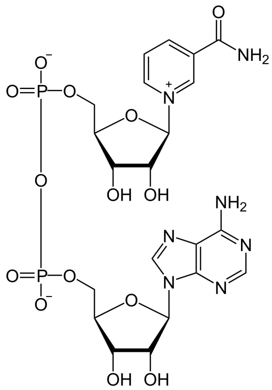
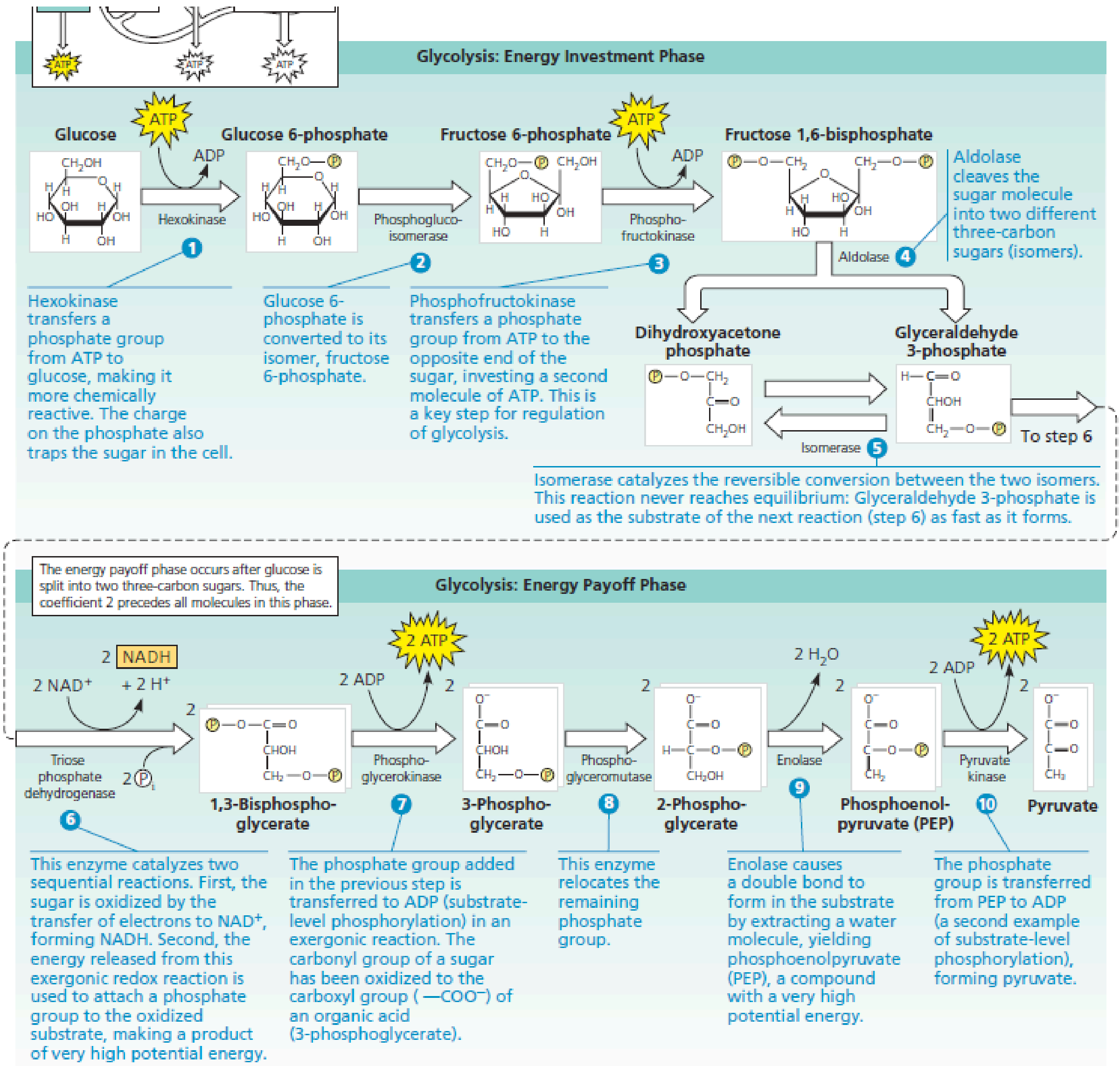
