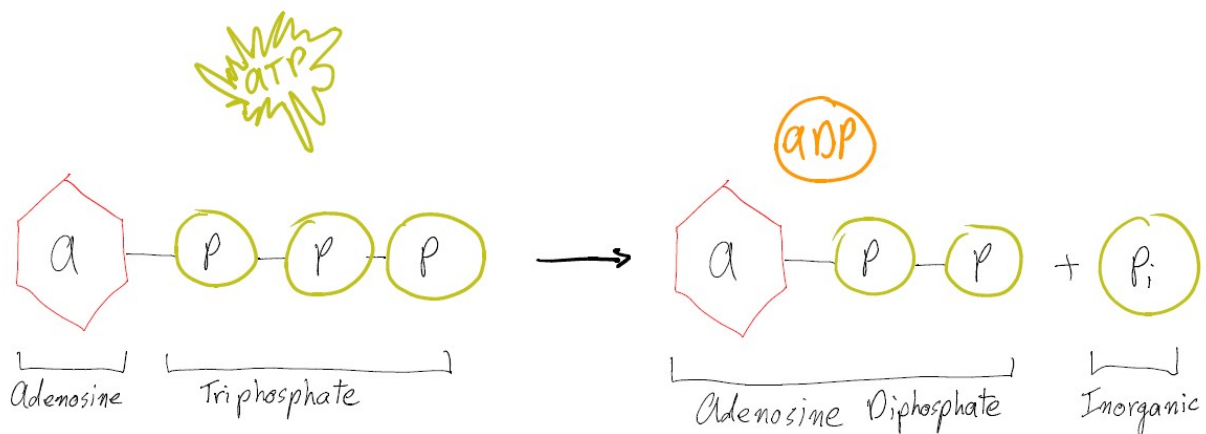


Energy Systems- The Ultimate Hybrid

Muscles are great, but without a way to fuel them they are just dead weight. Energy needs to be constantly supplied and recycled in each muscle cell. The energy is generated from three engines that work together like a hybrid car to supply energy required. **These engines are the foundation of how we train, how we improve and how we feel in the water.**

ATP: Pure Energy

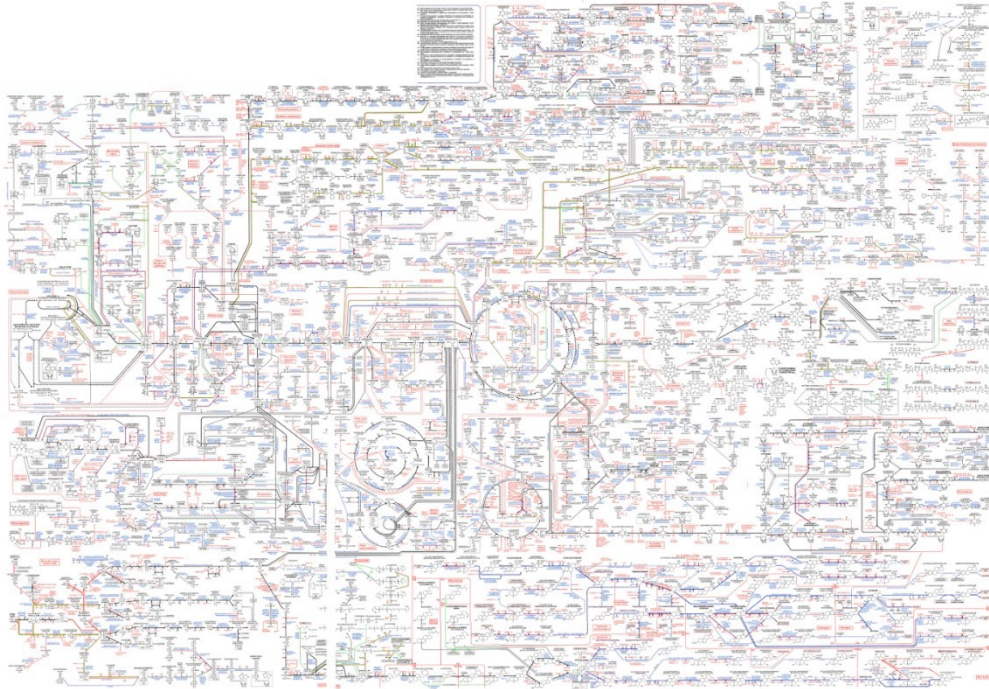
Last time we talked about how muscles work and we mentioned that different myosin heads can use up energy at different rates to change how much power a muscle cell produces; and manage how much energy it spends. That energy comes from ATP. But what is ATP? ATP stands for “adenosine triphosphate,” and it is the **major energy transporter in every single cell, of every single organism on Earth.**



