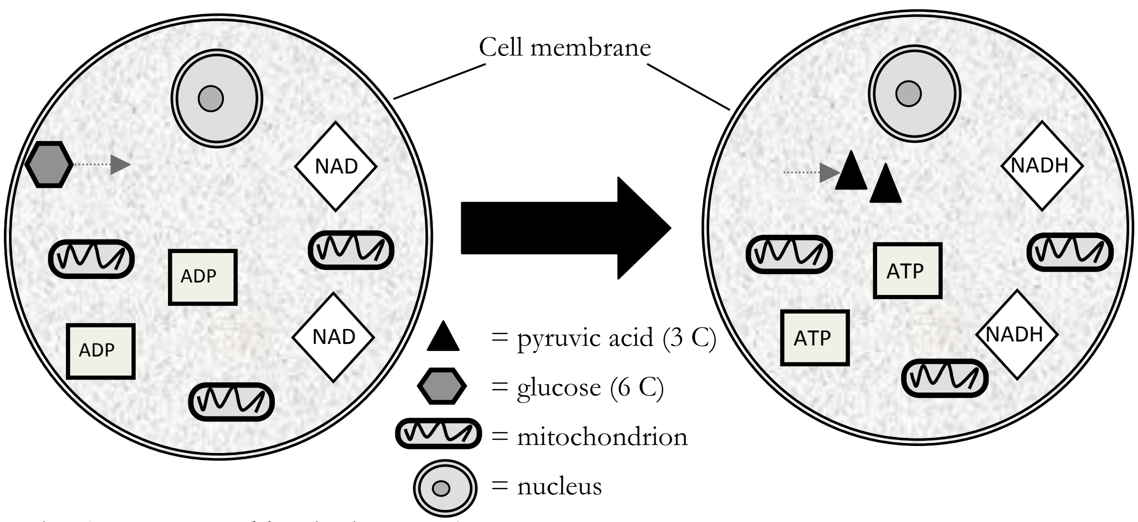
Cellular Respiration

How is energy transferred and transformed in living systems?

Why?

Living organisms display the property of metabolism, which is a general term to describe the processes carried out to acquire and use energy. We know that people need to eat and in our foods are various kinds of nutrients that our cells can use. One large group of nutrients in our foods is carbohydrates, which supply our cells with glucose ($C_6H_{12}O_6$). So the question is: How does the food we chew and swallow fuel our cells?

Model 1 - Glycolysis



1. What is represented by the hexagon?

2. What is represented by the triangles?

3. How many carbon atoms (C) are there in one molecule of glucose?

4. How many carbon atoms (C) are there in one molecule of pyruvic acid?

5. What happens to glucose after it crosses the cell membrane into the cytoplasm of the cell?

6. What is the name of this process?

7. How many ATP molecules are produced during this process?

8. Hydrogen-carrying molecules are also produced during this process. What is the name of these hydrogen-carrying molecules?

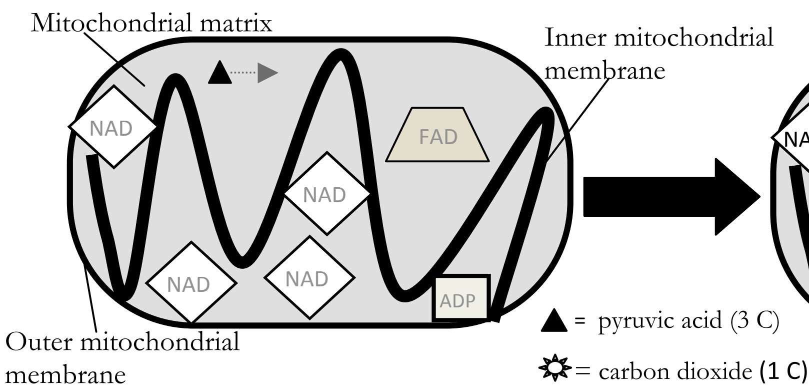
9. Does glycolysis occur inside or outside the mitochondria?

Read This!

Glycolysis happens in the cytoplasm of cells and does not require the presence of oxygen. It is said to be **anaerobic.** It is the first step used by cells to extract energy from glucose in the form of ATP. ATP can be directly used by cells.

10. Thinking about the number of carbon atoms in glucose and in pyruvic acid, tell why there is one molecule of glucose on the left side of the arrow and two molecules of pyruvic acid on the right side of the arrow.

Model 2 – Krebs Cycle



11. What happens to pyruvic acid during the Krebs cycle?

12. According to the diagram, where does the change identified in the previous question occur?

13. Thinking again about the number of atoms of carbon in pyruvic acid, why are three molecules of carbon dioxide produced?

