How do muscles get the energy they need for athletic activity?  

All athletic activity depends on muscle contractions that require energy. Inside muscle cells, the hydrolysis of ATP provides the energy for the molecular reactions that result in muscle contraction.

A typical muscle cell at rest has only enough ATP for ~1 or 2 seconds of contraction. To continue contraction for more than 1 or 2 seconds, a muscle cell needs to restore the ATP molecules.

Two processes can use glucose to produce ATP:
- **aerobic respiration** (Aerobic means that a process requires air or, specifically, oxygen = O₂. Aerobic respiration is also called cellular respiration.)
- **anaerobic fermentation** (Anaerobic means that the process does not require O₂.)

1a. In the diagram above, label the arrow that shows the hydrolysis of ATP.
1b. Label the arrow that shows energy input from anaerobic fermentation or aerobic respiration.

Anaerobic fermentation and aerobic respiration are summarized in the coupled chemical reactions shown in the boxes below. In both processes, glucose is broken down to smaller molecules in chemical reactions that release energy which is used in the production of ATP.

2. Write in the names of the molecules in the first chemical equation in each box. (Anaerobic fermentation in muscles produces lactic acid.) Fill in the blanks in the last chemical equation shown.

![Chemical equations](image)

3. During vigorous physical activity a person breathes faster and deeper. This increases the supply of O₂ for the muscles. How does this contribute to better athletic performance?
Anaerobic fermentation and aerobic respiration produce most of the ATP for muscle contraction, but muscle cells can make a rapid, brief burst of ATP using creatine phosphate (also called phosphocreatine.)

\[
\text{creatine phosphate} + H_2O \rightarrow \text{creatine} + P
\]

\[
\text{ADP} + P \rightarrow \text{ATP} + H_2O
\]

4. Fill in the blanks in the first reaction below to show how hydrolysis of ATP provides the energy for muscle cells to contract. (Hint: See the top of page 1.)

\[
\text{many } \_\_\_ + \text{many } H_2O \rightarrow \text{many } \_\_\_ + \text{many } P
\]

\[
\text{muscle cell relaxed} \rightarrow \text{muscle cell contracted}
\]

5. During physical activity muscle cells have increased rates of anaerobic fermentation, aerobic respiration and/or the hydrolysis of creatine phosphate. Explain why it is useful for these rates to increase in muscle cells during physical activity.

General Principles

- Energy can be transformed from one type to another (e.g. chemical energy can be transformed to the kinetic energy of muscle motion). Energy is not created or destroyed by biological processes.
- All types of energy transformation are inefficient and result in the production of heat. For example, when hydrolysis of ATP provides the energy for muscle contraction, only about 20-25% of the chemical energy released is captured in the kinetic energy of muscle contraction. The rest of the energy from the hydrolysis of ATP is converted to heat.
- The atoms in molecules can be rearranged into other molecules, but matter (atoms in molecules) is not created or destroyed.

6. Aerobic respiration occurs mainly inside the mitochondria in cells. A website claims that "The mitochondria in muscle cells make the energy needed for athletic activity." Explain what is wrong with this sentence, and give a more accurate sentence.

7. Explain why your body gets warmer when you are physically active.
You have seen that anaerobic fermentation and aerobic respiration of glucose provide the energy to produce ATP, and hydrolysis of ATP provides the energy for muscle contraction. The obvious next question is "How does glucose get to the muscles?" As shown in this chart, glucose can be derived from:

- carbohydrates in food (e.g. starch or sugars such as sucrose)
- glycogen (a polymer of glucose used to store glucose in muscles and in the liver).

Then, glucose is carried by the blood from the digestive system to the muscles.

Notice that the energy supply for muscle contraction depends on the cooperation of:

- the digestive system (to provide glucose)
- the respiratory system (to provide O₂)
- the circulatory system (since the blood pumped by the heart carries glucose and O₂ to the muscles).

