Chapter 9: Cellular Respiration and Fermentation

9.1 Explain how the redox reactions of catabolic pathways yield energy by oxidizing organic fuels.

9.2 Trace the pathway of glucose oxidation during glycolysis.

9.3 Describe the oxidation of pyruvate and the process by which further oxidation occurs in the citric acid cycle.

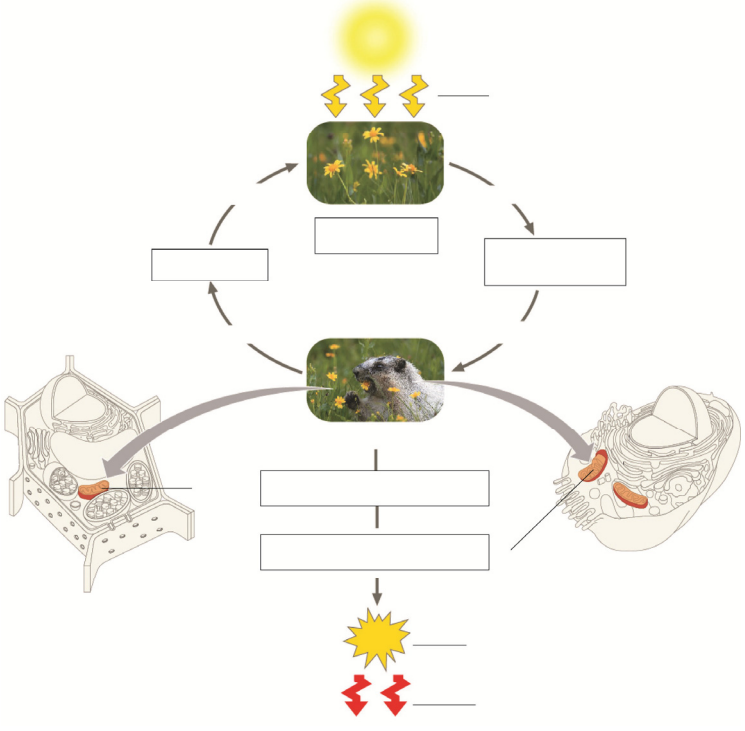
9.4 Identify the steps of oxidative phosphorylation and account for the total ATP produced per glucose molecule during cellular respiration.

9.5 Name two types of fermentation and explain how they result in ATP production.

9.6 Use examples to illustrate the interactions of glycolysis and the citric acid cycle with other metabolic pathways.

Although this is a challenging topic, it will give you the background necessary to understand much about energy transfer at the cellular level. Each concept builds on the previous concept, so take your time working through the figures and text, and you will find you have mastered a difficult area of biology when you finish.

Study Tip: Before getting involved with the details of cellular respiration, take a second to look at the big picture as shown in Figure 9.1. Both photosynthesis (the topic for Chapter 10) and cellular respiration are key ecological concepts involved with energy flow. Use Figure 9.1 to label the indicated parts in the following figure.



Concept 9.1 Catabolic pathways yield energy by oxidizing organic fuels

LO 9.1: Explain how the redox reactions of catabolic pathways yield energy by oxidizing organic fuels.

1. Explain the difference between *fermentation* and *aerobic respiration*.

2. Summarize the catabolic degradation of food by aerobic respiration in words (rather than using chemical symbols).

3. The breakdown of glucose in cellular respiration yields _____ of energy, meaning this reaction has a *positive/negative* ΔG and is *exergonic/endergonic*. (Circle the correct choices.)

4. The breakdown of glucose is linked to cellular work by a chemical driveshaft known as _____.

5. Both cellular respiration and photosynthesis are *redox reactions*. In redox reactions, pay attention to the flow of electrons. What is the difference between oxidation and reduction?

6. The following is a generalized formula for a redox reaction:

$$Xe^- + Y \rightarrow X + Ye^-$$

Draw an arrow showing which component (X or Y) is oxidized and which is reduced. _____ is the reducing agent in this reaction, and _____ is the oxidizing agent.

