Lesson 6: Take in Energy - Part 2

Slide 1: Introduction

Slide 2: Heterotrophs

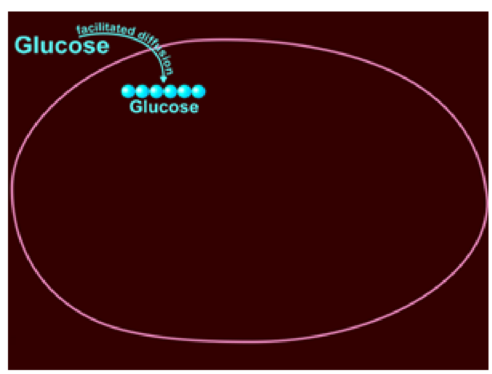
Heterotrophs derive their energy by eating and digesting organic molecules instead of making them. Since all organic molecules are made by autotrophs, heterotrophs depend completely on autotrophs for food.

Heterotrophs either have to eat autotrophs or eat the food they produce. Of course, heterotrophs can also eat each other.



How do heterotrophs derive energy from food?

Slide 3: Glucose metabolism



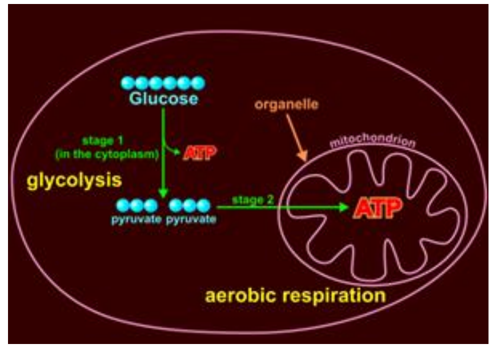
Suppose an animal eats glucose and glucose enters a cell.

Glucose enters a cell by facilitated diffusion.

The energy in glucose's chemical bonds will be transferred to the high energy molecule adenosine triphosphate, ATP. This happens in two stages.

Stage 1 occurs inside the juice, or cytoplasm, of the cell, where glucose, a 6-carbon molecule, is broken down, or metabolized, into two 3-carbon molecules, called pyruvate.

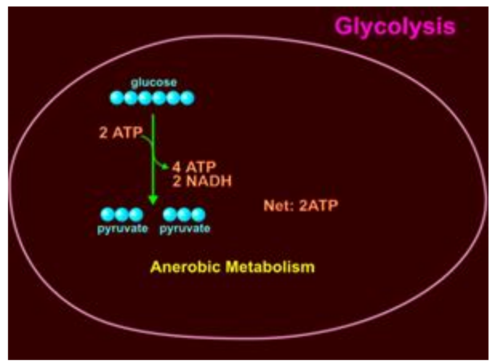
This first phase is called “glycolysis.” “Glyco-” refers to glucose and “-lysis” means break apart. No oxygen is needed for glycolysis. Glycolysis is anaerobic. Glycolysis probably evolved before cyanobacteria began accumulating oxygen in the atmosphere.



Only a few ATP molecules are made from glycolysis. Most of glucose’s chemical energy is extracted in Stage 2, which takes place inside an organelle called the mitochondrion. An organelle is any specialized sac inside a cell.

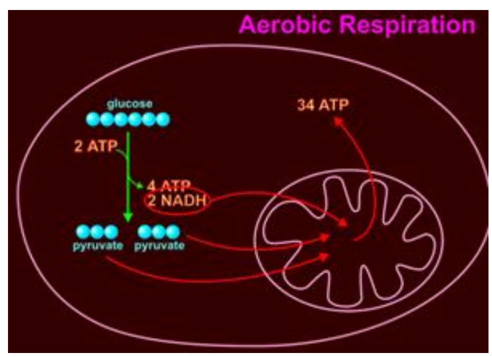
Stage 2 begins when pyruvate enters the mitochondrion. Unlike glycolysis, which is anerobic, the metabolism of pyruvate does require oxygen, so the metabolism of pyruvate is called “aerobic respiration.” This stage of glucose metabolism probably evolved after oxygen began to accumulate in the atmosphere.

Slide 4: ATP production from glucose



In glycolysis, the energy from 2 ATP is used to break down glucose into two molecules of pyruvate. The energy released from anerobic glycolysis makes 2 molecules of high-energy NADH and 4 molecules of ATP.

