Name____ Per______ Date________

What is Glycolysis? Answersheet

Check your Progress 1

1. ____________ ____________

2. __________

3. __________

4. _____

Check your Progress 2

1. ______________________

2. _____

3. _____

4. _____

5. _____________________

6. _____

Check your Progress 3

1. _____

2. _________________________

3. _________________________

4. _________________________

5. _____ 6. ______

Check your Progress 4

1. _____ 2. _____ 3. _____

4. _________________________

5. _________________________

6. ______

7. ________________ 8. _____

There is an answer to this riddle: the cell's original energy source is *glucose*. In *cellular respiration*, a cell breaks down glucose molecules and uses the energy that was locked up in the glucose molecules to make ATP.

WHAT IS GLYCOLYSIS?

Take a look at this word: *glycolysis*. That's glyco (as in "glucose") and lysis (as in "to break apart"). Now whenever you see this intimidating-looking word, you will immediately recognize that it names the biochemical process in which glucose is broken down.

Let's zero in on one little cell. More specifically, we'll be looking at the cell's cytoplasm, where glycolysis takes place.

$$1 \text{ Glucose} \xrightarrow{\text{glycolysis}} 2 \text{ pyruvic acid}$$

So in glycolysis, 1 glucose molecule gets broken down into 2 *pyruvic acid* molecules.

FYI

Don't be surprised if you see the word "pyruvate" instead of "pyruvic acid." They both mean the same thing.

Anything else about glycolysis? Yes. The cell needs to supply 2 ATP to the process, but it gets a total of 4 ATP at the end. Final tally: for each glucose molecule, glycolysis yields 2 new ATP molecules.

Now you know glycolysis. (Of course, we've skipped all of the intermediate steps in the process in order to present it to you so neatly, but that's okay. We have to leave some things for when you get to college.)

WHAT HAPPENS TO THE PYRUVATE?

So the cell has performed glycolysis on one glucose molecule, and it has gained 2 extra ATP molecules. It also has 2 molecules of pyruvic acid as the end product of glycolysis. What does it do with the pyruvic acid molecules? Well, it turns out that there's still loads of energy locked up in them—energy that the cell wants. So the cell keeps working on the pyruvic acid molecules. In the next phase of molecular manipulation, the cell sends the 2 pyruvic acid molecules over to the mitochondria. There the 2 pyruvate are converted to 2 *acetyl CoA* molecules. Now the acetyl CoA molecules are ready to enter the *Krebs cycle*.