7. When compounds lose electrons, they _____ energy; when compounds gain electrons, they _____ energy.

8. In cellular respiration, electrons are not transferred directly from glucose to oxygen. Following the movement of hydrogens allows you to follow the flow of electrons. What *electron carrier* is hydrogen transferred to first?

9. ***NAD***$^+$ is a coenzyme. What are coenzymes? (If you have forgotten, look at p. 158 in Chapter 8.)

10. Describe what happens when NAD^+ is reduced. What enzyme type is involved?

11. It is essential for you to understand the concept of oxidation/reduction and energy transfer. For the following pair, which molecule is the oxidized form, and which is reduced? Which molecule holds higher potential energy? Which is lower in potential energy?

	Oxidized or Reduced?	Higher Energy/Lower Energy
NAD^+		
NADH		

12. What is the function of the *electron transport chain* in cellular respiration?

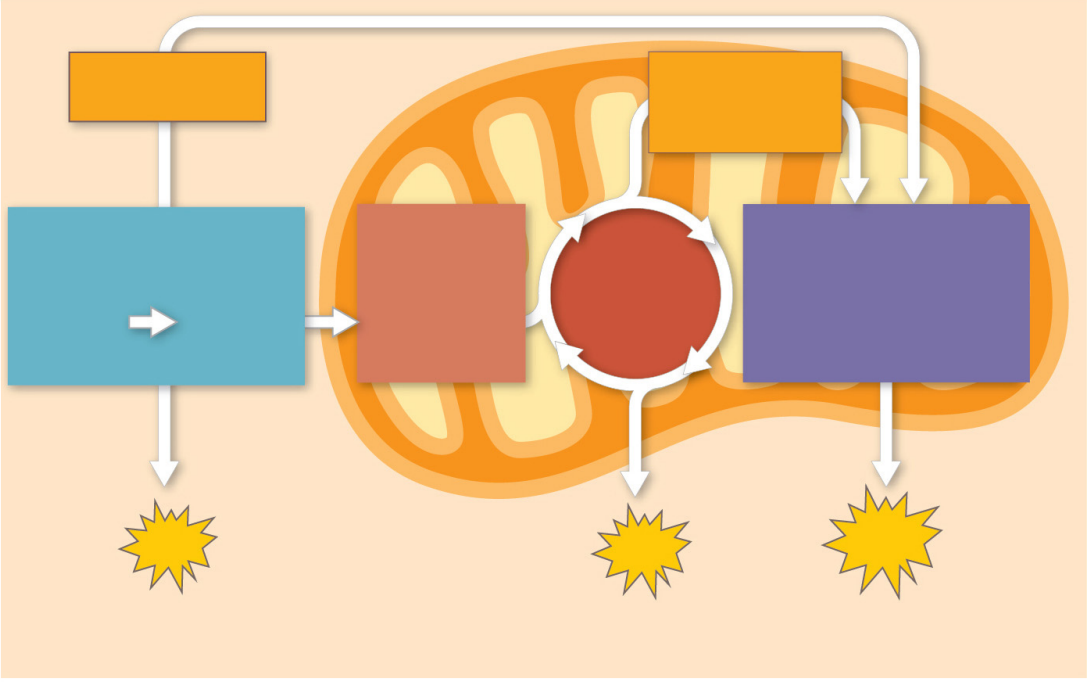
13. Electron transport involves a series of electron carriers, mostly proteins.

    a. Where are these carrier molecules found in eukaryotic cells?

    b. Where are the carrier molecules found in prokaryotic cells?

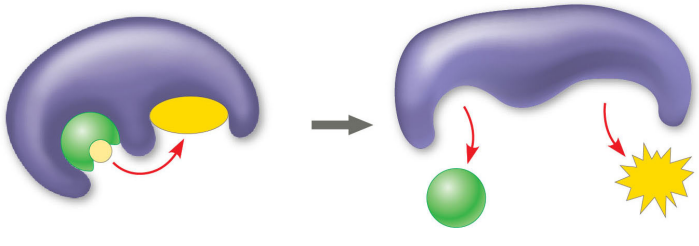
14. Which strongly electronegative atom, pulling electrons down the electron transport chain, is the final electron acceptor?