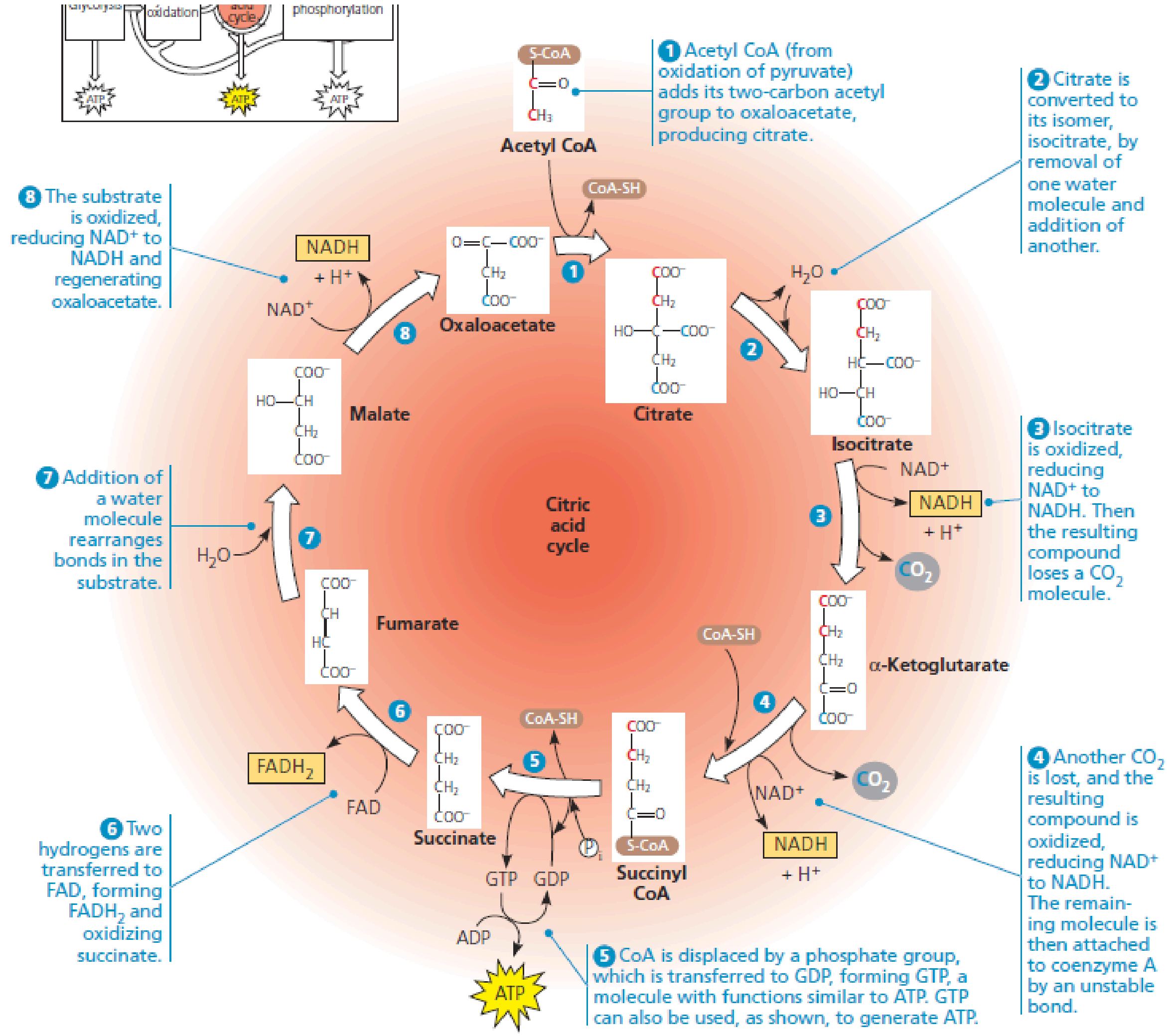
Cheat Sheet