CHECK YOUR PROGRESS 1

1. Glycolysis is a process that breaks 1 glucose molecule down into 2 ________ ________ molecules.

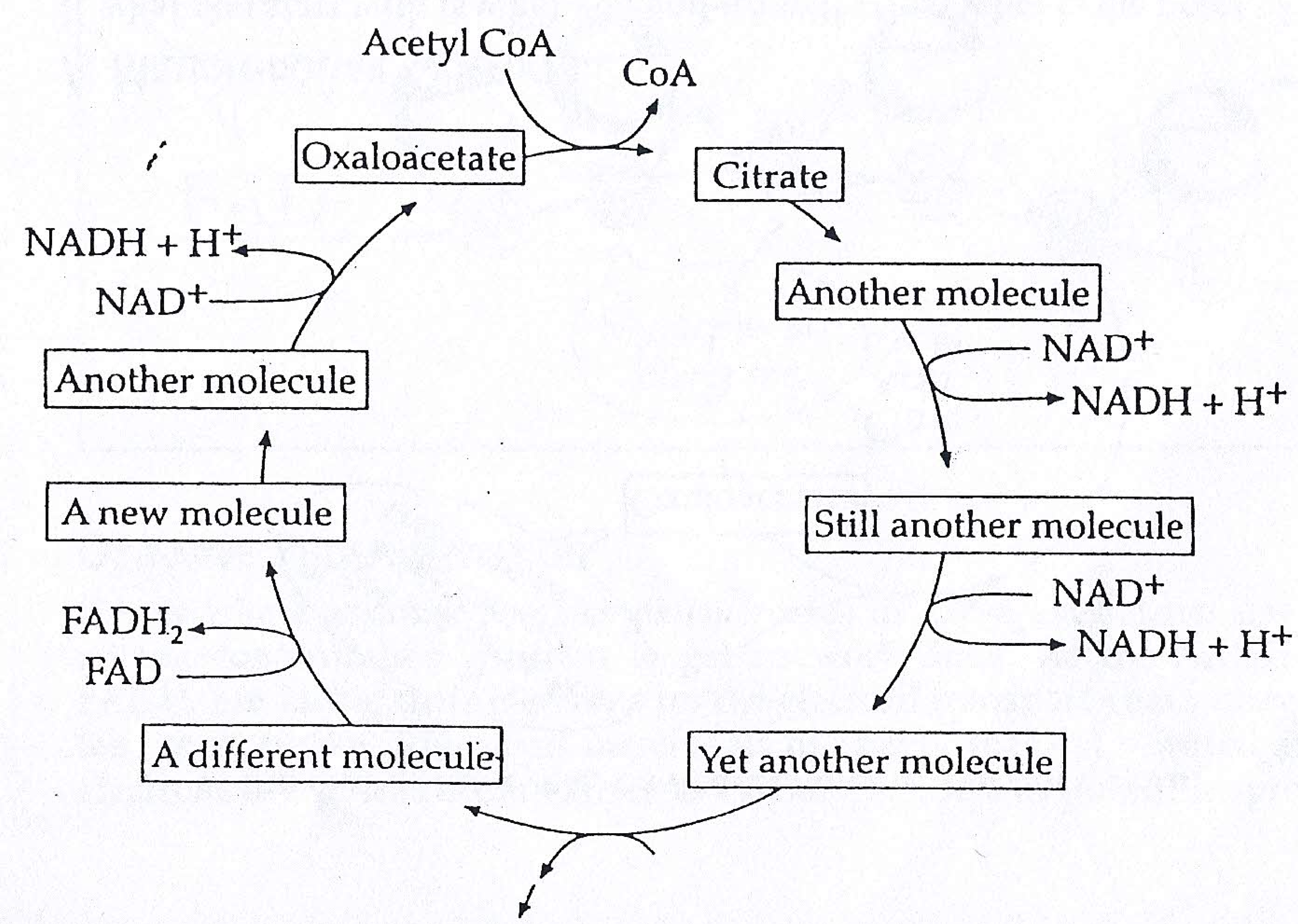
2. How many net ATP molecules are produced when 1 molecule of glucose is broken down via glycolysis? ________

3. How many ATP molecules are used in the breakdown of 1 glucose molecule during glycolysis? ________

4. Which of the following is true regarding pyruvic acid?
   A. It contains little if any potential energy in its structure.
   B. It contains less energy than does glucose.
   C. It is created from acetyl CoA.
   D. It is formed in the mitochondria.

THE KREBS CYCLE

The Krebs cycle is also located in the mitochondria, where all the rest of the reactions will take place. Whenever you see this:



Check Your Progress 2

1. The Krebs cycle takes place in the ______________________________.

2. Which one of the following molecules joins up with oxaloacetate and enters the Krebs cycle?

   A. Pyruvate
   B. Glucose
   C. Citrate
   D. Acetyl CoA

3. Which one of the following molecules remains once one complete turn of the Krebs cycle has occurred?

   A. Acetyl CoA
   B. Oxaloacetate
   C. Citrate
   D. Pyruvate

4. Which of the following get generated by the Krebs cycle?

   A. NAD^+ and FAD
   B. NADH and $FADH_2$
   C. ADP and inorganic phosphate
   D. H_2O

5. Another name for the Krebs cycle is the ______________________________.

6. The breakdown of 1 glucose molecule by glycolysis would result in how many turns of the Krebs cycle?

   A. 1
   B. 2
   C. 3
   D. 4

THE ELECTRON TRANSPORT CHAIN

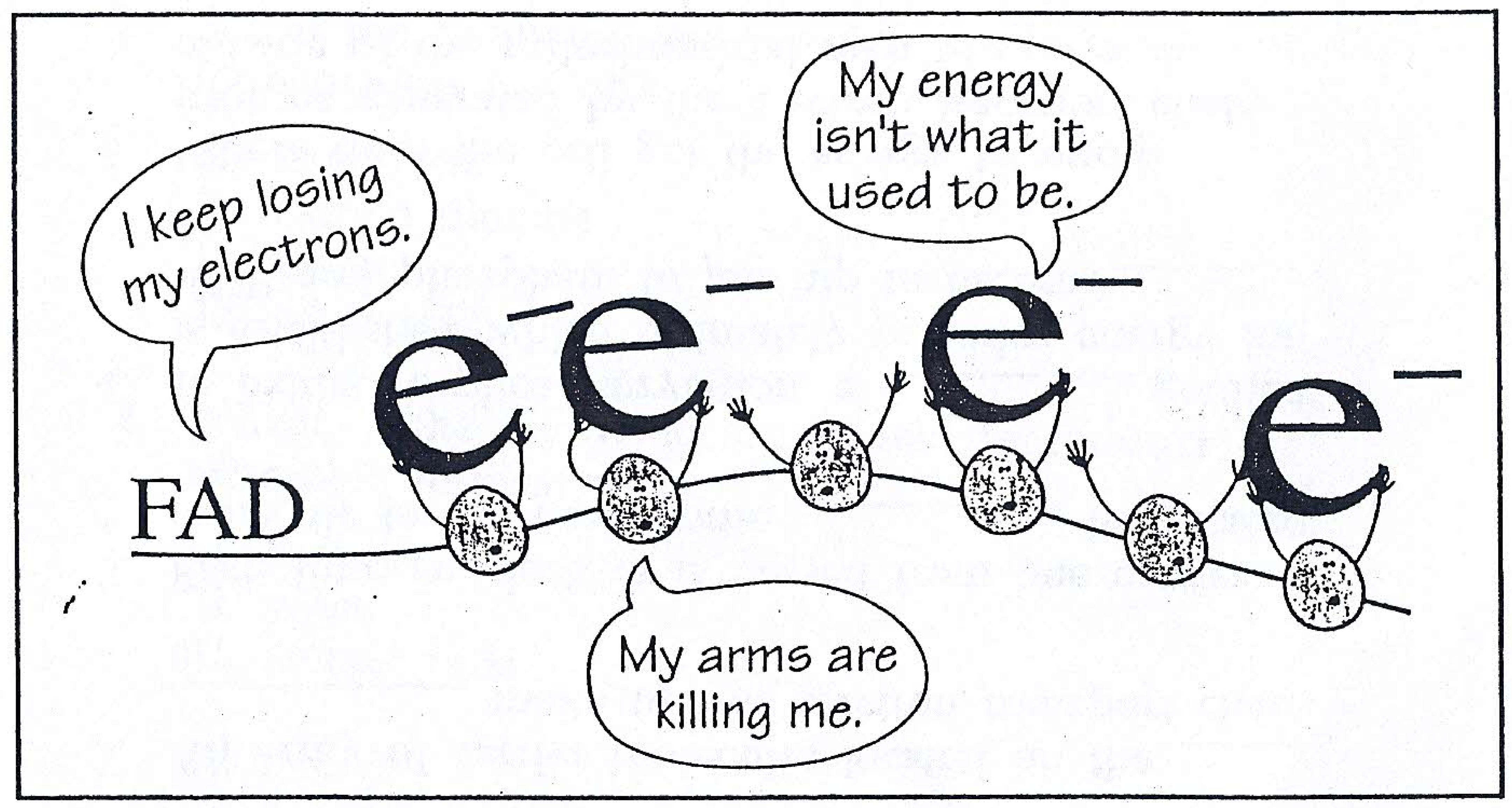
Remember when we told you that the mitochondria make nearly all of a cell's ATP? Well, they need $FADH_2$ and NADH in order to do so. Here's what happens.

The Set-up: Sitting on all of that extra surface area of the inner mitochondrial membrane is the *electron transport chain.* Don't let the name intimidate you. If we said, "sitting on the inner mitochondrial membrane is an assortment of blackbirds," you wouldn't be phased. The electron transport chain is simply some different carrier molecules sitting near one another. (They have names like *ubiquinone* and *cytochrome b.*)

The Action: Electrons from our NADH and $FADH_2$ get passed down this chain—"handed," so to speak, from carrier to carrier down the line. Since the electrons are first given and then passed on to each successive carrier, the electron transport chain is essentially a series of oxidation-reduction (or *redox)* reactions. As electrons get handed from carrier molecule to carrier molecule, they give up a little energy at each point along the way.