15. Understanding the overall map of how cellular respiration works will make the details easier to learn. Use Figure 9.5 from your text to label the missing information in the following figure. *This summary figure is central to understanding Chapter 9. Talk through what is occurring as you label it.*



16. Three types of *phosphorylation* (adding a phosphate) are covered in the text, and two of these occur in cellular respiration. Explain how the electron transport chain is utilized in *oxidative phosphorylation*.

17. The second form of phosphorylation is *substrate level*. Label the following figure to show the direct transfer of a phosphate from an organic substrate to ADP to form ATP.



Concept 9.2 Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

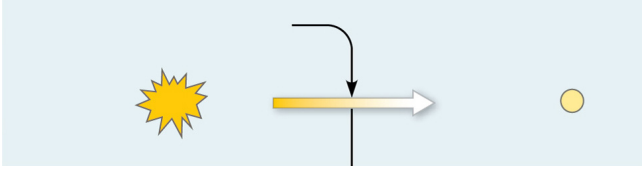
LO 9.2: Trace the pathway of glucose oxidation during glycolysis.

18. What is the meaning of *glycolysis*? What occurs in this step of cellular respiration?

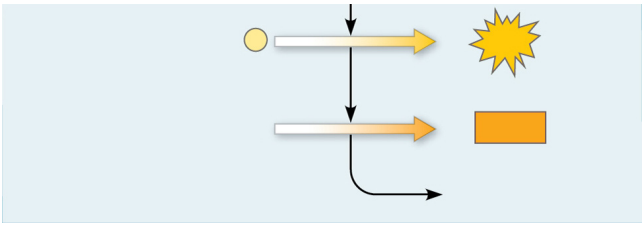
19. The starting product of glycolysis is the six-carbon sugar _____ and the ending products are two _____-carbon molecules of _____.

The 10 individual steps of glycolysis can be divided into two stages: *energy investment* and *energy payoff*. These steps are shown in Figure 9.8 in your text, which details the enzymes and reactions at each of the 10 steps. Although you are not expected to memorize these steps, structures, or enzymes, you *should* understand the figure. The next few questions will help you focus your study.

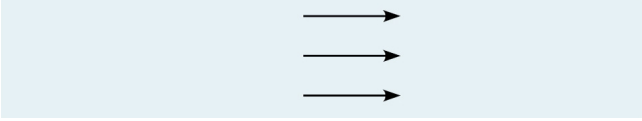
20. The following figures show a summary of glycolysis. Label the *energy investment phase* below and complete the figure. Then turn to Figure 9.8 on p. 170 of your text to find the two specific steps where ATP is used.



21. The second phase in glycolysis is the *energy payoff phase*. Label this phase and complete the figure. Note that it provides both ATP and NADH. Look at Figure 9.9 from your text to locate the two steps where ATP is formed and the one step where NADH is formed.



22. This final figure shows the net gain of energy for the cell after glycolysis. *Most of the energy is still present in the two molecules of pyruvate.* Complete the following figure to show the net energy gains.

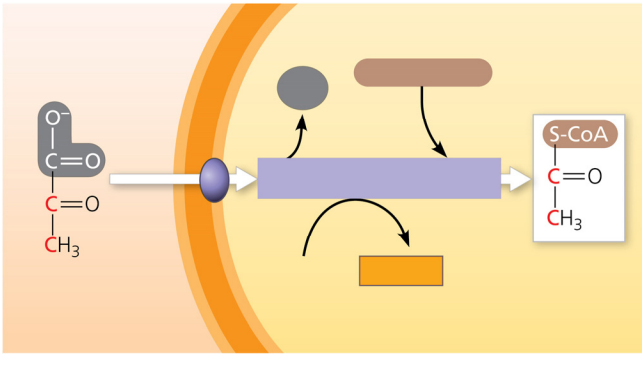


23. Where does glycolysis occur in the cell? Is oxygen required?

Concept 9.3 After pyruvate is oxidized, the citric acid cycle completes the energy-yielding oxidation of organic molecules

LO 9.3: Describe the oxidation of pyruvate and the process by which further oxidation occurs in the citric acid cycle.