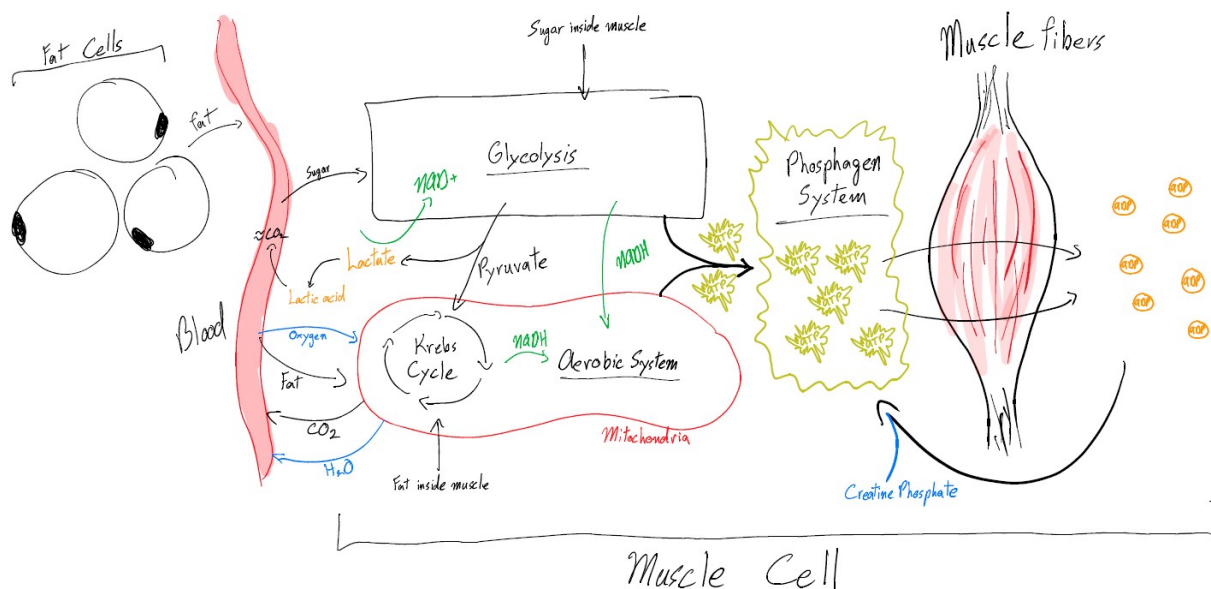
The energy it carries is contained in those phosphates (ok the bonds of the phosphate for you nerds), every time one breaks off, energy is released and ATP become ADP (adenosine diphosphate). This energy is used to power enzymes, transporters and muscle shortening.

Once ATP's energy is used and is converted to ADP, the **ATP needs to be regenerated**, and that is what the rest of this chapter is all about. Here is the full set of reactions and enzymes required to regenerate ATP:

Tangent: ADP can be further broken into AMP (adenosine mono-phosphate) and more energy will be released, but it's less important for our purposes so we will ignore it.