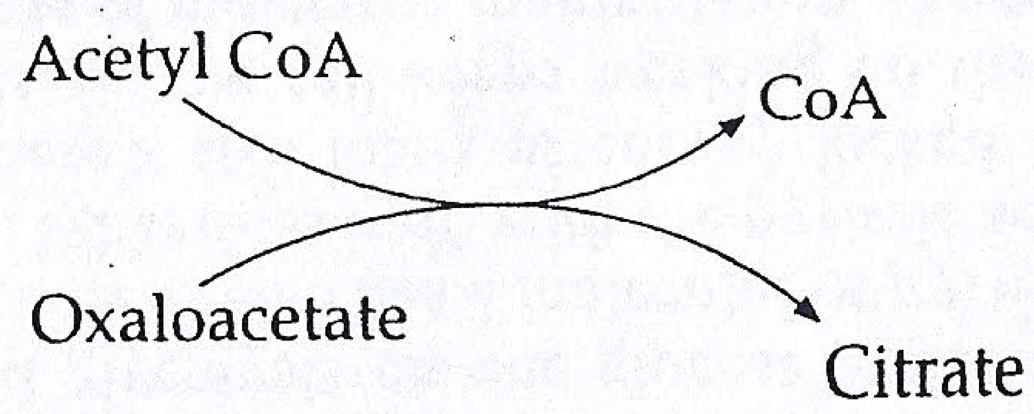
The End of the Line

At the end of the carrier molecule chain, an oxygen awaits. The electrons get handed to the oxygen and water forms.



Oxidative Phosphorylation

Here's where *oxidative phosphorylation* comes in. OP makes clever use of a proton concentration gradient to get its work done. As the NADH and $FADH_2$ are losing their electrons on the electron transport chain, they also lose their *protons.* The small increments of energy that get released as the electrons are passed from carrier to carrier get used to pump the protons you're looking at the Krebs cycle (a.k.a. the *citric acid cycle*). Each acetyl CoA enters the Krebs cycle one molecule at a time. It joins up with *oxaloacetate* to gain entrance as *citrate*.



Think of it this way: you (acetyl CoA) arrive at a dance club (the Krebs cycle) and find out at the door that you can only get in as a couple. So you join up with the person hanging out at the entrance (oxaloacetate). Now you're not a single (acetyl CoA) anymore—you're a couple (citrate), so you're allowed to enter the dance club (the Krebs cycle).

Once in the Krebs cycle, the citrate quickly becomes transformed into something else and undergoes a bunch of further reactions. By the end of the cycle, however, oxaloacetate becomes available once again. It's as though the original couple that gained entrance (citric acid) doesn't exist anymore, and the person who arrived at the dance (acetyl CoA) is long gone, but the person who was hanging out at the entrance is back again, available for the next single (acetyl CoA) who arrives at the door. The oxaloacetate is available once again to join up with a new acetyl CoA for a spin around the Krebs cycle.