24. To enter the citric acid cycle, pyruvate must enter the mitochondria by active transport. Three things are necessary to convert pyruvate to acetyl CoA. Complete the missing parts of the following figure and then explain the three steps in the conversion process.



a.

b.

c.

25. Use Figure 9.10 from your text to help you answer the following summary questions about the citric acid cycle:

    a. How many NADHs are formed?

    b. How many total carbons are lost as pyruvate is oxidized?

    c. The carbons are lost in which molecule?

    d. How many $FADH_2$ are formed?

    e. How many ATPs are formed?

    f. How many times does the citric acid cycle occur for each molecule of glucose?

26. The step that converts pyruvate to acetyl CoA at the top of the diagram occurs twice per glucose. This oxidation of pyruvate accounts for two additional reduced _____ molecules and two molecules of CO_2.

27. Explain what has happened to the six carbons found in the original glucose molecule.

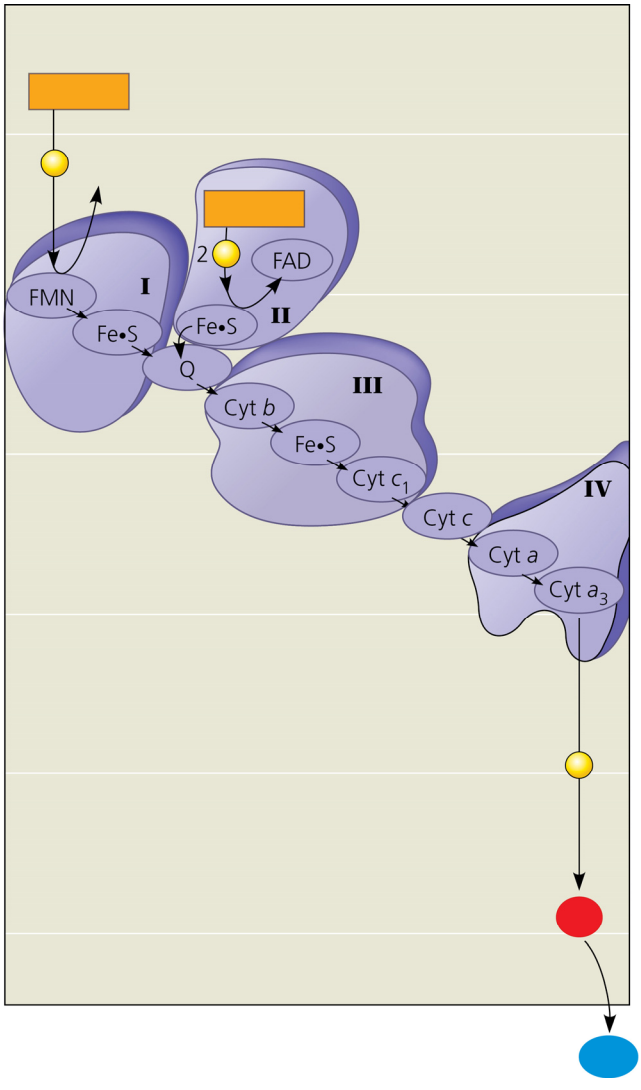
28. Figure 9.11 takes a closer look at the citric acid cycle. Notice that acetyl CoA combines with the four-carbon compound oxaloacetate to form the six-carbon citrate. The *cycle* then begins with the production of NADH, $FADH_2$, and ATP. Look for where CO_2 is lost in the cycle. As the citric acid cycle is completed what compound is regenerated? _____. Note that little ATP has been produced. Where is most of the energy at this point in cellular respiration?

Concept 9.4 During oxidative phosphorylation, chemiosmosis couples electron transport to ATP synthesis

LO 9.4: Identify the steps of oxidative phosphorylation and account for the total ATP produced per glucose molecule during cellular respiration.