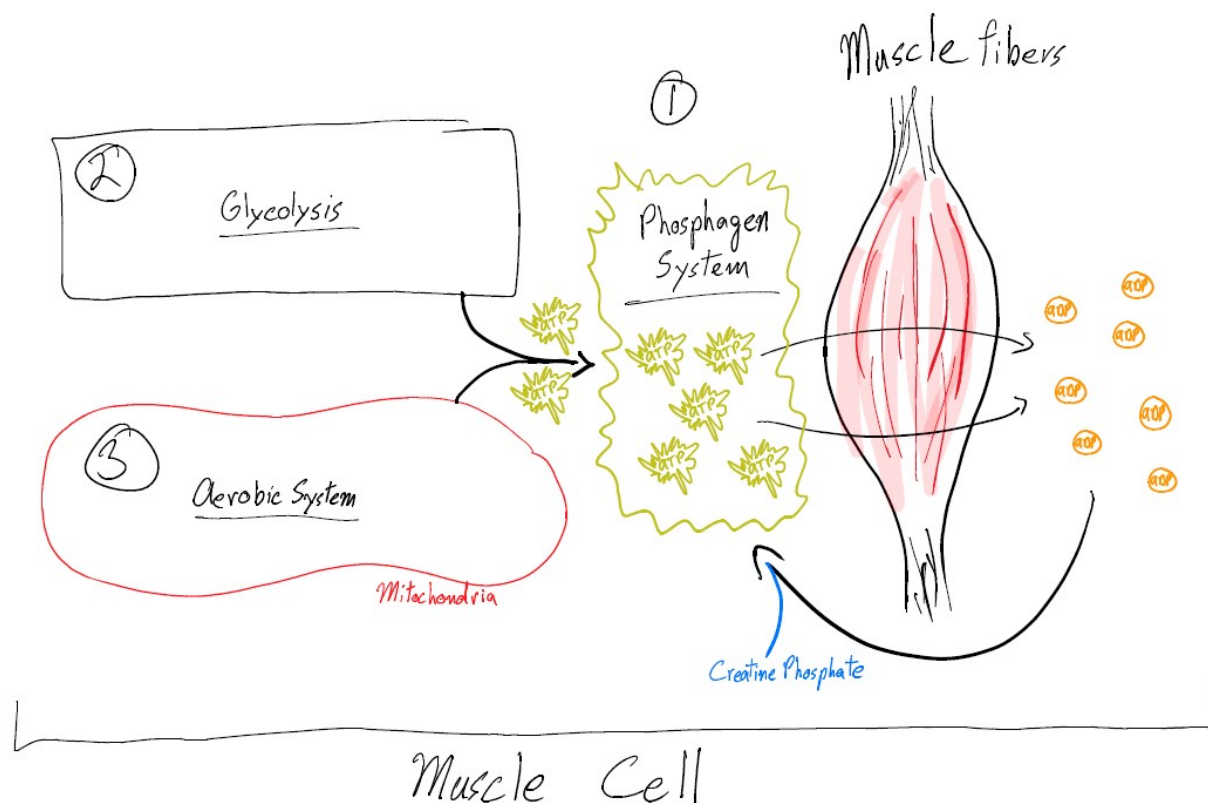


Very complicated... but it can be simplified



Ok...it's still a little complicated, but Einstein once said "Everything should be as simple as it can be, but not simpler." This is as simple as it gets so buckle up swimmers!

Your cells use a hybrid of three energy systems that act like engines to regenerate the same ATP molecule: Phosphagen system, Glycolysis and the Aerobic system (that's right, hybrids have been around for a while). While all three systems end up making the same ATP, each system has distinct advantages and disadvantages in terms of how quickly they make ATP, what byproducts they make on the way, what fuel sources they can use and whether they use oxygen or not. Here is a summary:



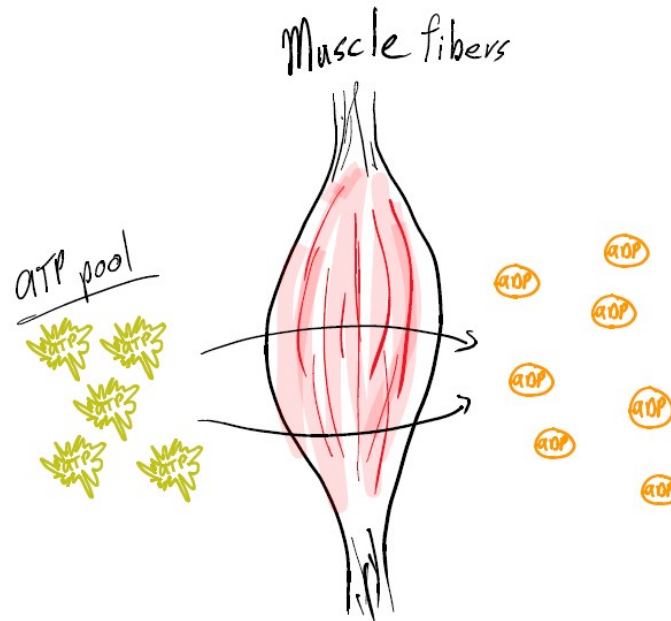
	Fuel	Duration	Byproducts	Relative Power	O ₂ used?
Phosphagens	Glycolysis + Aerobic	5 seconds	none	3.6	nope
Glycolysis	Sugar	30-40 minutes	Lactate	1.6	nope
Aerobic	Pyruvate + Fat	Forever	CO ₂ + H ₂ O	1.0	Yup

We are going to build this picture up one step at a time. It is important to understand this energy system concept for two reasons. Number one, it explains a lot about how you feel and function during workout and during races. And two, coaches use things like color systems, heart rate and perceived exertion to estimate which energy system swimmers are using most during workout, which is a **big part of understanding your training.**