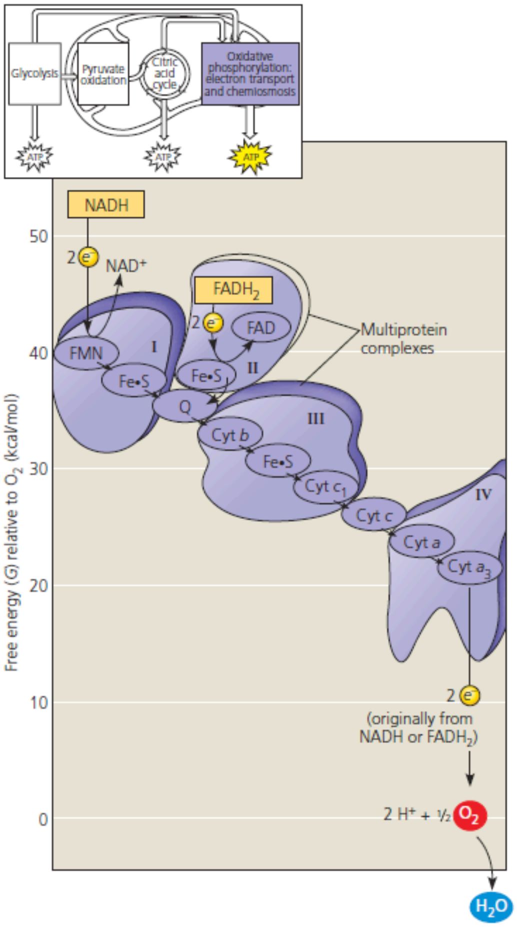


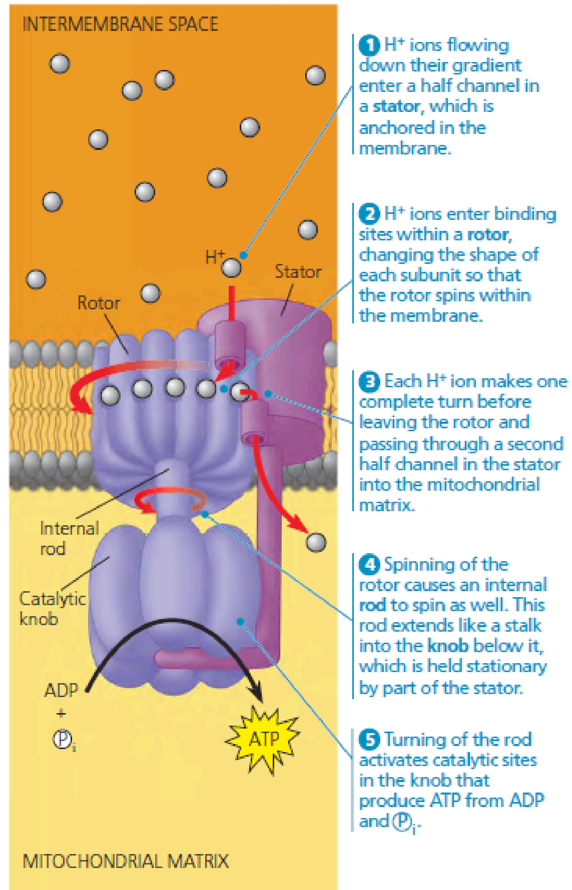


Glycolysis: Energy Investment Phase
Glucose
ATP
ADP
Hexokinase
1
Glucose 6-phosphate
Phosphogluco-isomerase
2
Fructose 6-phosphate
ATP
ADP
Phospho-fructokinase
3
Fructose 1,6-bisphosphate
Aldolase
4
Aldolase cleaves the sugar molecule into two different three-carbon sugars (isomers).
Hexokinase transfers a phosphate group from ATP to glucose, making it more chemically reactive. The charge on the phosphate also traps the sugar in the cell.
Glucose 6-phosphate is converted to its isomer, fructose 6-phosphate.
Phosphofructokinase transfers a phosphate group from ATP to the opposite end of the sugar, investing a second molecule of ATP. This is a key step for regulation of glycolysis.
Dihydroxyacetone phosphate
Glyceraldehyde 3-phosphate
Isomerase
5
To step 6
Isomerase catalyzes the reversible conversion between the two isomers. This reaction never reaches equilibrium: Glyceraldehyde 3-phosphate is used as the substrate of the next reaction (step 6) as fast as it forms.
The energy payoff phase occurs after glucose is split into two three-carbon sugars. Thus, the coefficient 2 precedes all molecules in this phase.