Since two ATP were used to start glycolysis, the net production of high-energy molecules by glycolysis is 2 ATP and 2 NADH.



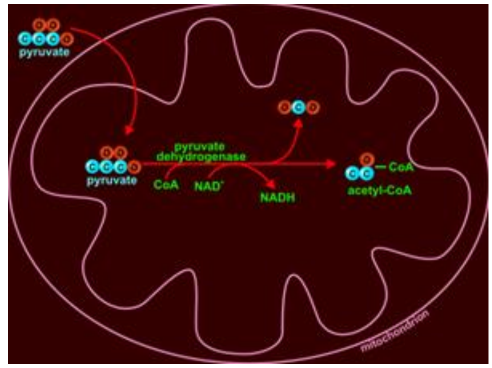
Unfortunately, the 2 NADH can’t make any energy until they enter the mitochondria. Mitochondria requires oxygen to run its machinery, so in the absence of oxygen glycolysis only makes a net of 2 ATP from a molecule of glucose and the 2 molecules of NADH simply accumulate.

The good news is that because glycolysis is anerobic metabolism, and doesn’t depend on oxygen, glycolysis functions quite nicely in the absence of oxygen. That’s going to come in handy if the cell ever runs out of oxygen, because the cell will still have a way to make at least some ATP.

If there is oxygen around, however, the cell can squeeze out a lot more energy from a molecule of glucose than the measly 2 ATP it got from glycolysis. With the help of oxygen, mitochondria can release enough energy from the two NADH and the two pyruvate molecules to generate another 34 ATP molecules.

Slide 5: Pyruvate dehydrogenase

Let's see where all those 34 ATP come from in a mitochondrion.



Pyruvate contains 3 carbon atoms and 3 oxygen atoms.

As soon as pyruvate enters the mitochondrion, the end carbon and its two oxygen atoms are removed and discarded as CO_2. That's our first product of aerobic respiration.

The enzyme that removes CO_2 from pyruvate is called pyruvate dehydrogenase.

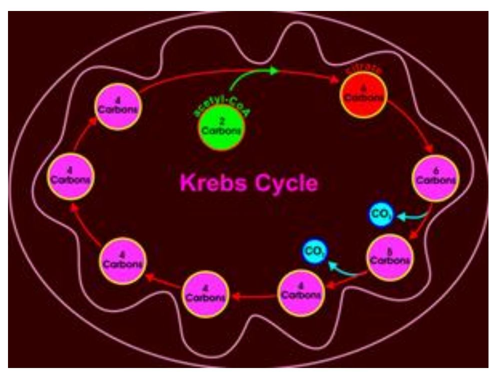
"De-" means to remove, so pyruvate dehydrogenase removes a hydrogen from pyruvate.

Where does it put it? On to NAD^+ to make a high-energy NADH.

Pyruvate dehydrogenase attaches the 2-carbon fragment, called acetyl, to coenzyme A. The result is acetyl-coenzyme A (acetyl-CoA).

So far, from a single glucose molecule, we've made 2 acetyl-CoAs and 2 molecules of high-energy NADH. Each NADH is going to generate 3 ATP, which I will demonstrate in a few slides. So with two NADH, we have 6 ATP. All we need to make now is 28 more ATP.

Slide 6: The Krebs Cycle



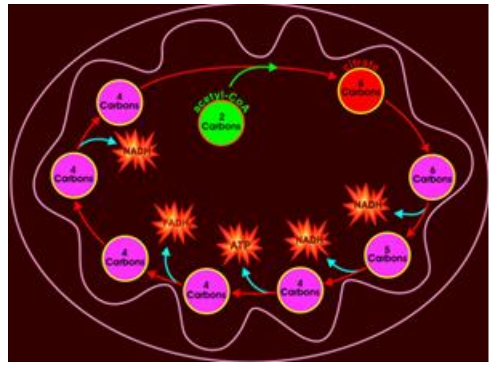
The other 28 ATP are made inside the mitochondrion by attaching each acetyl-CoA to a 4-carbon molecule to make citrate.

Citrate is then passed through a series of 7 chemical reactions. The 7th chemical reaction produces the same 4-carbon molecule that acetyl-CoA attached to, to begin the cycle.