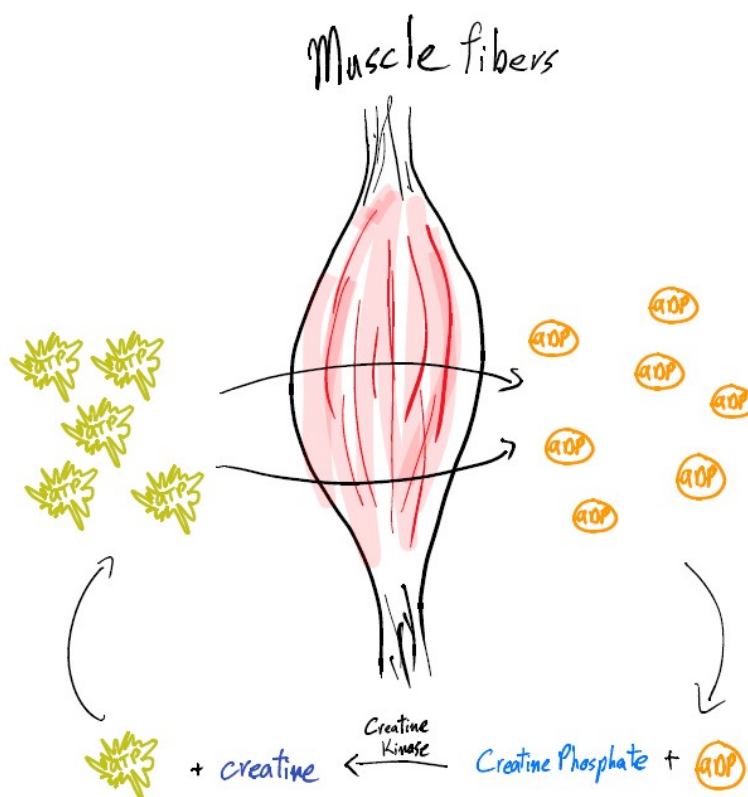
Let's begin!

Phosphagen System: The Energy Already Sitting Around

The word “Phosphagen” tells us a lot about how this energy system works. Every component of the system **uses or replaces a phosphate directly**. Let’s start with a phosphagen compound we already know about, ATP. When you move a muscle, there is no lag time...it just moves right away. That’s because your muscle is using the ATP that is already lying around. In theory, if you had an unlimited supply of ATP immediately available, you would be able to work the muscle at maximum power for all time!



But in reality, you have about one second’s worth of ATP lying around before it runs out. Do not fear, creatine phosphate is here! Yup, same creatine some people eat as a supplement (we will review supplements in Part III). **When the levels of ADP increase (aka when you are using your muscle) the lost phosphate is instantly replaced as creatine phosphate regenerates the ATP.** Think of creatine phosphate as a battery that recharges ATP.



The enzyme creatine kinase (kinase=kinein= “to move”) makes the transfer of phosphate from creatine phosphate to ADP possible. Remember, creatine kinase from the Muscle chapter? It’s the same enzyme “CK” that leaks out of damaged muscles and can be measured in the blood as a marker of damage...cool right?

That’s the phosphagen system. **One reaction, instant ATP regeneration** which means no lag when you decide to use your muscles. This cycle of regeneration of ATP can happen about 4-5 times in quick succession, giving you about 5 seconds worth of immediate and almost maximum energy, and then the creatine phosphate will run out.

If you are a good swimmer this will get you about half way across the pool, which is not enough for a full race. We need more ATP... a lot more.

Tangent: Weightlifters the world over know that in competition, if the weight isn’t up in 5 seconds, it’s not coming up. That’s because this is the only energy system lifters use for a one rep max.

It is also important to mention... this is **NOT improvable with training** (not even weightlifting), and probably not with supplementation either. The main reason to understand this system is because **the next two energy systems feed directly into this one.**