Glycolysis: Energy Payoff Phase
2 NADH
2 NAD+
+ 2 H+
Triose phosphate dehydrogenase
2 Pi
6
1,3-Bisphospho-glycerate
2 ADP
2 ATP
Phospho-glycerokinase
7
3-Phospho-glycerate
Phospho-glyceromutase
8
2-Phospho-glycerate
2 H2O
Enolase
9
Phosphoenol-pyruvate (PEP)
2 ADP
2 ATP
Pyruvate kinase
10
Pyruvate
This enzyme catalyzes two sequential reactions. First, the sugar is oxidized by the transfer of electrons to NAD+, forming NADH. Second, the energy released from this exergonic redox reaction is used to attach a phosphate group to the oxidized substrate, making a product of very high potential energy.
The phosphate group added in the previous step is transferred to ADP (substrate-level phosphorylation) in an exergonic reaction. The carbonyl group of a sugar has been oxidized to the carboxyl group (—COO−) of an organic acid (3-phosphoglycerate).
This enzyme relocates the remaining phosphate group.
Enolase causes a double bond to form in the substrate by extracting a water molecule, yielding phosphoenolpyruvate (PEP), a compound with a very high potential energy.
The phosphate group is transferred from PEP to ADP (a second example of substrate-level phosphorylation), forming pyruvate.

