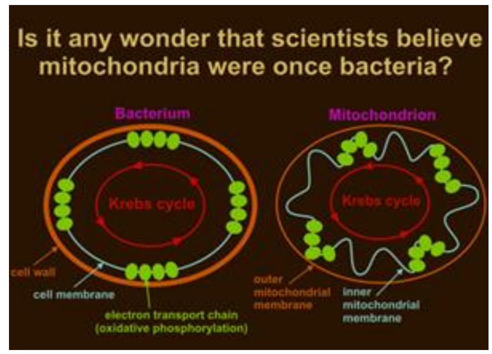
Fascinating Education Script
Fascinating Biology Lessons

Lesson 8: Take in Energy - Part 4

Slide 1: Introduction

Slide 2: Bacteria without oxygen



Bacteria are about the same size as mitochondria and thus do not contain mitochondria. Despite this, they do contain many of the enzymes for the Krebs cycle and oxidative phosphorylation to convert pyruvate and oxygen into ATP, carbon dioxide, water, and heat.

What happens to bacteria when the oxygen supply is low and the Krebs cycle can no longer make ATP?

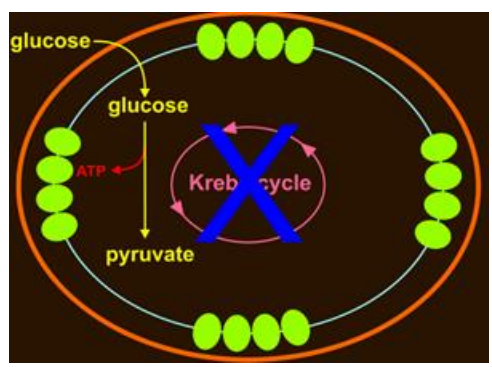
They can still make ATP using glycolysis, but glycolysis only makes 2 ATP per molecule of glucose. That doesn't seem like very much ATP.

How can bacteria make enough ATP to survive?

There's only one thing bacteria can do, and that's increase the rate of glycolysis. That's not so easy because without oxygen, pyruvate has no place to go and soon begins accumulating inside the cell.

As pyruvate accumulates inside the cell it slows down glycolysis. Why?

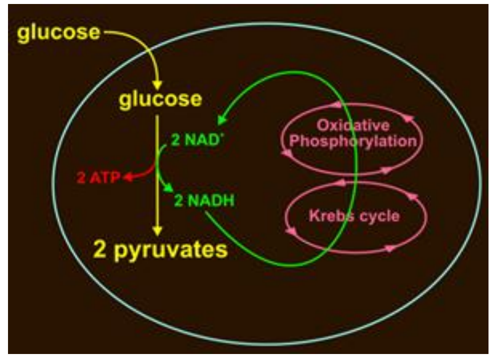
Slide 3: NAD^+



Here's why. In order to extract energy from glucose, glycolysis has to remove high-energy electrons from glucose and transfer them to a molecule that will accept a high-energy electron. That molecule is NAD^+.

When NAD^+ accepts glucose's high-energy electron in the form of a hydrogen atom, NAD^+ becomes NADH. To remove more high-energy electrons from other glucose molecules more NAD^+ is needed. That's what oxidative phosphorylation does.

Oxidative phosphorylation removes that high-energy electron, in the form of a hydrogen atom, from NADH and uses the high-energy electron to make ATP.

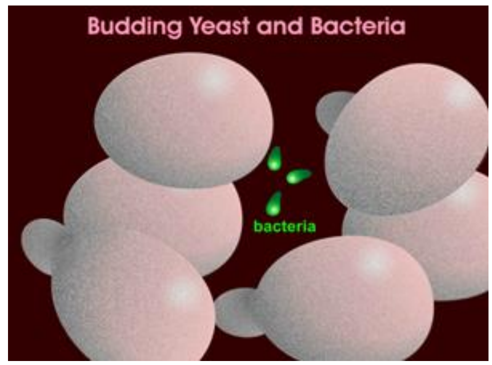


When the hydrogen atom is removed from NADH, NADH becomes NAD^+ again.