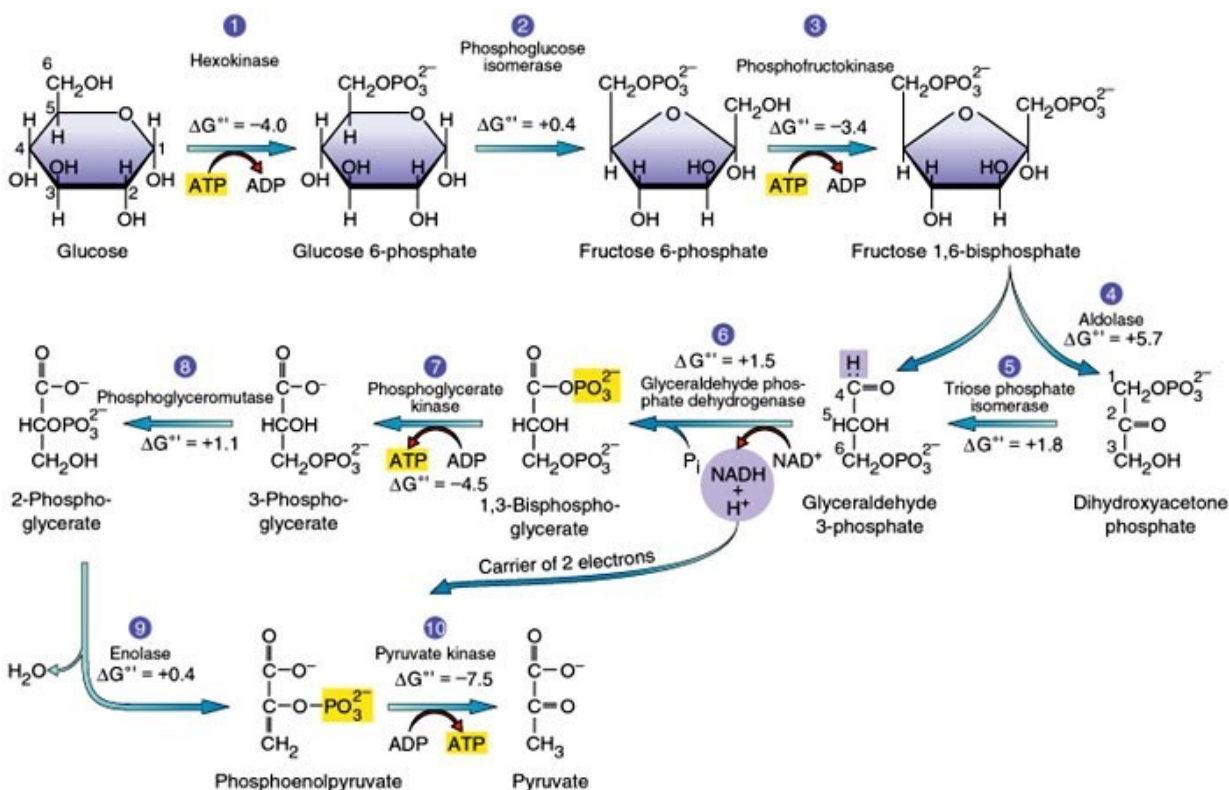
Glycolysis: Burning Sugar

Glycolysis, like many science terms, translates into a literal explanation. Glyco means “glucose” which is a simple sugar, and lysis means “to break.” Together it means “to break glucose.” **Glucose is a simple sugar that is most commonly used by many organisms and is the fuel of choice for hard working muscle.** Together with the phosphagen system, these two energy systems make up the anaerobic part of ATP regeneration. “an-“ means “in the absence of” and aerobic means “oxygen,” so it means “without oxygen.”



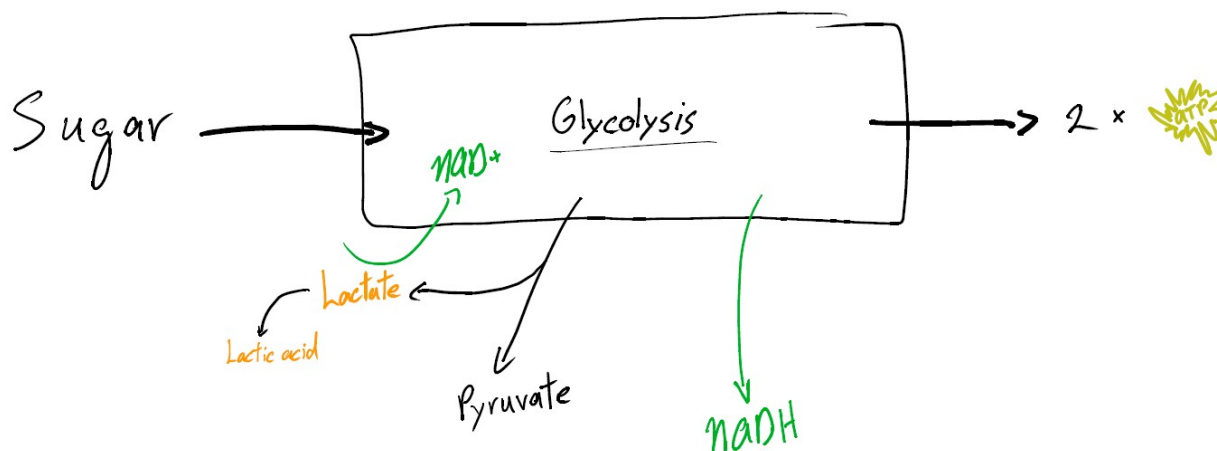
Tangent: The granulated sugar in your cupboard is a glucose molecule and a fructose molecule stuck together. We are going to keep things simple and pretend glucose is the only sugar that exists. So when we say “sugar,” we mean glucose and no other carbohydrates, disaccharides or monosaccharides.