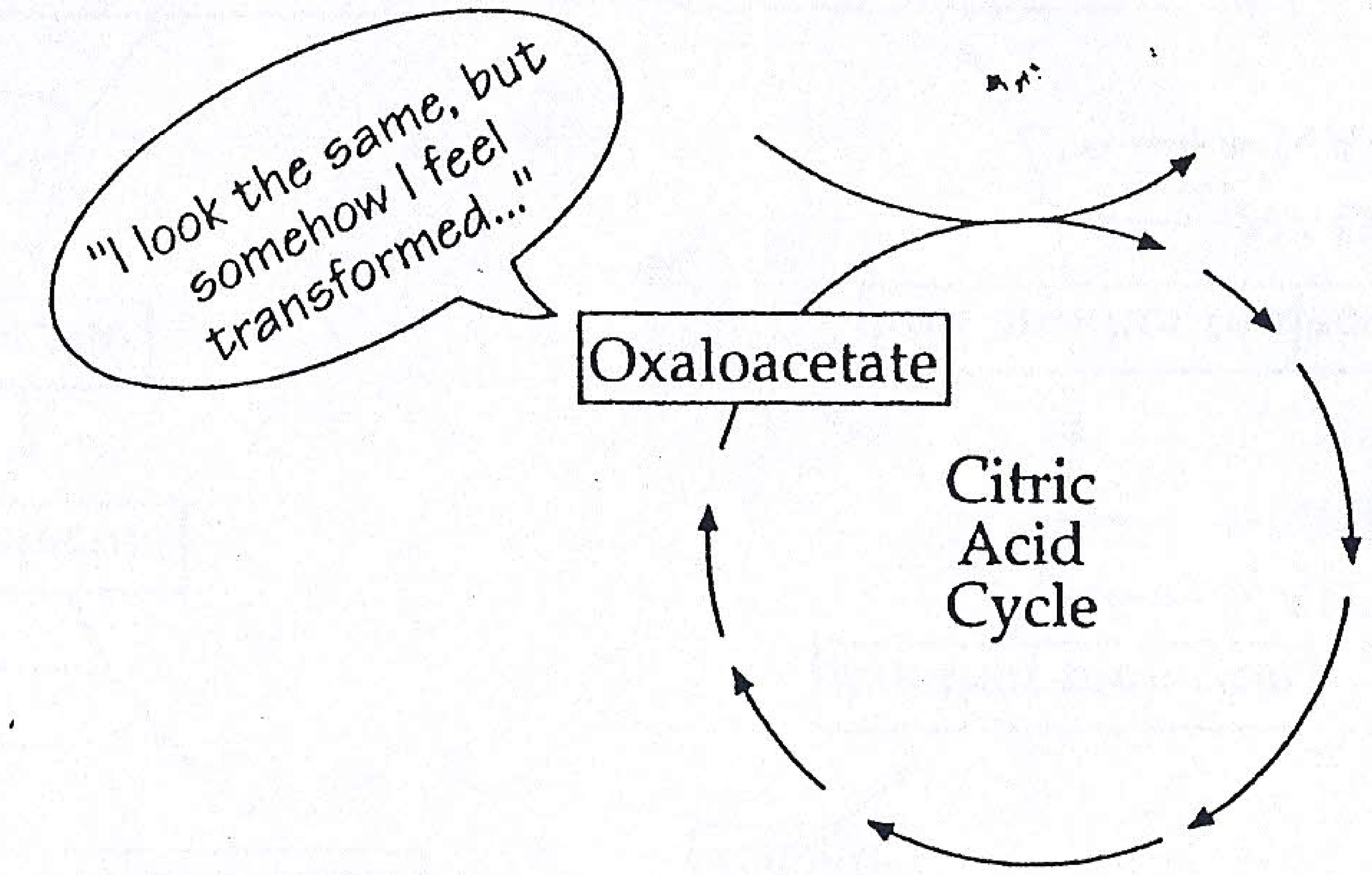
FYI

When we say that acetyl CoA enters the Krebs cycle, we mean that it enters as citrate and the citrate then undergoes a series of biochemical reactions that keep transforming it into different compounds. Those reactions happen in the mitochondrion because that's where the enzymes that catalyze those reactions are located.

The reactions that make up the Krebs cycle are often depicted as one big circle in order to emphasize the fact that the oxaloacetate molecule the acetyl CoA initially joined up with becomes available once again by the end of the cycle.

Here's a little recap of Krebs cycle events, because we know it takes a few rounds in order to become familiar:

1. acetyl CoA joins up with oxaloacetate and enters the Krebs cycle as citrate
2. all sorts of things happen to the citrate and its successors during the Krebs cycle
3. at the end of the cycle, oxaloacetate emerges once again



A Million-Dollar Question

If what you start with is what you end up with, then what is the point of the Krebs cycle?

This: it generates an ATP, but more importantly, it pulls hydrogens and electrons off of the molecules that are going for a spin. It sticks those hydrogens and electrons onto something else (called NAD^+ and FAD), so that these new molecules harbor lots of potential energy. These new molecules are called $FADH_2$ and NADH, and they promptly get shifted to the mitochondrion's inner membrane.

LEO Goes GER

Let's take a moment to look at oxidation and reduction, because it so happens that the crux of cellular respiration is all about oxidizing glucose and its successor molecules as far as the cell can push it.