29. *Oxidative phosphorylation* involves two components: the electron transport chain and ATP synthesis. Referring to Figure 9.13 in your text, notice that each member of the electron transport chain is lower in free _____ than the preceding member of the chain, but higher in _____. The molecule at zero free energy on this chart, which is _____, is the lowest of all the molecules in free energy and the highest in electronegativity. Use your new knowledge to label the missing parts of the following diagram.

Concentrate on the overall picture of electron transport without getting bogged down in the numerous details.

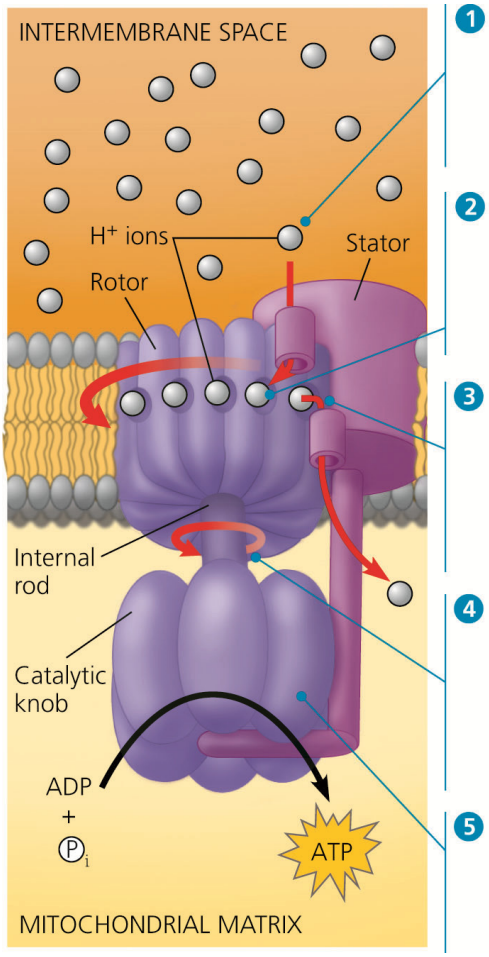


30. Explain why oxygen is considered the ultimate electron acceptor.

31. Oxygen stabilizes the electrons by combining with two hydrogen ions to form what compound?

32. What are the two electron carrier molecules that feed electrons into the electron transport system?

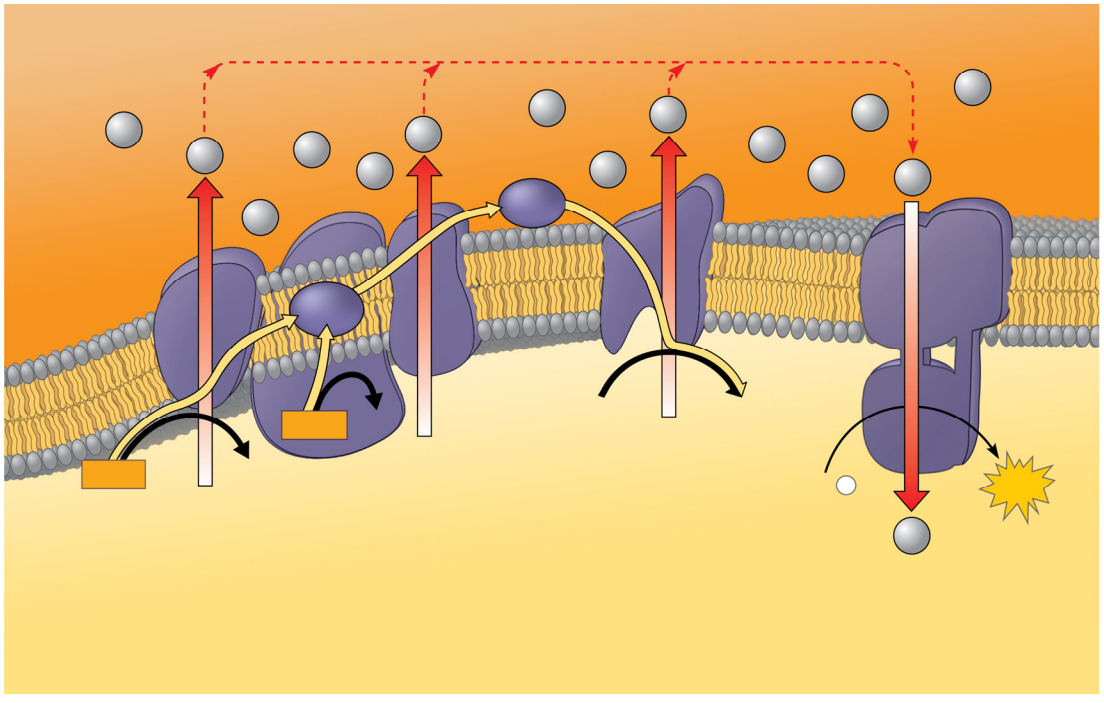
33. Use Figure 9.13 in your text of ATP synthase to explain and label the five steps to the production of ATP.