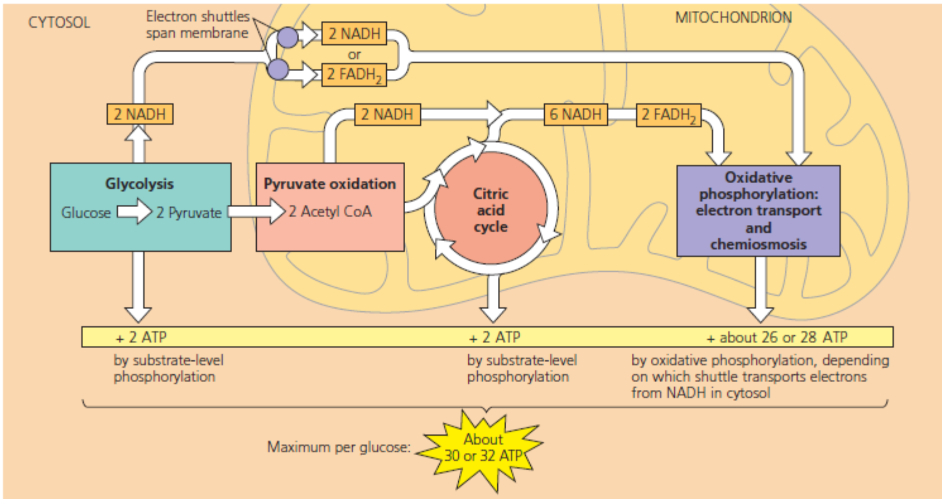


oxidation
cycle
phosphorylation
ATP
ATP
ATP
S-CoA
C=O
CH3
Acetyl CoA
1 Acetyl CoA (from oxidation of pyruvate) adds its two-carbon acetyl group to oxaloacetate, producing citrate.
CoA-SH
2 Citrate is converted to its isomer, isocitrate, by removal of one water molecule and addition of another.
8 The substrate is oxidized, reducing NAD+ to NADH and regenerating oxaloacetate.
NADH
+ H+
NAD+
O=C—COO−
CH2
COO−
Oxaloacetate
1
8
H2O
COO−
CH2
HO—C—COO−
CH2
COO−
Citrate
2
COO−
CH2
HC—COO−
HO—CH
COO−
Isocitrate
COO−
HO—CH
CH2
COO−
Malate
Citric acid cycle
3 Isocitrate is oxidized, reducing NAD+ to NADH. Then the resulting compound loses a CO2 molecule.
NAD+
NADH
+ H+
3
CO2
7 Addition of a water molecule rearranges bonds in the substrate.
7
H2O
COO−
CH
HC
COO−
Fumarate
CoA-SH
COO−
CH2
CH2
C=O
COO−
α-Ketoglutarate
4
6
CoA-SH
5
COO−
CH2
CH2
COO−
Succinate
COO−
CH2
CH2
C=O
S-CoA
Succinyl CoA
CO2
NAD+
NADH
+ H+
4 Another CO2 is lost, and the resulting compound is oxidized, reducing NAD+ to NADH. The remaining molecule is then attached to coenzyme A by an unstable bond.
FADH2
FAD
Pi
GTP
GDP
ADP
ATP
6 Two hydrogens are transferred to FAD, forming FADH2 and oxidizing succinate.
5 CoA is displaced by a phosphate group, which is transferred to GDP, forming GTP, a molecule with functions similar to ATP. GTP can also be used, as shown, to generate ATP.



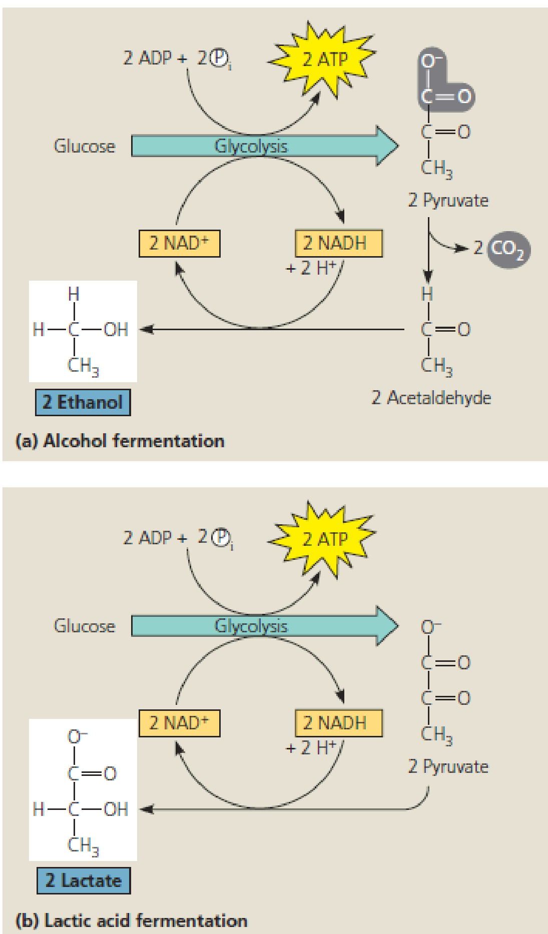


▲ **Figure 9.14 ATP synthase, a molecular mill.** The ATP synthase protein complex functions as a mill, powered by the flow of hydrogen ions. Multiple copies of this complex reside in mitochondrial and chloroplast membranes of eukaryotes and in the plasma membranes of prokaryotes. Each of the four parts of ATP synthase consists of a number of polypeptide subunits.