Because Dr. Hans Krebs was the first to describe the cycle, the cycle was named after him. It's also called the citric acid cycle.

Before we get to the ATP's, notice that as citrate, a 6-carbon molecule, is cycled around the Krebs cycle, two of its carbons are peeled off and discarded as CO_2.

Slide 7: ATP from the Krebs Cycle



Now the 28 ATP. In three of the Krebs cycle reactions, a molecule of NADH was made.

Each of these NADH is going to make 3 ATP, a total of 9 ATP for each acetyl-CoA. In one of the reactions, a molecule of $FADH_2$ was made.

Each hydrogen on $FADH_2$ will make 2 ATP, or 4 for each $FADH_2$. So far that's 13 ATP.

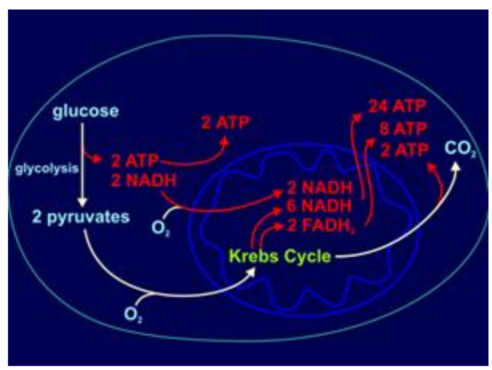
Finally, in one of the reactions a single ATP was made. That makes 14 ATP for each acetyl-coenzyme A. Since each glucose molecule generates two acetyl-coenzyme A's, one molecule of glucose can squeeze out 28 ATP from its two acetyl-CoA's.

Slide 8: Catching our breath

Let's review.

During glycolysis, one molecule of glucose is broken down into 2 pyruvates.

Along the way, 2 ATP and 2 NADH are given off. The 2 ATP are free in the cytoplasm. The 2 NADH, however, have to be transported into a mitochondrion along with oxygen.



Meanwhile, the 2 pyruvates are delivered to the Krebs cycle in the mitochondrion. With these two pyruvates, the Krebs cycle makes 6 NADH. With the 2 NADH from glycolysis, that's 8 NADH in total.

Each NADH generates 3 ATP or 24 ATP all together.

The Krebs cycle also makes 2 $FADH_2$.

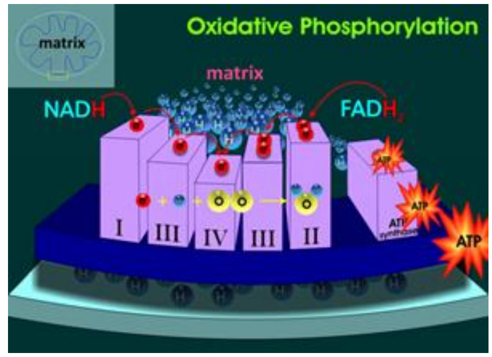
Each hydrogen on $FADH_2$ generates 2 ATP, so each $FADH_2$ generates 4 ATP, or 8 total for the two molecules of $FADH_2$. That's a total now of 32 ATP.

Finally the Krebs cycle also releases 2 ATP itself, for a total of 34 ATP.

So without oxygen, only 2 ATP are made from a molecule of glucose. With oxygen another 34 ATP are made. In the next slide we'll see how this is done.

Slide 9: The electron transport chain

Here is a short section of a mitochondrion with its blue inner membrane and turquoise outer membrane. The space inside the inner mitochondrial membrane is called the matrix, and the space between the inner and outer mitochondrial membranes is the intermembrane space.



NADH and $FADH_2$ carry high-energy electrons in their hydrogen atoms. They release their hydrogen atoms onto the blue inner mitochondrial membrane.

NADH passes its hydrogen atom to a group of proteins called complex I. $FADH_2$ passes its two hydrogen atoms to complex II.

Complexes I and II split the hydrogen atoms into an electron and proton. They remove some of the energy from the electron and pass the electron on to complex III. Both NADH and $FADH_2$ use the same complex III.

Complex III removes some more energy from the electron and passes it on to complex IV which removes even more energy from the electron.

What happened to the protons after the hydrogen atoms were split apart? And what do complexes I, II, III, and IV do with all the energy removed from those electrons?