Let's take a look at this energy system in all its glory...



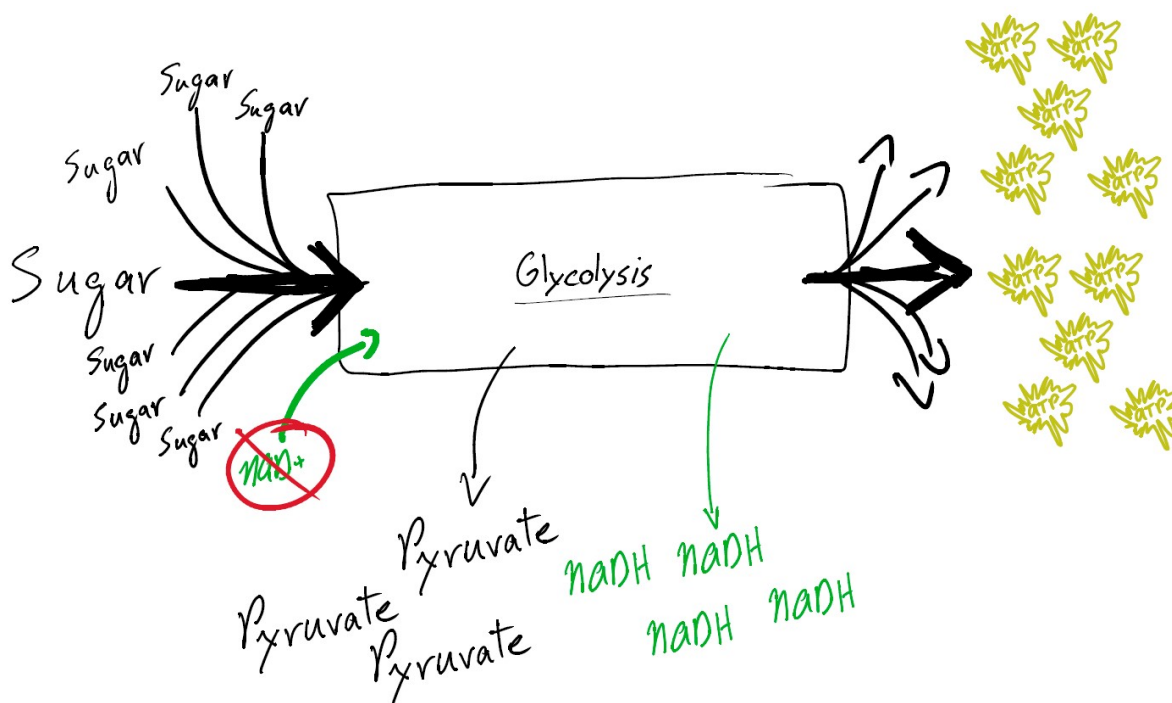
As you can see, this is a little more complicated than the simple phosphagen system we talked about earlier. The increased complexity is a big deal. If you didn't have ATP and creatine phosphate just lying around, there would be a delay every time you tried to move your muscles because **it takes time to break down the glucose and make ATP out of it**. It's not much time, maybe a few seconds or less... but try waiting a few seconds on the blocks after the gun goes off and see what happens to your 50 time ☹.

For our purposes, we don't need to bother with most of these reactions and enzymes, so here is a simplified version of everything you need to know.



As you can see, **this energy system needs sugar. Fat cannot be used as a fuel source here**, and proteins make up such a small amount it is generally ignored. From the single molecule of sugar we get two ATPs, some pyruvate and NADH too. Pyruvate is a harmless by-product of glycolysis that will be fed to the mitochondria and burned in the aerobic system (coming up). NADH is created from NAD⁺ and is an electron transporter that also goes to the mitochondria to make ATP. (Stick with us, these molecules matter).

While two ATP is not a lot of energy, **glycolysis is still simple enough to cycle through at a very fast rate, eating up a whole lot of glucose molecules to make a lot of ATP per minute**. Maybe not as much as the phosphagen system, but enough to get you moving very fast.