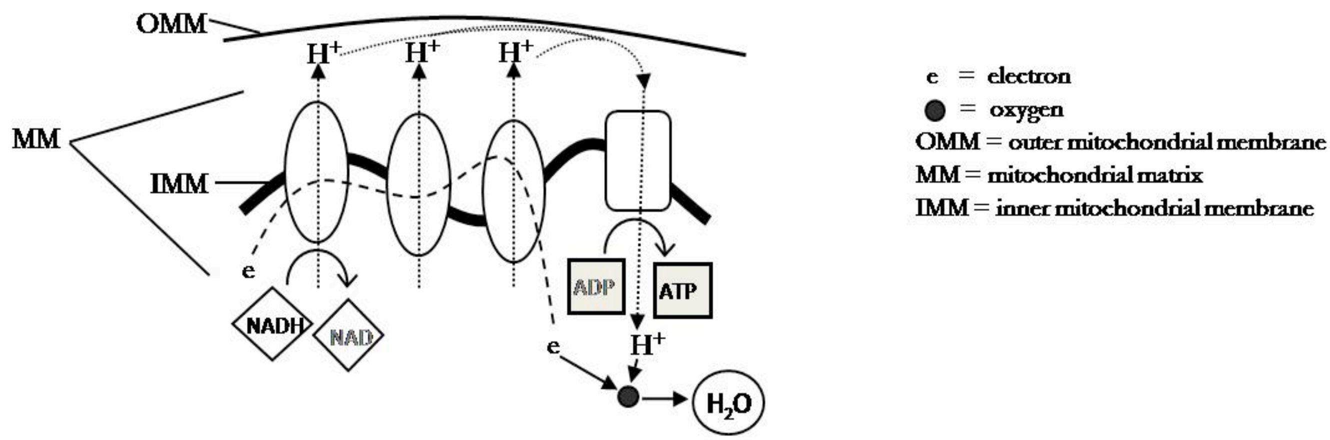
14. Considering that glycolysis produces two pyruvic acid molecules per glucose molecule, how many total CO_2 molecules will be produced from the complete breakdown of each glucose molecule? Support your answer.

15. Name the H-carrying molecules that are formed during the Krebs cycle.

16. Fill out the chart by looking back at the entire process of glycolysis and Krebs cycle to list the total number of ATP's and hydrogen-carrying molecules produced.

Process	ATP	NADH	$FADH_2$
Glycolysis			
Krebs cycle (1st pyruvic acid)			
Krebs cycle (2nd pyruvic acid)			

Model 3 - The Electron Transport Chain



Read This!

The inner mitochondrial membrane contains a series of carrier proteins that make up the Electron Transport Chain (ETC). Electrons move along the ETC, providing energy to move hydrogen atoms. The movement of hydrogen atoms dropped off by the NADH and $FADH_2$ leads to the production of large amounts of ATP. Those H's had no value until they reached the Electron Transport Chain.

17. What chemical molecule acts as the final H^+ acceptor, and what molecule is formed as a product of that acceptance?

18. The **energy** from the H+ is then transferred to an enzyme that initiates the formation of what?

19. Formulate an explanation for why the Electron Transport Chain is an aerobic process rather than an anaerobic process like glycolysis.

Read This!

Remember that glycolysis produces two pyruvic acid molecules per glucose molecule. It is important to know that each NADH has enough energy stored in the hydrogens to make about three ATP molecules while each $FADH_2$ has enough energy stored in the hydrogens to make about two ATP molecules.

20. Fill in the chart below to calculate the total amount of ATP produced from each glucose molecule during aerobic respiration.

Process	**Number of ATP produced from one glucose molecule**	**Number of H-carriers produced from one glucose molecule**
Glycolysis		NADH: $FADH_2$:
Krebs Cycle		NADH: $FADH_2$:
Electron Transport Chain	from H^+ in NADH: from H^+ in $FADH_2$:	
TOTAL ATP PRODUCED		

21. Look at the equation for cellular respiration and tell which stage of the process is each molecule either **used** or **produced.**

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 38\ ATP$$

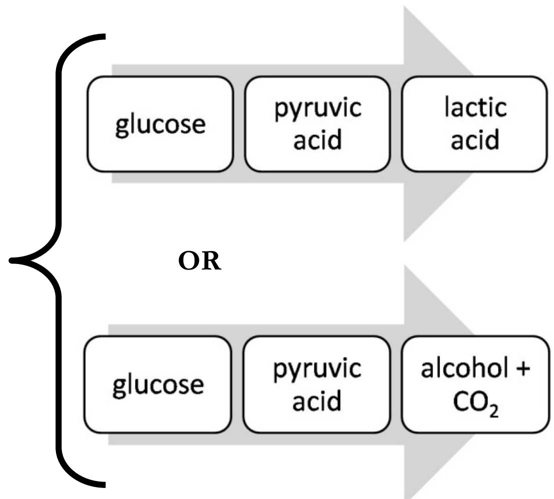
$C_6H_{12}O_6$	$6O_2$	$6CO_2$	$6H_2O$	38 ATP
USED IN	USED IN	PRODUCED IN	PRODUCED IN	PRODUCED IN

22. Compare the ATP available to cells when oxygen is present versus when it is absent. How might this help explain why brain and heart functions are so quickly affected when a person cannot breathe?