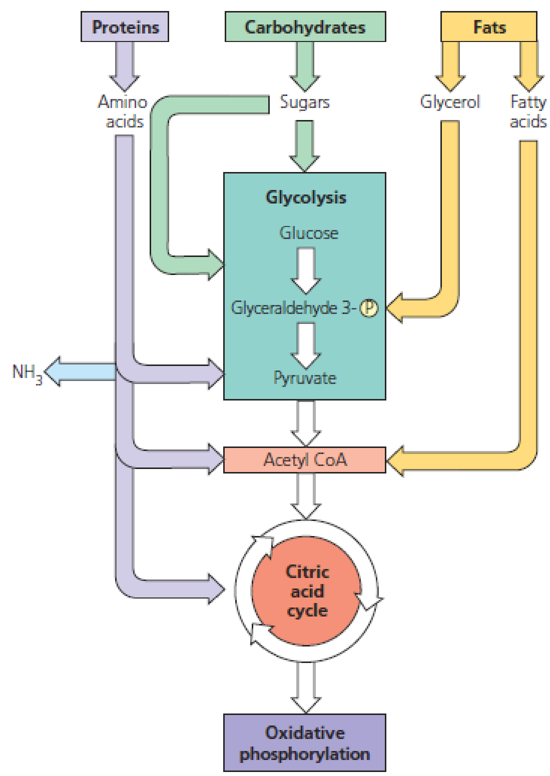


▲ **Figure 9.16** **ATP yield per molecule of glucose at each stage of cellular respiration.**

? *Explain exactly how the numbers "26 or 28" were calculated.*



▲ **Figure 9.17** **Fermentation.** In the absence of oxygen, many cells use fermentation to produce ATP by substrate-level phosphorylation. Pyruvate, the end product of glycolysis, serves as an electron acceptor for oxidizing NADH back to NAD^+, which can then be reused in glycolysis. Two of the common end products formed from fermentation are **(a)** ethanol and **(b)** lactate, the ionized form of lactic acid.



▲ **Figure 9.19** **The catabolism of various molecules from food.** Carbohydrates, fats, and proteins can all be used as fuel for cellular respiration. Monomers of these molecules enter glycolysis or the citric acid cycle at various points. Glycolysis and the citric acid cycle are catabolic funnels through which electrons from all kinds of organic molecules flow on their exergonic fall to oxygen.

Chapter 9 Questions

1. **What are the three key pathways of respiration?**
2. **How does the recycling of energy compare with the recycling of chemical elements?**
3. **What is the difference between catabolic and anabolic pathways?**
4. **What is the free-energy change of the breakdown of glucose?**
5. **What are redox reactions? What are reducing and oxidizing agents?**
6. **What provides the oxygen for the water yielded by respiration? What about the carbon dioxide?**
7. **What is the electron carrier that hydrogen atoms are first transferred to? What are its oxidized and reduced forms?**
8. **What enzymes remove a pair of hydrogen atoms from glucose and delivers both electrons and one proton to the electron acceptor?**
9. **What is the structure of the electron carrier?**
10. **What is an electron transport chain?**
11. **What is the free energy change of electron transfer from the electron carrier to oxygen?**
12. **What is glycolysis and where does it occur?**
13. **What occurs in pyruvate oxidation and where does it occur?**
14. **What occurs in oxidative phosphorylation?**
15. **What is substrate-level phosphorylation?**
16. **How much ATP is produced per glucose molecule, and how much energy does each ATP contain?**
17. **What occurs in the energy investment phase? What about the energy payoff phase? What is the net energy yield per glucose molecule?**
18. **Draw the glycolytic pathway.**
19. **What must be present for the pyruvate molecules to enter a mitochondrion?**
20. **What are the three steps of pyruvate oxidation?**
21. **What are the two other names for the citric acid cycle?**
22. **Draw the citric acid cycle.**
23. **What energy-rich molecules are produced per citric acid cycle per acetyl group?**
24. **How are electron transport chains organized and where are they located?**
25. **What is the overall energy drop for an electron that goes through an electron transport chain?**
26. **Draw the electron transport chain.**
27. **Describe the passage of electrons through complex I.**
28. **What are cytochromes?**
29. **Where do electrons from $FADH_2$ enter the electron transport chain?**
30. **Compare the energy produced from $FADH_2$ electrons and NADH electrons.**
31. **What is chemiosmosis?**