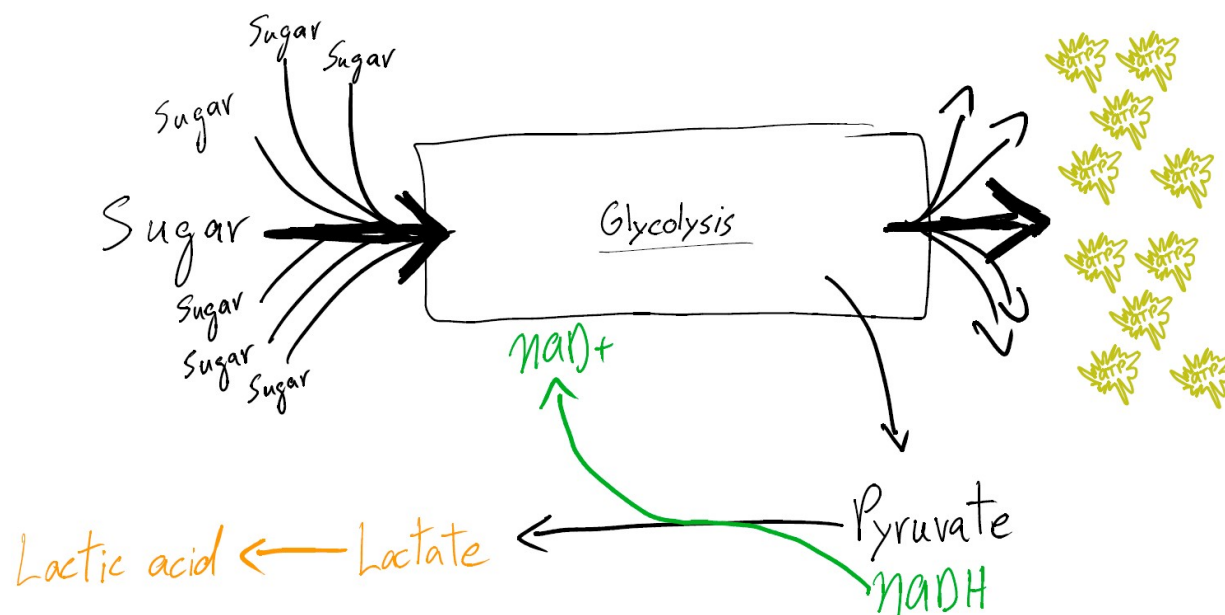


This is the main energy system in short fast races. The 50 and 100 utilize the glycolysis system almost exclusively. So...if glycolysis is so great and can make so much ATP and doesn't even use oxygen, what's the problem? Why can't I just keep up my 50 pace for however long I want? That's the downfall of this system...and it has to do with NADH.

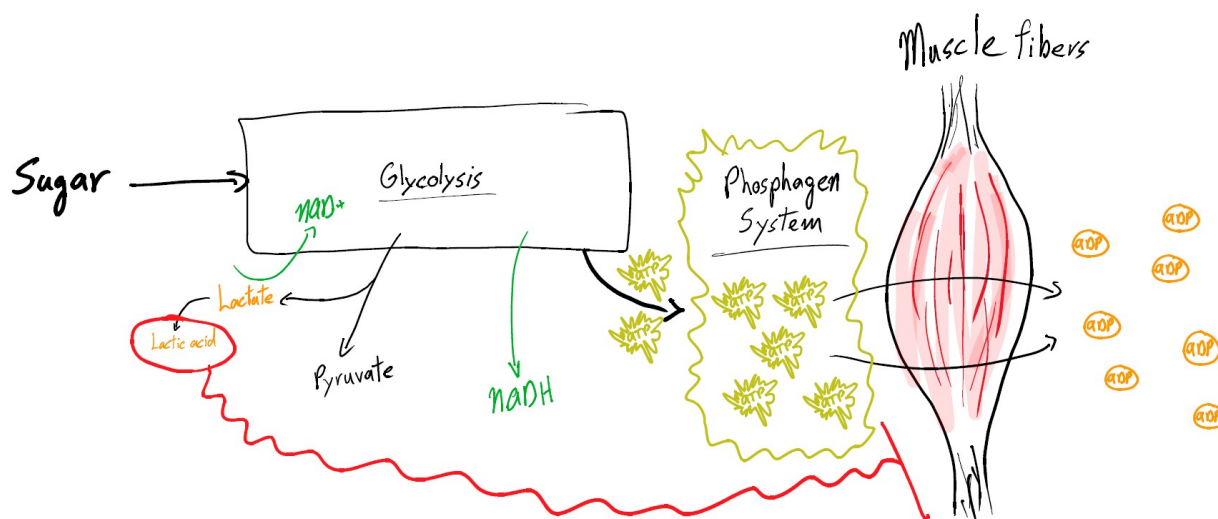
NADH stands for a big long name of a molecule, and it is important to understand because it is the root cause of all of your pain and suffering! **Glycolysis cannot function without NAD⁺**, so if you run the system very fast and make a lot of NADH, you will run out of NAD⁺ before it can be regenerated...and the whole system clogs up and stops working.