Extension:

Two different processes of anaerobic respiration are shown below.

Fermentation (no O_2 present in cell)



23. List the final products of the breakdown of glucose if no oxygen is present.

24. Recall that two molecules of ATP are formed during glycolysis. Neither fermentation processes shown above creates any more ATP. Knowing this, what would you predict about the cellular energy available to organisms that carry out fermentation?

25. Research the relationship between overexertion of muscles and the formation of lactic acid. How does this relate to muscle soreness after workouts or games?

26. What common foods involve the process of fermentation? Use your textbook or other resource to make a list of the foods and the specific organisms used.

Teacher's Resources

Learning Objectives:

1. To examine how glucose in food can be used to produce ATP.

2. To understand what molecules are made and where they are made during aerobic respiration.

Pre-requisites:

NOTE: this activity is meant for 1st year students whose knowledge of chemistry is minimal. Thus, you will find it to be very general in explaining the concepts.

1. Knowledge of cell structure/organelles and functions, and membrane structure (presence of proteins)

2. Minimal knowledge of periodic table (C is carbon) and chemistry (CO_2 is carbon dioxide; bonds can be broken and re-formed, *etc.*)

3. Knowledge that ATP is a chemical used by cells to fuel their processes

Assessment Questions:

1. Of the following stages of aerobic respiration, which produces the most ATP?
   A. Glycolysis

   B. Conversion of pyruvic acid to CO_2

   C. Electron transport chain

   D. These processes produce equal amounts of ATP

2. Compare the amount of energy available to cells resulting form aerobic respiration and anaerobic respiration.

3. Trace the path of a glucose molecule from the time it enters a cell until it is completely broken down. Be sure to list the energy molecules formed during the processes. Assume that oxygen is present in the cell.

Assessment Questions Targeted Responses:

1. C. Electron transport chain

2. Aerobic respiration produces many times more ATP for cells than anaerobic respiration

3. Glucose enters the cytoplasm and is broken into 2 molecules of pyruvic acid, creating 2 molecules of ATP and 2 molecules of NADH. Next the pyruvic acid enters a mitochondrion where it is completely broken down into 3 molecules of CO_2, forming 4 NADH and 1 $FADH_2$ molecules along with 1 ATP molecule. Finally, NADH and $FADH_2$ molecules participate in the electron transport pathway, creating 3 ATP per NADH and 2 ATP per $FADH_2$. Because there are 2 pyruvic acid molecules produced from each glucose molecule, there are a total of 38 ATP molecules formed from each glucose.

Teacher Tips:

- This is a very condensed version
- Use stop signs to check that students are attending carefully to what each model is conveying and that students have correct answers to use in later questions. The 2nd stop sign (after the energy molecule tally chart) is especially critical. Students need to understand that each "turn" of the Krebs cycle requires only one pyruvic acid, but that each glucose molecule produces 2 pyruvic acid molecules after glycolysis.
- Students with more chemistry knowledge can appreciate the chemical equation for cellular respiration along with reduction/oxidation terminology for NADH and $FADH_2$
- These students may also be able to understand the action of ATP synthase at the end of the electron transport pathways and the resulting formation of water
- The following link has excellent information and animations http://www.sumanasinc.com/webcontent/animations/content/cellularrespiration.html
- A potential alternative/performance assessment that could be interesting for students and reveal much about their true understanding of this aspect of metabolism would be the following: Work with your group to create a skit or puppet show to tell the story of a single molecule of glucose as it enters a cell and provides it with energy.