The complexes are using that energy to pump the protons into the intermembrane space. When enough of the hydrogen ions accumulate in the intermembrane space, all that positive electrical charge and high concentration of protons, forces the protons into the matrix.

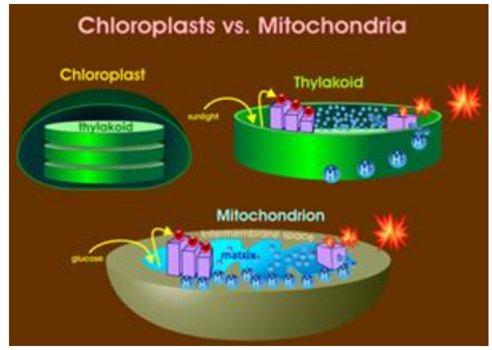
The hydrogen ions are channeled through ATP synthase. Each proton that passes through ATP synthase generates a molecule of ATP.

What are we going to do with all the protons accumulating in the matrix and what about the electron left sitting on top of complex IV?

This is why we need oxygen. The electron is simply recombined with a hydrogen ion to make a hydrogen atom, and two hydrogen atoms are attached to each oxygen atom to make a molecule of water.

The name for the series of proteins that, in a step-wise fashion, strips high energy electrons of their energy is the electron transport chain. The energy extracted by the electron transport chain is used to make ATP in a process called oxidative phosphorylation because it makes ATP using oxygen.

Slide 10: Oxidative phosphorylation



Isn't oxidative phosphorylation in mitochondria similar to the way chloroplasts make ATP in thylakoids?

Mitochondria and chloroplasts both take a source of energy, photons of light for chloroplasts and glucose for mitochondria, and create high energy electrons.

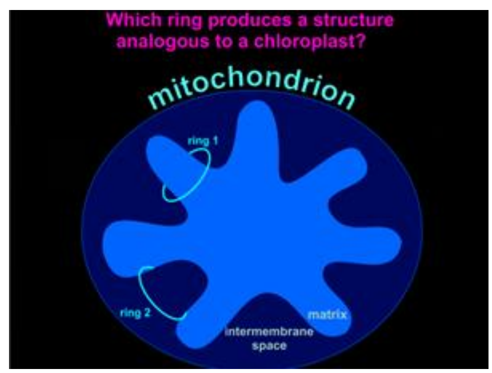
They both remove energy from the electron one step at a time. They both use that energy to pump hydrogen ions from one space to another.

In mitochondria, the hydrogen ions are pumped from the interior space into the intermembrane space, while in chloroplasts the hydrogen ions are pumped from the intermembrane space between the thylakoid and the chloroplast into the interior of the thylakoid.

Forcing hydrogen ions into a closed space like this creates an electrochemical gradient forcing hydrogen ions back to where they came from.

In the case of mitochondria, the hydrogen ions diffuse back into the interior space and, as they do, they are channeled through ATP synthase to make ATP. In the case of chloroplasts, the hydrogen ions diffuse back into the intermembrane space between the thylakoid and the chloroplast, and as they do so, they are channeled through ATP synthase to make ATP.

The name for this process of using energy from electrons to pump hydrogen ions from one space to another, and letting them slide back down a concentration gradient is called chemiosmosis.

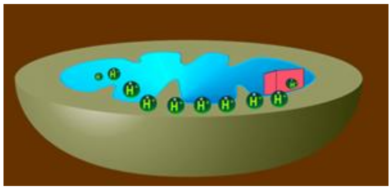


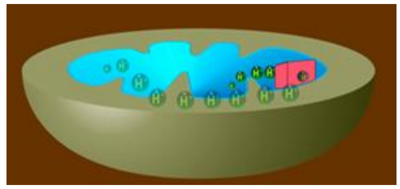
So which ring produces a structure analogous to a chloroplast: ring 1 or ring 2? Which ring pinches off the enclosed space for the hydrogen ions to be pumped into?

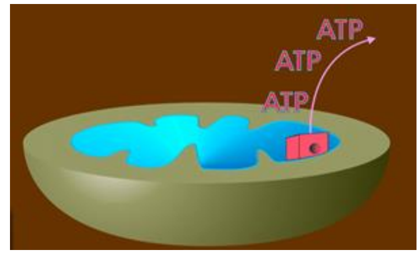
Ring 2, because the enclosed space is the intermembrane space of the mitochondrion, not the matrix of the mitochondrion.