34. What is the role of the electron transport chain in forming the H^+ gradient across the inner mitochondrial membrane?

35. Two key terms are *chemiosmosis* and *proton-motive force*. Relate both terms to the process of oxidative phosphorylation.

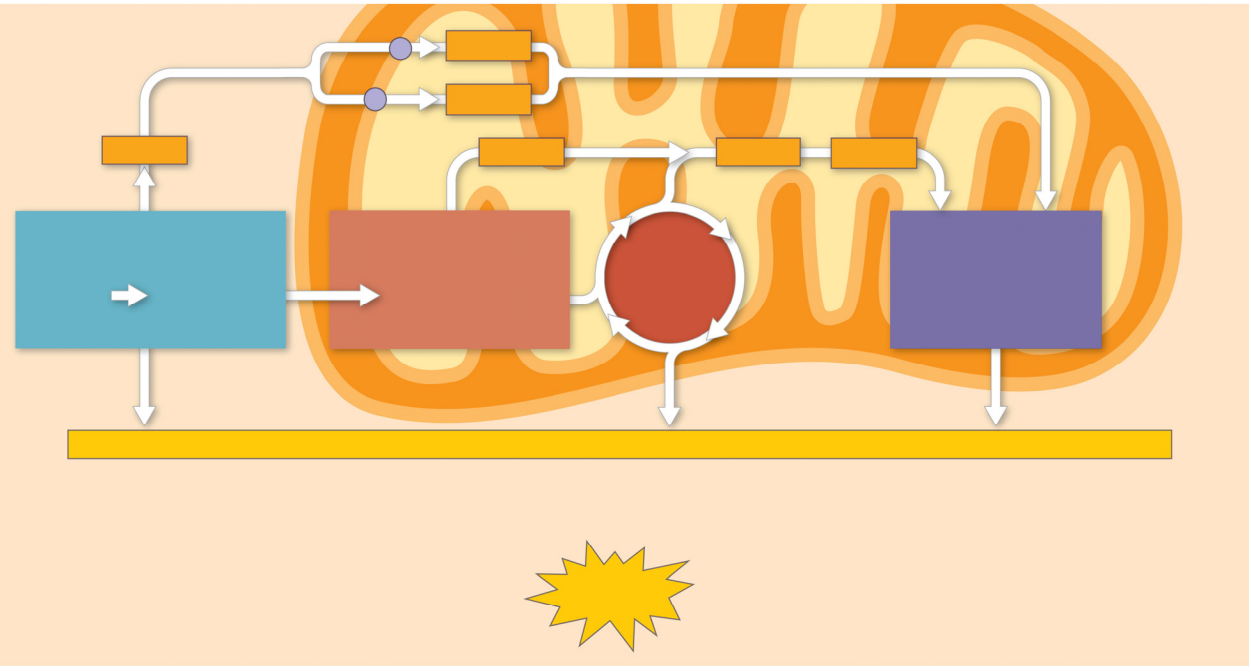
36. Figure 9.14 in your text will help you understand the production of ATP in the mitochondria. Label the figure to study this process. Then, label the pathway of protons and the pathway of electrons on the figure.