When low-oxygen conditions stop oxidative phosphorylation, NAD^+ stops being replenished and glycolysis grinds to a halt.

Slide 4: Yeast cells and muscle cells in low oxygen

Yeast cells are considerably larger than bacteria and they do have mitochondria. In the absence of oxygen, though, they have the same problem as bacteria.



They want to increase glycolysis to generate more ATP, but without oxygen to run their mitochondria, pyruvate accumulates inside the yeast cells and shuts down glycolysis.

Muscle cells are also faced with the problem of suddenly having to generate lots of ATP in low oxygen situations. When does that happen?

During anerobic exercise when muscles are contracting for long periods of time without ever relaxing.

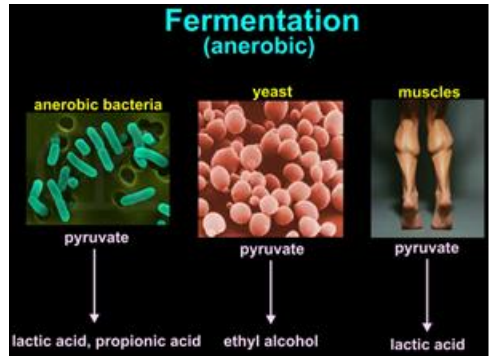
In order to keep contracting for a long period of time, muscles need lots of ATP, and its mitochondria are working overtime to produce that ATP. But when a muscle contracts for a long time without relaxing, blood flow to the muscle slows.

When the blood flow slows, so does oxygen delivery to the mitochondria. Muscle cells must then figure out another way to replenish NAD^+ so that glycolysis can at least generate some ATP.

Bacteria, yeast, and continuously contracting muscles all have the same problem when there's not enough oxygen around: they all have to rely on glycolysis for their ATP.

But, glycolysis requires a steady supply of NAD^+, that’s one problem.

The other problem is that glycolysis only makes 2 ATP from a molecule of glucose. That's not very much ATP.



The only way to increase the amount of ATP is to speed up glycolysis. Certain bacteria, yeasts, and continuously contracting muscles each concocted a way, called fermentation, to regenerate enough NAD^+ to keep glycolysis running.

Anaerobic bacteria (anaerobic means without oxygen) generate NAD^+ by converting pyruvate to either lactic acid or propionic acid.

Yeasts generate NAD^+ by converting pyruvate to CO_2 and ethyl alcohol.

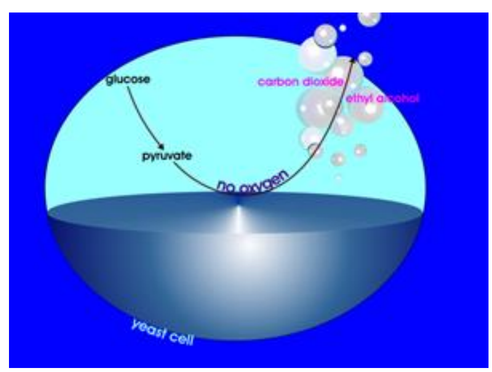
Muscle cells generate NAD^+ by converting pyruvate to lactic acid and discharging lactic acid into the blood stream.

Slide 5: Fermentation is quite useful!

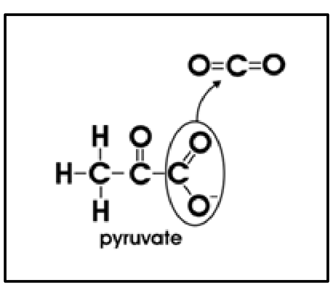
Being able to live in places with low oxygen, like this sea snake, can be quite an advantage. If it weren't for anaerobic bacteria in our intestines we wouldn't be able to digest much of our food!

We also wouldn't be able to manufacture much of the food we enjoy like cheese and alcoholic drinks. For example, we make beer, wine, champagne, brandy, and liquor by allowing yeast to convert pyruvate to ethyl alcohol and CO_2 in a low-oxygen atmosphere.