- *In oxidation, a molecule loses an electron. That's LEO: Loss of Electron is Oxidation.*
- *In reduction, a molecule gains an electron. That's GER: Gain of Electron is Reduction.*
- *NAD^+ is a coenzyme that takes on electrons. Its reduced form is NADH.*
- *FAD is another coenzyme that takes on electrons. Its reduced form is $FADH_2$.*

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right out of the *mitochondrial matrix* (the innermost part of the mitochondria). By establishing this proton gradient, the mitochondrion sets up some potential energy for it to tap into.

The Set-up: In certain spots on the inner mitochondrial membrane are special openings, or channels. Situated at these channels like ticket-takers are certain enzymes. These enzymes (like all enzymes) do one specific thing, and they do it well.

The Action: The protons that were pumped out of the matrix can only get back in one way: through the special channels on the inner mitochondrial membrane. Because there are more protons outside the matrix than inside, every time a proton enters the matrix through that opening some energy becomes available. And an enzyme sitting at that opening snaps up that energy and uses it to add a phosphate onto an ADP (adenosine diphosphate) molecule. Vóila—the mitochondrion has made some ATP.

BACKTRACKING

Because we just threw a whole lot of information at you, let's do a little backtracking to keep things straight.

The mitochondria made ATP.

It got its source of energy from the movement of protons down a concentration gradient.

The protons came from the electron transport chain.

The electron transport chain pulled them off of NADH and $FADH_2$.

The NADH and the $FADH_2$ were generated by the Krebs cycle.

Citric acid was the starting molecule for the Krebs cycle.

It came from acetyl CoA and oxaloacetate.

The acetyl CoA came from pyruvate.

The pyruvate was created via glycolysis.

Glycolysis broke down a glucose molecule.

There you have it—aerobic cellular respiration—forwards and backwards. Look over this whole section a few times and then construct the sequence of events your own way.

CHECK YOUR PROGRESS 3

1. The electron transport chain transports
   A. fuel
   B. spices
   C. electrons
   D. gold

2. An array of carrier molecules located on the _____ __________ make up the electron transport chain.

3. Each time an electron is passed from one carrier molecule to the next, some __________ is released.

4. In oxidative phosphorylation, a __________ gradient is established which ultimately provides energy for ADP and phosphate to join up to become ________.

5. Where does the cell get the energy to pump protons generated by the electron transport chain outside of the mitochondrial matrix?
   A. From energy released when electrons are handed down the electron transport chain
   B. From ATP generated by the process of glycolysis
   C. From the conversion of pyruvate to acetyl CoA prior to when it enters the Krebs cycle
   D. From an ATP source located outside the cell

6. Which of the following species serves as the final hydrogen/electron acceptor in the electron transport chain?
   A. Hydrogen
   B. Nitrogen
   C. Oxygen
   D. Carbon

Aerobic vs. Anaerobic Respiration

With the exception of glycolysis, everything we've just covered is called *aerobic respiration* (it requires oxygen). Specifically, the Krebs cycle, the electron transport chain, and oxidative phosphorylation are all aerobic processes. Aerobic respiration is extremely efficient, squeezing out as much ATP as it can from a molecule of glucose. Overall, aerobic respiration yields 38 molecules of ATP per glucose. Organisms that conduct aerobic respiration (like us) are called *aerobes*.

Anaerobic respiration, on the other hand, is not very efficient. But don't tell that to the bacteria, yeast and muscle cells that engage in it. How is anaerobic respiration different from aerobic respiration? Well, it doesn't use oxygen at all. Anaerobic respiration starts out the same as aerobic respiration—with the process of glycolysis, which is anaerobic. We told you that glycolysis yields the cell a net of 2 ATP. Well, that's all that any cell that engages in anaerobic respiration gets—2 ATP. Compare that to 38 ATP for aerobic respiration, and you see why we say it's comparatively inefficient. Organisms that conduct anaerobic respiration are called *anaerobes*.

Fermentation

Anaerobic respiration doesn't end with glycolysis—only ATP production ends with glycolysis. In anaerobic respiration, *fermentation* takes up where glycolysis leaves off. Let's take a look:

$$\text{1 glucose} \xrightarrow{\text{glycolysis}} \text{2 pyruvic acid}$$

$$\text{2 pyruvic acid} \xrightarrow{\text{fermentation}} CO_2 \text{ (carbon dioxide) and alcohol (ethanol)}$$

We're looking at what happens to a glucose molecule in a yeast cell or a bacterium. The glucose molecule undergoes fermentation. (This is how we get things like beer and wine.)