8. The chart shows that at some times glycogen is broken down to release glucose, and at other times many glucose molecules are combined to form glycogen.
- Use an X to mark the arrows for the reaction that occur at a higher rate during vigorous exercise.
- Use an M to mark the arrows for the reaction that occurs at a higher rate during rest after a meal.

During exercise, fat molecules stored in muscles and in adipose tissue are broken down to fatty acids which muscle cells can use as another input for aerobic respiration.

9. Regular aerobic exercise such as walking, running or swimming results in changes in the body called training effects. Complete the following table to explain how each listed training effect contributes to an increased capacity for aerobic respiration in muscle cells.

<table>
<thead>
<tr>
<th>Training Effect Produced by Regular Aerobic Exercise</th>
<th>Explain how this training effect can contribute to an increase in the rate of aerobic respiration in muscle cells.</th>
</tr>
</thead>
<tbody>
<tr>
<td>The heart can pump more blood per second and the muscles have more capillaries (small blood vessels where O₂, glucose, and fatty acids move from the blood to the muscle cells).</td>
<td></td>
</tr>
<tr>
<td>Muscle cells have more and larger mitochondria and more enzymes for aerobic respiration.</td>
<td></td>
</tr>
<tr>
<td>Muscle cells have more stored glycogen and more of the molecules that facilitate uptake of glucose and fatty acids into cells.</td>
<td></td>
</tr>
</tbody>
</table>
In active muscle, both anaerobic fermentation and aerobic respiration produce ATP. In addition, creatine phosphate can be used to produce ATP. The relative importance of these three energy sources varies depending on the intensity and duration of the physical activity. To learn how the primary source of muscle ATP differs for races of different lengths, read the following information and answer questions 10-12.

- **Creatine phosphate** can be used to produce ATP more rapidly than anaerobic fermentation or aerobic respiration. Muscle cells typically have enough creatine phosphate to supply ATP for ~10 seconds of intense activity.
- **Anaerobic fermentation** is faster than aerobic respiration and does not require O₂, so anaerobic fermentation can provide a lot of ATP for brief intense athletic events. However, anaerobic fermentation can only be a major source of energy for a minute or two, in part because anaerobic fermentation produces lactic acid and too much lactic acid has harmful effects.
- **Aerobic respiration** is the slowest of these processes, but aerobic respiration produces more ATP per glucose molecule than anaerobic fermentation and aerobic respiration can continue for hours.

<table>
<thead>
<tr>
<th>Running Distance</th>
<th>Running Time (world record; US high school record)</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m</td>
<td>9.6 seconds; 10.0 seconds</td>
<td>10.4; 10.0 m/sec.</td>
</tr>
<tr>
<td>400 m</td>
<td>43.2 seconds; 44.7 seconds</td>
<td>9.3; 8.9 m/sec.</td>
</tr>
<tr>
<td>Marathon (42.2 km)</td>
<td>2 hours 3 min. 23 sec.; 2 hours 23 min. 47 sec.</td>
<td>5.7; 4.9 m/sec.</td>
</tr>
</tbody>
</table>

10. What do you think is the primary source of ATP for muscles during a marathon?  
   aerobic respiration __  anaerobic fermentation __  creatine phosphate __  

Explain your reasoning.

11. Explain why creatine phosphate is the most important contributor to ATP production during a 100 m race and less important for longer races.

12. Explain why, for a 400 m race, anaerobic fermentation supplies more of the ATP than aerobic respiration.

13. Complete this table concerning two of the recovery processes that occur after an athletic event.

<table>
<thead>
<tr>
<th>Recovery Process</th>
<th>Explain why this recovery process is useful after a marathon which ended with an intense sprint.</th>
</tr>
</thead>
<tbody>
<tr>
<td>In muscle cells and liver cells, glycogen is synthesized from glucose derived from food molecules.</td>
<td></td>
</tr>
<tr>
<td>In liver cells, lactic acid is converted back to glucose.</td>
<td></td>
</tr>
</tbody>
</table>