Slide 6: Chemistry of fermentation



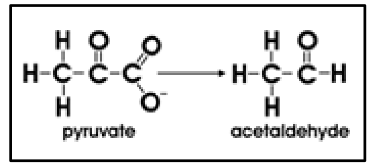
Yeast cells convert pyruvate to ethyl alcohol and CO_2 in the cytoplasm of the cell. The process requires two steps.



In the first step, an enzyme takes pyruvate and removes the end carbon and its two oxygen atoms. Carbon and two oxygen atoms is CO_2.

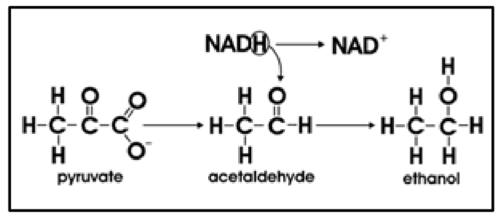
In a sugary liquid you can see bubbles of CO_2 forming at the surface.

All the tiny holes in this slice of bread were produced by CO_2 bubbling up through the dough, which of course causes the dough to rise.



After a CO_2 molecule is removed from pyruvate, what remains is a two-carbon fragment called acetaldehyde.

Here comes the hard part, breaking that double bond on acetaldehyde between carbon and oxygen. Oxygen is a very electron-loving atom and is very stable surrounding itself with two of carbon's electrons.



The only way to break this arrangement is for NADH to give oxygen another electron, and also toss in a hydrogen atom for oxygen to bond to. Adding an electron reduces a molecule, so NADH reduces acetaldehyde to ethanol.

In giving an electron and a hydrogen atom to acetaldehyde, NADH becomes NAD^+ again.

Slide 7: Sugar

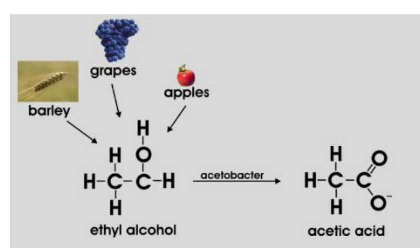
The sugar used by yeast to make the ethyl alcohol in beer comes from barley. Scotch is also made from barley and other grains.

The sugar used to make the ethyl alcohol in wine and champagne comes from grapes. Brandy also comes from grapes, but also from peaches and apricots.

Vodka is made from potatoes, rye from rye grain, and bourbon from corn.

Slide 8: Vinegar

Regardless of what fruit is used as a source of sugar, by adding a special bacterium called acetobacter to the alcohol, some of that alcohol will be converted to sour acetic acid. That's vinegar.



The acetic acid is what gives vinegar its sour taste and pungent odor. Depending on what fruit or vegetable provided the sugar to make the alcohol, you can make wine vinegar, apple vinegar, rice vinegar, or malt vinegar.

Balsamic vinegar is much finer vinegar made from a special grape, the Trebbiano grape. The grape juice is first boiled down to a third of its original volume. Only then does fermentation begin. Fermentation takes place in large wooden vats and barrels.

Yeast converts the grape sugar to alcohol and acetobacter bacteria converts ethyl alcohol to acetic and other acids. At various steps in the fermentation, the mixture is transferred to different barrels made of cherry, oak, mulberry, and others, which add distinctive flavors. In addition, evaporation from the barrels concentrates the developing flavors.

Slide 9: Pasteurization

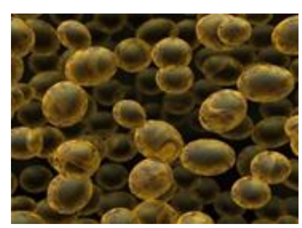
The word vinegar comes from two words; vin which means wine in French, and aigre which means sour. In the mid 1800's sour vinegar would periodically ruin batches of wine production in France. Enter Louis Pasteur.

What Pasteur discovered was that certain bacteria were contaminating the wine vats and converting ethyl alcohol to vinegar. He proposed heating the sugar solution first in order to kill all the yeast and bacteria and then adding back the yeast to ferment the sugar solution into ethyl alcohol.