Slide 11: Uncoupling of mitochondria

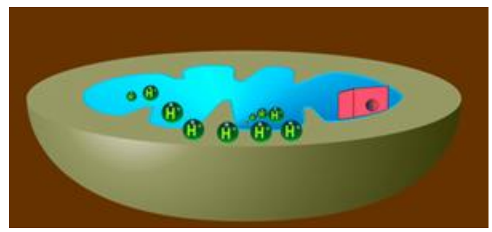
In chemiosmosis, hydrogen ions are pumped out of the interior of the mitochondria into the intermembrane space, and after collecting there, they return to the interior of the mitochondrion through ATP synthase making ATP in the process.



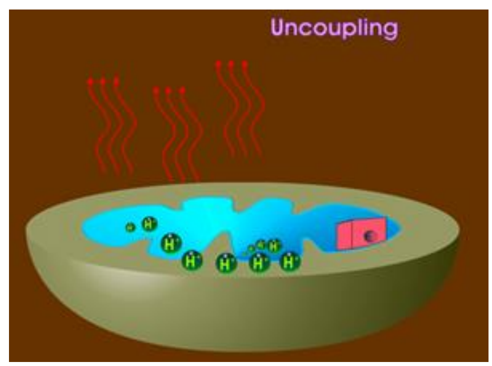




Chemiosmosis is not that efficient, because instead of being converted into ATP some of the energy stored in glucose is lost as heat.



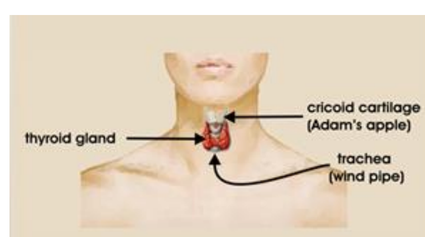
Some of the hydrogen ions start out in the intermembrane space, but are able to return to the interior of the mitochondrion without going through ATP synthase, which means no ATP is made. All that effort to break down glucose in order to extract the electron and the hydrogen ion is simply wasted as heat instead of ATP.



It turns out, that's okay because that's how we stay warm! Our mitochondria generate the heat we need to stay warm. That's why we shiver when we're cold. Shivering makes our muscles rapidly contract and our mitochondria kick into action to make extra ATP, but they end up making extra heat, too!

The name of the process whereby protons sneak back into the interior of the mitochondrion without passing through ATP synthase and making ATP is called "uncoupling," because the reentry of protons is no longer coupled to the making of ATP.

Slide 12: Overactive thyroid glands



Something similar happens to people with overactive thyroid glands. The thyroid gland is at the base of the windpipe, the trachea, and when it releases too much thyroid hormone into the bloodstream, the extra thyroid hormone allows protons to slip past ATP synthase more easily. These patients generate excessive heat and end up feeling hot all the time.

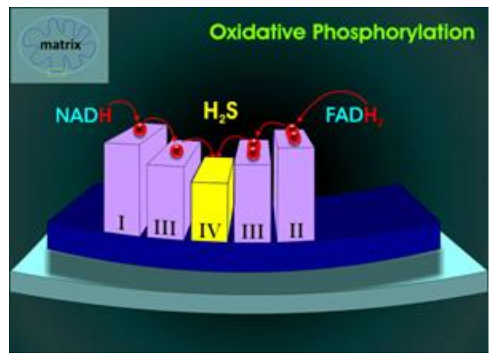
Slide 13: Brown fat

Hibernating animals and newborn babies have special type of fat, called brown fat, which helps keep them warm. Brown fat has lots of mitochondria, which is unusual for fat. The mitochondria in brown fat are rather inefficient at making ATP.

Hydrogen ions easily slip through the inner mitochondrial membrane without going through ATP synthase and making ATP. So food ends up making heat instead of ATP, which is what hibernating animals and babies need in order to survive.

Now if we could just do that in all of us, we wouldn't gain weight, because food would be converted to heat instead of being converted to fat and stored.