32. What complex makes ATP from ADP and inorganic phosphate, and how does it work (5 steps, 4 parts)?
33. What are the two mobile carriers in an electron transport chain?
34. What creates the proton motive force required for ATP synthesis and what is special about complex II?
35. Draw/label ATP and molecule yield for all 4 stages of glucose breakdown.
36. How much ATP does each NADH molecule produce and how many hydrogen ions does it pump out?
37. How much ATP is produced by each $FADH_2$ molecule?
38. What causes ATP yield to vary?
39. How much energy does phosphorylation of ADP store, what percent of glucose molecule energy is stored in ATP?
40. What is brown fat?
41. What is the difference between anaerobic respiration and fermentation?
42. Give an example of anaerobic bacteria.
43. What is fermentation?
44. What are the two types of fermentation and what occurs in each (draw cycle)?
45. How many ATP molecules does fermentation produce?
46. What are the two types of anaerobes?
47. How can proteins be used in glycolysis?
48. How can fats be used in respiration?
49. How does ATp production of fat compare to that of carbohydrate?
50. Draw diagram of molecule usage.
51. What can humans make from various intermediates of respiration?
52. What is considered to be the pacemaker of respiration and why?
53. Draw where reactant elements go to in products.

Chapter 9 Answers

1. Glycolysis, pyruvate oxidation, citric acid cycle
2. Energy enters as light and leaves as heat, while chemical elements are recycled
3. Catabolic pathways release energy by breaking down complex molecules, anabolic pathways build up molecules
4. -686 kcal/mol of glucose
5. Oxidation-reduction reactions where electrons are transferred from one substance to another. Reducing agents donate electrons, oxidizing agents receive electrons.
6. Oxygen, Glucose
7. the coenzyme nicotinamide adenine dinucleotide, derivative of vitamine niacin, cycles between oxidized form NAD^+ and NADH, its reduced form
8. dehydrogenases
9. Two nucleotides joined together at their phosphate groups, nicotinamide as upper nitrogenous base, adenine as the bottom nitrogenous base, ribose as sugar, top carbon of nicotinamide gains hydrogen, electron reduces N+ at bottom of nicotinamide.
10. Consists of molecules(mostly proteins) built into inner membrane of mitochondria of eukaryotic cells, plasma membrane of respiring prokaryote, NADH shuttles electron to higher energy part of chain, O_2 pulls electrons in, movement is harnessed, oxygen becomes water
11. -53 kcal/mol
12. It occurs in the cytosol, breaks glucose into two molecules of pyruvate. glucose is broken into two 3-carbon sugars, which are oxidized, remaining atoms rearranged to form two molecules of pyruvate (ionized form of pyruvic acid), split into energy investment phase and energy payoff phase
13. The pyruvates are oxidized to acetyl CoA in the mitochondria.
14. Electron transport chains convert chemical energy into form that is used for ATP synthesis in process called chemiosmosis, accounts for 90% of ATP generated by respiration
15. Mode of ATP synthesis that occurs when enzyme transfers phosphate group from substrate from substrate molecule to ADP, rather than adding inorganic phosphate to ADP as in oxidative phosphorylation, very little ATP
16. 32 molecules, 7.3 kcal/mol
17. Cell spends ATP in investment phase, in payoff phase ATP generated by substrate-level phosphorylation and NAD^+ is reduced to NADH by electrons released from oxidation of glucose, yielding 2 ATP and 2 NADH per glucose molecule
18. DRAW IT
19. Oxygen
20. First, pyruvate's carboxyl group ($-COO^-$) (already fully oxidized and with little energy) is fully oxidized and given off as a molecule of CO_2. Next, remaining 2-carbon fragment is oxidized and electrons transferred to NAD^+, storing energy in the form of NADH. Third, coenzyme A (CoA, abbr. S-CoA when attached to molecule), a sulfur containing

compound derived from a B vitamin, is attached via its sulfur atom to the two-carbon intermediate, forming acetyl CoA (acetyl coenzyme A). Acetyl CoA has high potential energy