That seems pretty straightforward today, but in the mid 1800's almost no one believed that living organisms had anything to do with converting sugar to alcohol.

Pasteur got everyone thinking that maybe yeast and bacteria might even be the cause of infectious diseases.

Slide 10: Ethyl alcohol in bread?!



These golden yeast cells are big enough to house mitochondria, and using the oxygen in the bread dough, mitochondria convert pyruvate into ATP, carbon dioxide, water, and heat.

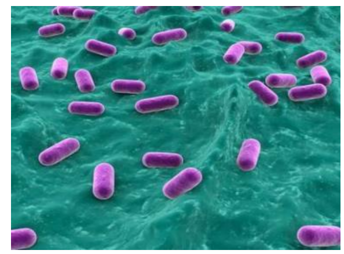
The carbon dioxide causes the bread to rise, leaving holes in the bread.

There are places in the dough, however, that don't get enough oxygen for the mitochondria to make pyruvate into ATP, carbon dioxide, heat, and water. In those places, the yeast converts pyruvate to ethyl alcohol and CO_2.

Can you get drunk eating freshly baked bread?

No, the oven's 350° F drives off the volatile alcohol. That wonderful smell of freshly baked bread is, in part, being carried into the air by the volatile alcohol being released from the baking bread.

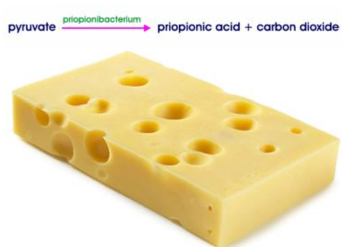
Slide 11: Sourdough



What would happen if we added a few of these purple lactic-acid-producing bacteria to the bread dough?

In areas of the bread dough where there isn't much oxygen, these bacteria would compete with yeast for pyruvate. Instead pyruvate being converted to alcohol and carbon dioxide, the bacteria would make pyruvate into lactic acid and other acids to give the bread a sour taste. The slightly sour taste of sourdough bread is made by adding some lactobacillus san francisco bacteria. Pay attention to the taste of rye bread the next time you bite into a sandwich of corn beef on rye. Rye bread has a slightly sour taste also because of lactobacillus bacteria.

Lactic-acid-producing bacteria are also used to convert the sugars in milk into lactic acid for use in the production of sour cream, yogurt, and a variety of cheeses.



The bacterium propionibacterium produces priopionic acid from pyruvate. Priopionic acid is what gives Swiss cheese its somewhat bittersweet flavor. The carbon dioxide bubbles produced in the process produce the holes in Swiss cheese.

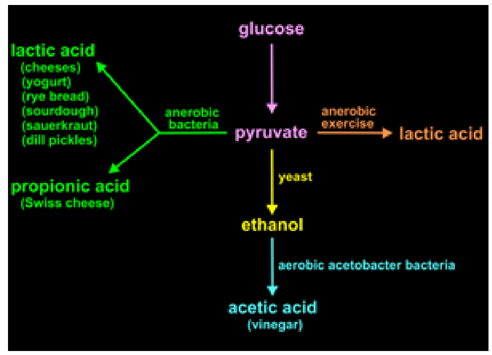
Slide 12: Pickling

In low oxygen conditions, lactic-acid producing bacteria ferment cabbage into sauerkraut and cucumbers into sour dill pickles.

The accumulating lactic acid lowers the pH, which serves to prevent other types of bacteria from growing, especially anerobic bacteria, that is, bacteria that grow in the absence of oxygen. This is important to do as anerobic bacteria tend to produce some very dangerous toxins.

One such toxin is botulinus toxin that kills by blocking nerve signals to all our muscles and preventing us from breathing.

Slide 13: Catching our breath



Let's rest here for a second and catch our breath.