37. At this point, you should be able to account for the total number of ATPs that could be formed from a glucose molecule. To accomplish this, add the ATPs formed by substrate-level phosphorylation in glycolysis and the citric acid cycle to the ATPs formed by chemiosmosis. Each NADH can form a maximum of _____ ATP molecules. Each $FADH_2$, which donates electrons that activate only two proton pumps, makes _____ ATP molecules.

Figure 9.15 in your text is very similar to the one you labeled earlier for question 15, but now additional details are added. Can you supply labels to indicate the fundamental process of cellular respiration without consulting your text?

38. Label the figure that follows to show the processes of cellular respiration. Then, show the production of NADH and $FADH_2$. Finally, show where ATP is formed, and indicate whether it is by substrate-level or oxidative phosphorylation. Use the text to be sure you understand how each subtotal on the bar below the figure is reached.



39. Why is the total count *about* 30 or 32 ATP molecules rather than a specific number?

Concept 9.5 Fermentation and anaerobic respiration enable cells to produce ATP without the use of oxygen

LO 9.5: Name two types of fermentation and explain how they result in ATP production.

40. Fermentation allows the production of ATP without using either _____ or any _____.

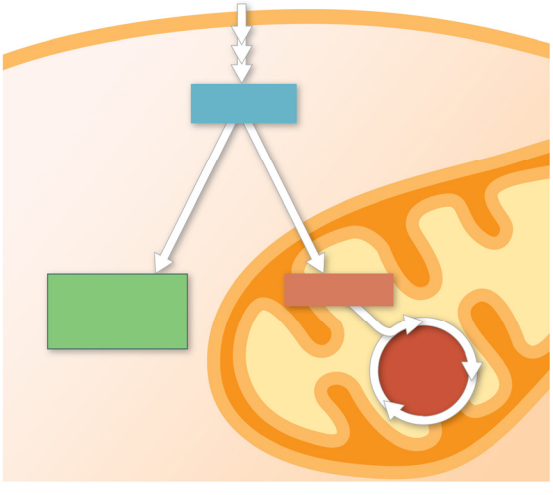
41. For aerobic respiration to continue, the cell must be supplied with oxygen—the ultimate electron acceptor. What is the electron acceptor in fermentation?

42. *Alcohol fermentation* starts with glucose and yields ethanol. Explain this process, and be sure to describe how NAD^+ is recycled.

43. Lactic *acid fermentation* starts with glucose and yields lactate. Explain this process and be sure to describe how NAD^+ is recycled.

44. Track coaches used to think that lactic acid accumulated in the muscles as a result of intense exertion, and would have athletes slowly jog to move more oxygen into the muscles so lactic acid would be oxidized and there would be less soreness the next day. What is currently known about lactate production and muscle soreness?

45. Completely label the following figure and then explain why pyruvate is a key juncture in metabolism.



46. Glycolysis is thought to have evolved very early in the evolution of life on Earth. Provide three pieces of evidence that justify this hypothesis.

Concept 9.6 Glycolysis and the citric acid cycle connect to many other metabolic pathways

LO 9.6: Use examples to illustrate the interactions of glycolysis and the citric acid cycle with other metabolic pathways.

47. Most of our discussion has focused on the use of glucose to produce ATP. However, other molecules are also used, and enter the process at different points in the process. Study Figure 9.18 in your text to see how various molecules and foods you eat are used to make ATP. What three organic macromolecules are often utilized to make ATP by cellular respiration?

48. Explain how and where each of these molecules may enter the process of cellular respiration:

    Starch

    Glycogen

    Proteins

    Fats

49. Explain the difference in energy usage between the catabolic reactions of cellular respiration and the anabolic pathways of biosynthesis.

50. Study Figure 9.19 in your text. Explain how AMP stimulates cellular respiration, whereas citrate and ATP inhibit it.

51. *Phosphofructokinase* is an allosteric enzyme that catalyzes an important step in glycolysis. Explain how this step is a control point in cellular respiration.

52. What molecule is the "pacemaker" of cellular respiration?

Test Your Understanding, p. 185

Now you should be ready to test your knowledge. Place your answers here:

1. ____ 2. ____ 3. ____ 4. ____ 5. ____ 6. ____ 7. ____