Target Responses:

1. What is represented by the hexagon? *glucose*

2. What is represented by the triangles? *pyruvic acid*

3. How many carbon atoms (C) are there in one molecule of glucose? *6*

4. How many carbon atoms (C) are there in one molecule of pyruvic acid? *3*

5. What happens to glucose after it crosses the cell membrane into the cytoplasm of the cell? *broken down into pyruvic acid*

6. What is the name of this process? *Glycolysis*

7. How many ATP molecules are produced during this process? *2*

8. Hydrogen-carrying molecules are also produced during this process. What is the name of these hydrogen-carrying molecules? *NADH*

9. Does glycolysis occur inside the mitochondria or outside? *Outside*

10. Thinking about the number of carbon atoms in glucose and in pyruvic acid, tell why there is one molecule of glucose on the left side of the arrow and two molecules of pyruvic acid on the right side of the arrow. *One glucose molecule has 6 carbon atoms; each pyruvic acid molecule has 3 so there have to be 2 to hold all 6 carbon atoms*

11. What happens to pyruvic acid during the Krebs cycle? *It is broken down into three molecules of carbon dioxide.*

12. According to the diagram, where does this process occur? *in the mitochondrial matrix*

13. Thinking again about the number of atoms of carbon in pyruvic acid, why are three molecules of carbon dioxide produced? *because each pyruvic acid contains 3 carbon atoms*

14.. Considering that glycolysis produces two pyruvic acid molecules per glucose molecule, how many total CO_2 molecules will be produced from the complete breakdown of each glucose molecule during the Krebs Cycle of aerobic respiration? Support your answer.

6 – each pyruvic acid has 3 carbons and there are 2 pyruvic acid molecules... 3 x 2 = 6

15. Name H-carrying molecules produced during the Krebs cycle. *NADH and $FADH_2$.*

16. Fill out the chart by looking back at the entire process of glycolysis and Krebs Cycle to list the total number of ATP's and energy-storing molecules produced.

Process	**ATP**	**NADH**	**$FADH_2$**
Glycolysis	*2*	*2*	*0*
Krebs cycle (1st pyruvic acid)	*1*	*4*	*1*
Krebs cycle (2nd pyruvic acid)	*1*	*4*	*1*

17. What chemical molecule acts as the final H^+ acceptor, and what molecule is formed as a product of that acceptance? *O_2 ; H_2O*

18. The **energy** from the H+ is then transferred to an enzyme that initiates the formation of what? *ATP*

19. Formulate an explanation for why the Electron Transport Chain is an aerobic process rather than an anaerobic process like glycolysis. *The ETC is an aerobic process because it requires oxygen to complete the process*

20. Fill in the box below page to calculate the total amount of ATP produced from each glucose molecule during aerobic respiration.

Process	**Number of ATP produced from one glucose molecule**	**Number of H-carriers produced from one glucose molecule**
Glycolysis	*2*	NADH: *2* $FADH_2$: *0*
Krebs Cycle *(two rounds for each glucose)*	*2 x 1 = 2*	NADH: *2 x 4 = 8* $FADH_2$: *2 x 1 = 2*
Electron Transport Chain *(3 ATP per NADH, 2 ATP per $FADH_2$)*	from H^+ in NADH: *(2 x 3) + (8 x 3) = 30* from H^+ in $FADH_2$: *2 x 2 = 4*	
TOTAL ATP PRODUCED	*2 + 2 + 30 + 4 = 38*	

21. Look at the equation for cellular respiration and tell which stage of the process is each molecule either **used** or **produced.**

$C_6H_{12}O_6$ + $6O_2$ → $6CO_2$ + $6H_2O$ + 38 ATP

$C_6H_{12}O_6$	$6O_2$	$6CO_2$	$6H_2O$	38 ATP
USED IN	USED IN	PRODUCED IN	PRODUCED IN	PRODUCED IN
Glycolysis	*ETC*	*Krebs cycle*	*ETC*	*glycolysis -2* *Krebs cycle- 2* *ETC - 34*

22. Compare the ATP available to cells when oxygen is present versus when it is absent. How might this help explain why brain and heart functions are so quickly affected when a person stops breathing.

Since there would be so little ATP produced without oxygen, the cells of the brain and heart would die and the functions would stop.

Extension

23. List the final products of the breakdown of glucose if no oxygen is present. *lactic acid* *or* *alcohol and* CO_2

24. Recall that two molecules of ATP are formed during glycolysis. Neither fermentation processes shown above creates any more ATP. Knowing this, what would you predict about the cellular energy available to organisms that carry out fermentation?
They must be small and require very little energy, since glycolysis produces so little ATP and fermentation produces no additional ATP

25. Research the relationship between overexertion of muscles and the formation of lactic acid. How does this relate to muscle soreness after workouts or games?

When muscles are overused and switch to anaerobic respiration the lactic acid produced builds up and takes time to be eliminated from the muscle cells

26. What common foods involve the process of fermentation? Make a list of the foods and the specific organisms used. *bread – Saccharomyces cerevisiae and other yeasts; cheese – various fungi; yogurt – various bacteria; sauerkraut – various bacteria; vinegar – various bacteria; wine – yeasts*