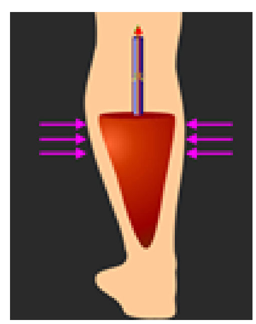
In low oxygen conditions, small amounts of ATP can be made by metabolizing glucose to pyruvate, but to keep up the production of even small amounts of ATP, pyruvate has to be metabolized further. Without oxygen, there are three major routes for pyruvate to take.

Anerobic bacteria can metabolize pyruvate to lactic acid, which is how we make various cheeses, yogurt, rye bread, sourdough bread, sauerkraut and dill pickles. Or, pyruvate can be metabolized by anerobic bacteria to propionic acid, which is how we make Swiss cheese.

Yeast cells metabolize pyruvate to ethyl alcohol, or ethanol. Pasteur figured this out when he realized that aerobic bacteria were further metabolizing ethanol into acetic acid and spoiling the wine.

We're now going to look at what muscles undergoing intense anerobic exercise do with their accumulating pyruvate.

Slide 14: Aerobic vs. non-aerobic exercise



Muscle cells can also encounter low oxygen situations -- during non-aerobic exercise like weightlifting when muscles are contracting continuously.

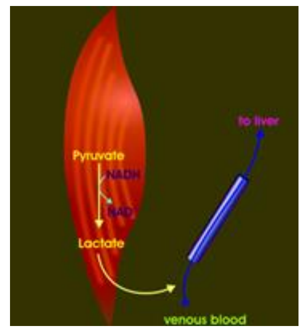
Why should aerobic exercise deliver more oxygen than non-aerobic exercise?

During aerobic exercise, muscles contract and relax, contract and relax, and contract and relax.

Each time a muscle contracts, it squeezes veins within the muscle. Blood is forced to flow forward, toward the heart, because of one-way valves inside the veins. Contracting muscles then, help the heart circulate the blood.

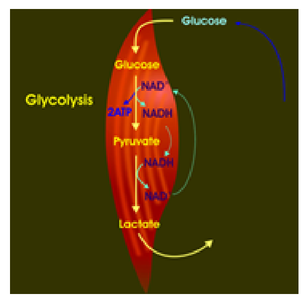
During anaerobic exercise, muscles contract continuously. They don't contract and relax. The veins remain squeezed shut and circulation through the muscles slows. Less oxygen is delivered to the mitochondria and pyruvate rapidly accumulates.

Pyruvate can accumulate during aerobic exercise, but only when the exercise is very intense. With really vigorous and prolonged exercise, even a normal heart, and lungs that haven't been damaged by smoking, and arteries that haven't been clogged by cholesterol can't deliver enough oxygen to the muscles' overworked mitochondria.



Slide 15: Muscle cells and lactate

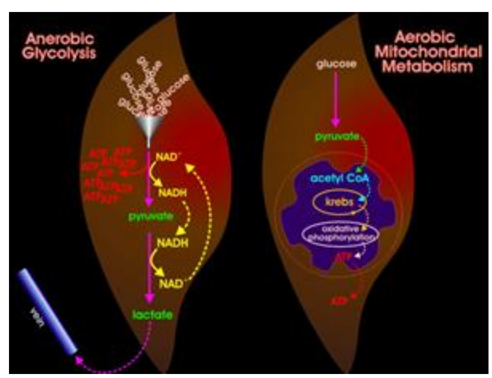
Muscle cells generate NAD$^+$ during low-oxygen situations by converting pyruvate into lactic acid and then removing the lactic acid to the blood stream where it's brought to the liver to be converted back into glucose.



When glucose is converted to pyruvate high-energy NADH is made. In low oxygen, NADH gives its high-energy electron to pyruvate and reduces pyruvate to lactate. NADH is converted back to NAD$^+$ and the NAD$^+$ is now available to help metabolize more glucose to pyruvate and generate another 2 ATP.

The lactate meanwhile, leaves the muscle cells and enters veins coursing through the muscle. The lactate is carried by the blood to the liver which recycles the lactate back into glucose again.