21. Tricarboxylic acid cycle and krebs cycle
22. DRAW IT
23. 3 NADH, 1 $FADH_2$, and either 1 GTP or 1 ATP molecule by substrate level phosphorylation
24. Protein components exist in multiprotein complexes numbered I through IV, prosthetic groups (nonprotein components) are tightly bound to these proteins
25. 53 kcal/mol
26. DRAW IT
27. Electrons transferred from NADH to flavoprotein in complex I, has prosthetic group called flavin mononucleotide (FMN). Flavoprotein oxidizes as it passes electrons to iron-sulfur protein (FeS) in complex I, one of a family of proteins with both iron and sulfur tightly bound. FeS passes electrons to ubiquinone(Q), which is small hydrophobic molecule that acts as electron carrier, only member of ETC that is not a protein, individually mobile within membrane (no particular complex), also called coenzyme Q (CoQ)
28. Proteins that make up most of electron carries in complexes III and IV, have prosthetic group called heme group (has iron atom that accepts and donates electrons, similar to heme in hemoglobin except carries electrons, not oxygen), different lettered “cyt”s mean slightly diff heme groups.
29. Complex II FeS protein at lower energy level than NADH does
30. $FADH_2$ electrons yield ⅓ less energy than NADH
31. Process in which energy stored in form of hydrogen ion gradient across membrane is used to drive cellular work
32. ATP synthase, exploits difference in H^+ concentration on opposite sides of the inner mitochondrial membrane, look at image
33. Ubiquinone and Cyt c
34. Certain members of chain accept protons from mitochondrial matrix and release them in the intermembrane space, complex II does not have components that shuttle hydrogen ions out of matrix
35. SEE PICTURE
36. max 3 ATP (generally accepted to be 2.5 ATP), exactly 10 H^+ (means 4 H^+ per ATP)
37. 1.5 ATP
38. Inexact ratio between NADH and ATP molecules, Type of shuttle used to transport electrons from cytosol into mitochondria (either NADH or $FADH_2$), use of proton-motive force to do other work
39. 7.3 kcal/mol, means that 34% of each glucose molecule converted to ATP energy
40. Tissue in hibernating animals that contains many mitochondria with channel proteins called uncoupling proteins that allow protons to flow back down concentration gradient without generating ATP, creating more heat and preventing cellular respiration from being shut off by excess ATP

41. Anaerobic respiration uses an electron transport chain, fermentation does not
42. “sulfate-reducing” marine bacteria use sulfate ion SO_4^{2-} at end of their respiratory chain, yields H_2S (hydrogen sulfide) instead of water
43. Extension of glycolysis that allows continuous generation of ATp by substrate-level phosphorylation of glucose, NADH recycled by transfer of electrons to pyruvate
44. Alcohol fermentation and lactic acid fermentation, alcohol is where carbon dioxide is released from pyruvate, which is converted to the two-carbon compound acetaldehyde. Acetaldehyde is reduced by NADH to ethanol, regenerating supply of NAD^+. Lactic acid, pyruvate reduced directly by NADH to form lactate as end product, regenerating NAD^+ w/out CO_2 release (lactate is ionized form of lactic acid). In humans, blood carries excess lactate to liver where it is converted to pyruvate by liver cells
45. 2
46. Obligate and facultative, obligate carry out only fermentation or anaerobic respiration, cannot survive in presence of oxygen. Facultative use either one or just aerobic respiration
47. Digested into constituent amino acids, many acids used by organism to build new proteins, excess converted by enzymes to intermediates of glycolysis and citric acid cycle, amino groups removed in deamination before entering processes, nitrogenous waste excreted in form of ammonia (NH_3), urea, or other waste product
48. Glycerol converted to glyceraldehyde 3-phosphate (intermediate of glycolysis). Fatty acids broken down into two carbon fragments by metabolic sequence called beta oxidation, fragments enter citric acid cycle as acetyl CoA, NADH and $FADH_2$ generated during beta oxidation
49. Same mass of fat produces twice as much ATP as carb
50. About half of amino acids can be made from compounds of citric acid cycle, glucose can be made from pyruvate, fatty acids from acetyl CoA, dihydroxyacetone phosphate can be converted to one of the major precursors of fats
51. The allosteric enzyme phosphofructokinase, catalyzes step 3 of glycolysis, first step that commits substrate irreversibly to glycolytic pathway. Has receptor sites for specific inhibitors and activators, inhibited by ATP, stimulated by AMP (adenosine monophosphate), which cell derives from ADP. Also sensitive to citrate (first product of citric acid cycle), which inhibits enzyme, helping to synchronize glycolysis and citric acid cycle
52. carbon in glucose to C in CO_2