Slide 14: Hydrogen sulfide



As you recall, oxidative phosphorylation makes a lot of ATP from a molecule of glucose and cells can't live without ATP.

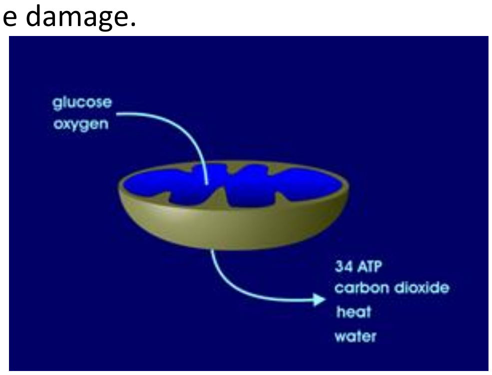
Researchers have been looking closely at hydrogen sulfide, the chemical that bacteria living in tubeworms use as a source of energy.

It turns out that hydrogen sulfide interferes with complex IV in oxidative phosphorylation. In large amounts, hydrogen sulfide can completely stop oxidative phosphorylation and kill someone.

Surprisingly, when mice are exposed to low levels of hydrogen sulfide, their heart rate slows dramatically and they drift off into a state of suspended animation.

If we could do that in humans, when somebody suffers a stroke or a heart attack, we could put them into a state of suspended animation and minimize the damage.

Slide 15: The inputs and outputs of mitochondria



The major lesson about mitochondria is that, with the help of oxygen, mitochondria are able to squeeze a heck of a lot of ATP out of glucose.

What goes into a mitochondrion and what comes out? First, what goes in?

Glucose, after it's been broken down to two pyruvates.

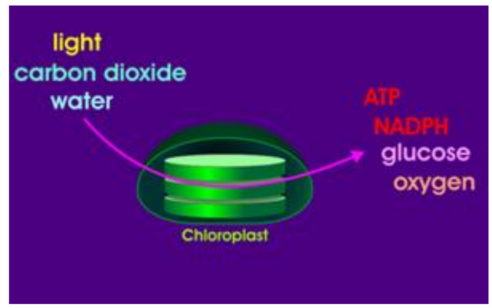
What else? Oxygen.

And what comes out? 34 ATP, CO_2, heat, and water when the proton and electron recombined and two of them hooked up with an oxygen atom.

Slide 16: The inputs and outputs of a chloroplast

How does this compare with a chloroplast? What goes into and what comes out of a chloroplast?

Light and CO_2 enter the chloroplast.



What else?

Water. Water molecules supply the electron ejected from chlorophyll.

What leaves the chloroplast?

ATP, NADPH, glucose, and oxygen.

Slide 17: What you know so far

1. Chloroplasts and mitochondria both generate chemical energy for the cell in the form of ATP and NADPH for chloroplasts and NADH for mitochondria.

2. Chloroplasts get the energy to make ATP and NADPH from the electromagnetic energy in sunlight, while mitochondria get the energy to make ATP and NADH from the chemical energy in glucose molecules.

3. Chloroplasts make ATP by pumping hydrogen ions into a closed space – the interior of the thylakoid in chloroplasts and the intermembrane space in mitochondria – and making the hydrogen ions force their way out of the enclosed space through ATP synthase, producing molecules of ATP in the process. This process is called "chemiosmosis."

Slide 18: What you know so far

4. The process in mitochondria by which hydrogen ions slip out of the enclosed intermembrane space without passing through ATP synthase is called "uncoupling."

5. The things that enter a chloroplast are light, carbon dioxide, and water, and the things that leave a chloroplast are ATP, NADPH, glucose, and oxygen.

6. The things that enter a mitochondrion are glucose and oxygen, and the things that leave are ATP, carbon dioxide, heat, and water.

Slide 19: What you know so far

7. A glucose molecule enters a mitochondrion only after it has been broken down into two pyruvate molecules. This occurs in the cytoplasm of the cell without the need for oxygen. Each 6-carbon glucose molecule is metabolized into two molecules of pyruvate, each three carbons long. To enter the mitochondria, one of the carbons on pyruvate is removed, and the remaining acetyl molecule is attached to coenzyme A. Acetyl coenzyme A then enters the mitochondria where the Kreb's cycle extracts its chemical energy to make high energy ATP and NADH.