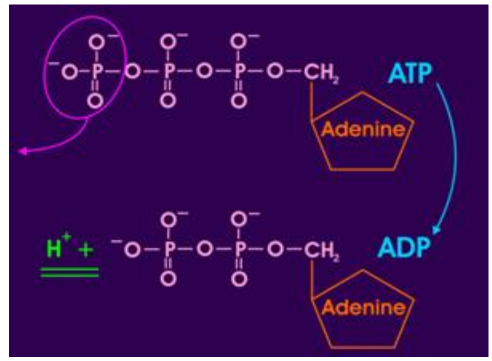
Slide 16: Glycolysis is great for short bursts of energy



At first glance glycolysis, which produces only 2 ATP from each molecule of glucose, seems very inefficient. But, what glycolysis has going for it is that it can metabolize a lot of glucose molecules in a hurry, and it doesn't have to waste time transporting pyruvate into a mitochondrion, attaching an acetyl group to make acetyl-CoA, running acetyl-CoA through the Krebs cycle, and then moving ATP back out into the cytoplasm.

Glycolysis occurs right where it's needed in the cytoplasm. Sure only 2 molecules of ATP are produced for every glucose, but by rapidly converting pyruvate to lactate, glycolysis can produce a heck of a lot of ATP in a very short period of time, ideal for short bursts of energy.

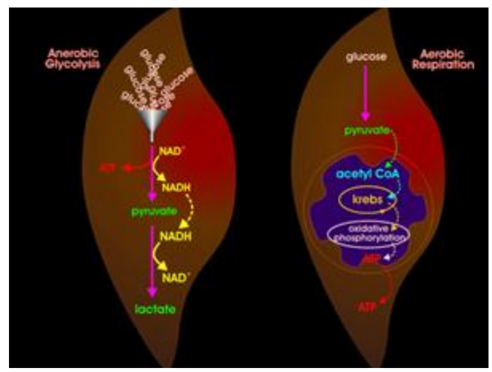
Slide 17: Glycolysis lowers muscle pH



So why not use glycolysis for long bursts of exercise?

Here's the problem. The huge amounts of ATP being made by glycolysis during intense exercise are being used, of course, to keep the muscles contracting. Each time a phosphate is removed from ATP however, so is a proton. It doesn't take long for the protons to lower the pH of the muscle cell, which you feel as a burning in your muscles. The low pH can stop your muscles from contracting**.**

Slide 18: Two ways for muscle to make ATP

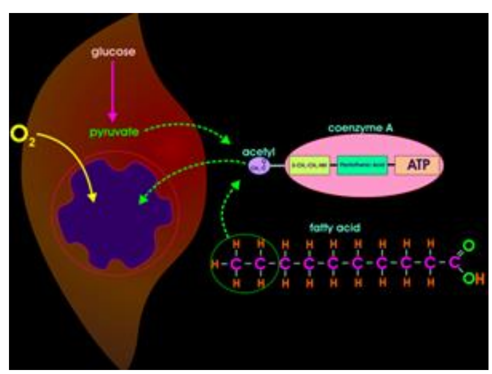


Muscles then, have two ways to make ATP, in the cytoplasm through glycolysis and in mitochondria through the Krebs cycle and oxidative phosphorylation. Some muscles depend primarily on glycolysis for ATP while other muscles depend primarily on their mitochondria.

These two types of muscles are readily discernible in chickens and turkeys. The muscles that depend on glycolysis are the white meat on a turkey or chicken, while the muscles that depend on mitochondria are the dark meat.

Why the difference in color?

Slide 19: Mitochondrial muscle cells have more fat



What do mitochondria need to feed their Krebs cycle?

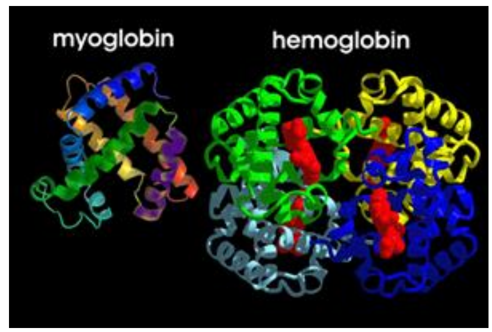
Oxygen and acetyl CoA. Acetyl CoA can come from pyruvate or from 2-carbon fragments sliced off of fatty acids.