Here's another fermentation process: once the cell gets its pyruvic acid, it does this:

$$\text{2 pyruvic acid} \xrightarrow{\text{fermentation}} \text{lactic acid}$$

(This is how we get things like yogurt.)

FYI

When you're doing aerobics, your muscle cells start doing anaerobics. When you exercise to the max, your muscle cells start facing an oxygen shortage. When this happens, even though you are an aerobic organism, your muscle cells start to respire anaerobically. They don't have much choice. Instead of doing:

glycolysis ——> Krebs cycle ——> electron transport chain and oxidative phosphorylation

they do:

glycolysis ——> fermentation

More specifically, they do:

glucose ——> pyruvic acid ——> lactic acid,

The lactic acid builds up in your muscles, and before you know it, you've got muscle fatigue.

Check Your Progress 4

1. All of the following are possible products of fermentation EXCEPT:

   A. lactic acid
   B. carbon dioxide
   C. ethanol
   D. citric acid

2. Which of the following are known to conduct anaerobic respiration?

   I. bacteria
   II. yeast
   III. animal cells

   A. I only
   B. II only
   C. I and II only
   D. I, II, and III

3. Which of the following is NOT an aerobic process?

   A. Fermentation
   B. The Krebs cycle
   C. Oxidative phosphorylation
   D. The electron transport system

4. Glycolysis is a process that does not require oxygen in order to occur. Based on that fact, glycolysis would be considered an ______________ process.

5. Muscle fatigue in humans is often due to a build-up of ______________ in the [absence ___ presence ___] of oxygen.

6. Which of the following processes yields a net total of 2 ATP?

   I. Glycolysis
   II. Electron transport and oxidative phosphorylation
   III. Fermentation

   A. I only
   B. II only
   C. I and II only
   D. I and III only

7. 1 glucose ———> pyruvic acid ———> ethanol and ________ ________

8. The sequence shown in question 7 includes which of the following process(es)?

   A. Glycolysis only
   B. Glycolysis and fermentation only
   C. Glycolysis and the Krebs cycle only
   D. Glycolysis, the Krebs cycle, the electron transport chain, and oxidative phosphorylation only

GLOSSARY

acetyl CoA
a 2-carbon molecule produced from pyruvate; joins oxaloacetate to form citrate in the Krebs cycle

aerobes
organisms that conduct aerobic respiration

aerobic respiration
the breakdown of glucose and its successor molecules in the presence of oxygen; relatively efficient yield of ATP

anaerobes
organisms that conduct anaerobic respiration

anaerobic respiration
the breakdown of glucose and its successor molecules in the absence of oxygen; relatively inefficient yield of ATP

citrate
(a.k.a. citric acid) a 6-carbon molecule of the Krebs cycle; formed by the addition of acetyl CoA to oxaloacetate

electron transport chain
an aerobic process in which carrier molecules on the inner mitochondrial membrane transport electrons ultimately to an oxygen molecule

ethanol
an alcohol; an end product of fermentation conducted by yeast and bacteria

FAD
a coenzyme that acts as an electron acceptor; this is its oxidized form

$FADH_2$
a coenzyme that acts as an electron acceptor; this is its reduced form

glycolysis
an anaerobic process in which glucose is broken down into 2 pyruvic acid molecules

Krebs cycle
(a.k.a. the citric acid cycle) an aerobic process; a series of biochemical reactions that take place in the mitochondria

lactic acid
the end product of fermentation in muscle cells and certain fungi and bacteria

matrix
the innermost portion of the mitochondria; it is surrounded by the inner mitochondrial membrane

NAD^+

a coenzyme that acts as an electron acceptor; this is its oxidized form

NADH

a coenzyme that acts as an electron acceptor; this is its reduced form

oxaloacetate

a 4-carbon molecule that joins acetyl CoA to create citrate in the Krebs cycle

oxidation

when a molecule loses one or more electrons

oxidative phosphorylation

an aerobic process on the inner mitochondrial membrane that makes use of a proton gradient to produce ATP

pyruvic acid

(a.k.a. pyruvate) the end product of glycolysis

reduction

when a molecule gains one or more electrons