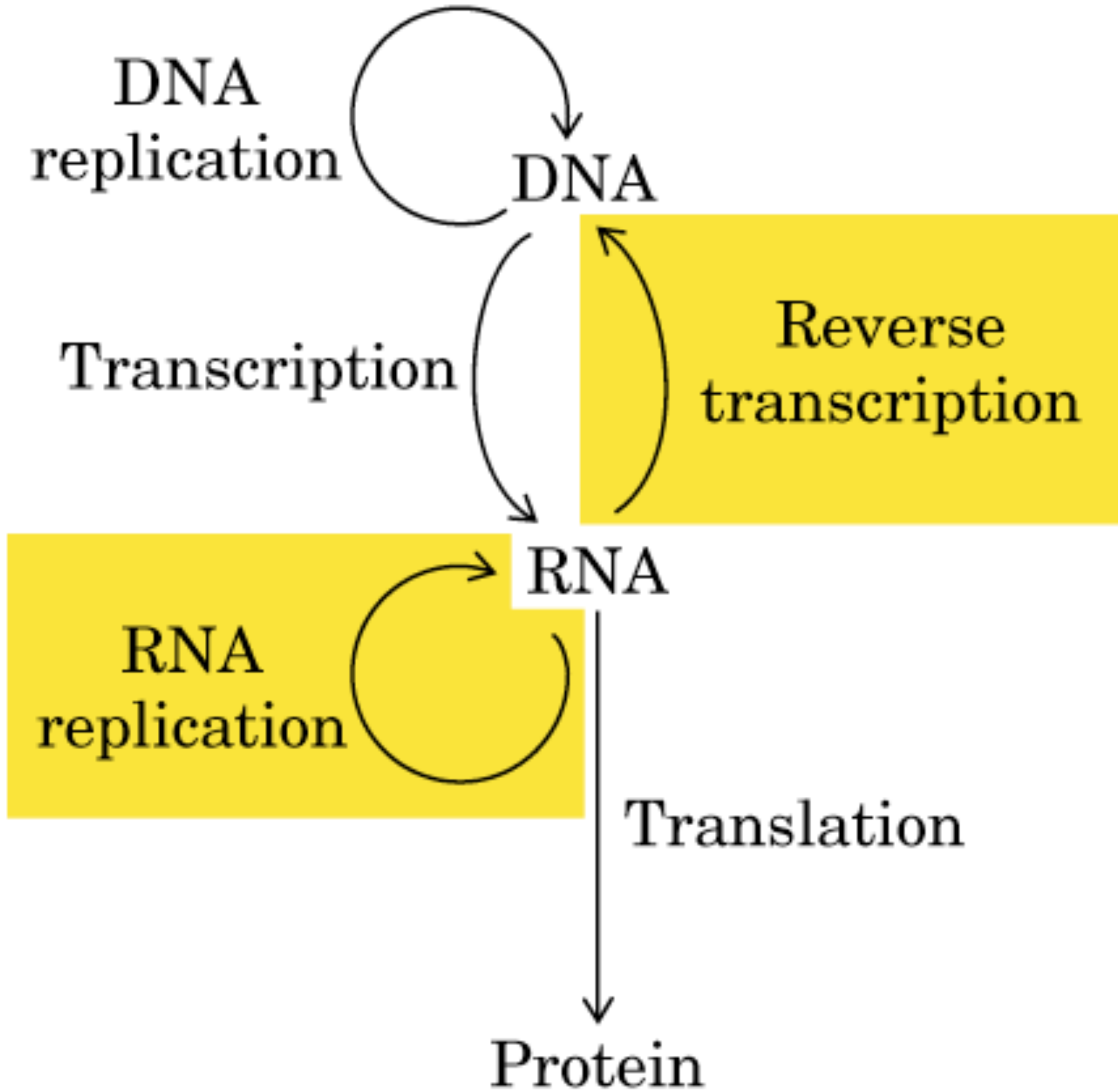
(A) (B)

Figure 1-6 *Molecular Biology of the Cell*, Fifth Edition (© Garland Science 2008)








DNA replication
DNA
Transcription
Reverse transcription
RNA
RNA replication
Translation
Protein