How do you think muscle cells that depend on their mitochondria for ATP differ from muscles cells that depend on glycolysis for ATP?

What will mitochondrial muscle cells have that glycolytic muscles cells won't?

Both will have lots of glucose, but mitochondrial muscle cells will have a lot more oxygen and fat.

Slide 20: Muscle myoglobin



Mitochondrial muscle cells store their own supply of oxygen within muscle cells. The muscle protein that does this is called myoglobin. No other tissue in the body, not the brain, not the liver, not the eyes stores its own supply of oxygen.

Myoglobin is very similar to the four globin proteins that make up hemoglobin. Like each globin in hemoglobin, each myoglobin can hold one molecule of oxygen.

Myoglobin is dark in color. Myoglobin is why the dark meat in a chicken or turkey is dark. Glycolytic muscles, which don’t contain myoglobin, remain white.

Slide 21: Diving mammals

Diving mammals like whales, seals, dolphins, porpoises, and otters are able to dive under water for up to 20-30 minutes at a time because their muscles are packed with myoglobin which provides these mammals with a continuous supply of oxygen.

Slide 22: White meat

White meat depends on glycolysis for its ATP. White meat is able to immediately generate, through glycolysis, gobs of ATP when faced with a sudden need to escape or perhaps chase its next meal.

So where do you predict you’d find white meat on a chicken or turkey?

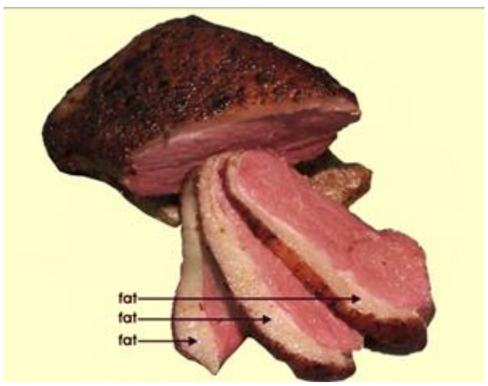
Breast meat, of course. When a chicken or turkey is suddenly threatened, its breast meat needs a sudden burst of ATP to flap its wings and fly away in a hurry. However, each time one of these ATP molecules is used to flaps its wings, a proton is released, and the muscle becomes more and more acidic. Consequently, white meat is only able to contract for a few minutes before it fatigues, which is usually long enough to carry the bird out of danger.

Slide 23: Dark meat

Dark meat, on the other hand, can contract all day long, but can only do so in a slow, steady fashion. Dark meat doesn't need to suddenly exert itself in a massive burst of contractions.

Dark meat is used for slow, steady work like milling around the barnyard pecking for food, so dark meat is found in a chicken or turkey's legs and thighs.

What about this duck?



The breast meat of a duck is very fatty.

Why is the breast meat of a duck fatty when the breast meat of a chicken or a turkey isn't?

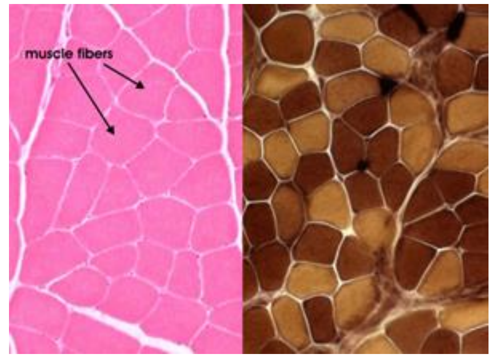
Because ducks don't use their breast meat for sudden bursts of activity.

Instead, ducks use their breast meat to keep their weeks outstretched as they migrate thousands of miles. This is slow, steady work that needs a slow, steady supply of ATP provided by fat, oxygen, and myoglobin.

Slide 24: Do humans have white and dark meat?

What about humans? Do humans have white and dark meat? Let's biopsy a human muscle and look at it in cross section.

On the left are the individual bundles of muscle. On the right the muscles are stained for mitochondria. Some of the muscle cells have lots of mitochondria and some don't. So humans also have white and dark meat, but the white and dark meat fibers are intermingled in every muscle.



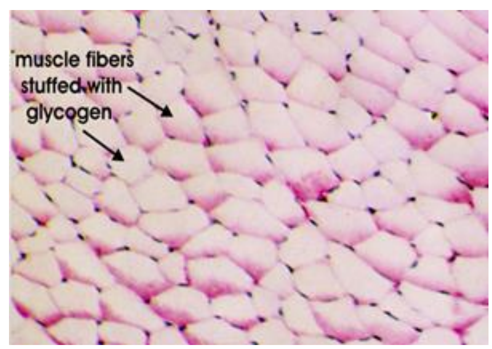
Unlike chickens and turkeys, in humans there is no bulk separation of white and dark meat. Each muscle is a mixture of white and dark meat fibers.

Slide 25: A sprint or a marathon?

About 80% of the muscles fibers in a world class sprinter depend on glycolysis for ATP, while about 80% of the muscles fibers in a world class marathoner depend on mitochondria for ATP.

What's unclear is whether you can increase the percentage of white or dark meat fibers in your own body by training for sprints or marathons.

Slide 26: Carbo-loading



If oxygen is stored in muscle, why not store glucose there, too?

Good idea! In fact, muscles do just that. They store their own supplies of glucose in long chains called glycogen. Since glucose is a carbohydrate, many athletes try to fill up their glycogen stores before endurance events by loading up on carbohydrates.

As mentioned, glycogen for the rest of the body is stored in the liver.

Slide 27: What you know so far

1. Extracting energy from glucose begins with anerobic glycolysis which requires NAD^+ to accept a high energy electron to become NADH. While this does produce 2 ATP, in order to <u>continue</u> making ATP from molecules of glucose, more NAD+ must be made available.

2. When oxygen is available, new supplies of NAD^+ are made available for glycolysis by stage 2 of photosynthesis. That's where NADH gives its high energy electron to oxygen in a process that makes glucose from carbon dioxide molecules in the air. Oxygen becomes an electron acceptor.

Slide 28: What you know so far

3. Where there is no oxygen available to accept electrons from NADH, and thus no way to make more NAD^+, glycolysis has to depend on some other electron acceptor, besides oxygen, to obtain NAD^+.

4. Anerobic bacteria generate NAD^+ from NADH by oxidizing pyruvate to lactic acid and propionic acid. In doing so, these anerobic bacteria make rye bread, sourdough bread, sour cream, yogurt, a variety of cheeses, including Swiss cheese, as well as sauerkraut and dill pickles.

Slide 29: What you know so far

5. Yeast cells generate NAD^+ from NADH by oxidizing pyruvate to ethanol.

6. Intensely exercising muscles generate NAD^+ from NADH by oxidizing pyruvate to lactic acid.

7. Glycolysis is well-suited to supply muscles with a quick and readily available supply of ATP because glycolysis occurs in the cytoplasm without having to be passed into mitochondria through the Krebs cycle and oxidative phosphorylation. Glycolysis cannot continue for long, however, because of the buildup of acid in the muscles as ATP is broken down to ADP.

Slide 30: What you know so far

8. Muscles that depend on glycolysis for short bursts of energy do not need a blood supply to deliver oxygen, nor do they need a supply of fatty acids for the Krebs cycle, so in chickens and turkeys, glycolytic muscle form the white meat. The dark meat is dark due to the presence of myoglobin storing oxygen and hemoglobin delivering oxygen to the muscles. Dark meat is also greasier because of the fatty acids present as a source of two carbon fragments to be made into acetyl-CoA for the Krebs cycle.

Slide 31: What you know so far

9. Diving mammals have a great deal of myoglobin in their muscles which allows them to stay submerged for many minutes at a time.

10. White and dark meat fibers in humans are intermixed in almost all muscles instead of being separated in bulk as they are in chickens and turkeys.