There are two ways of regenerating the NAD⁺. Keep moving it down the line and feed it to the mitochondria... which will take forever (coming up shortly) or **turn pyruvate into lactate**. During a 100 you don't have time to wait, so your body chooses the path of lactate, which becomes lactic acid. Through the fancy footwork of some electrons, this takes the NADH and regenerates NAD⁺ allowing glycolysis to continue.

Tangent: Yeast do the same thing, but they convert pyruvate into ethanol, or drinking alcohol. Your body doesn't do that because of the "bad" side effects alcohol has on advanced nervous systems.



That's where all your pain is. It is the burning in your muscles, the tightness in your chest, and the full stop to your race. **It physically gets in the way of your muscle firing and is responsible for the feeling that you can't pull the water at the end of a race.**



Your ability make lactic acid determines how well this engine is working. If you can't make a lot of lactic acid, you are not burning a lot of sugar, you are not making much ATP, and you are not going very fast. When we talk about Lactate Threshold later on, we will see that being able to produce a lot of lactic acid is the marker of a good sprinter.

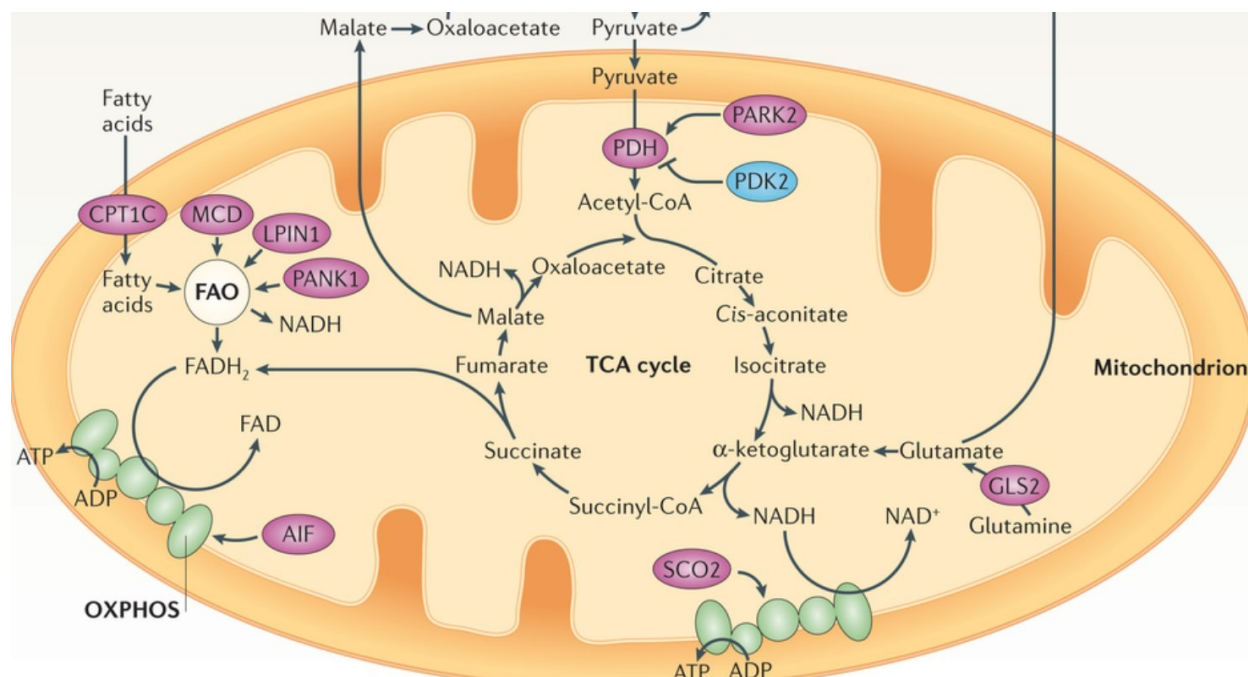
Tangent: Not convinced lactate is good? There are people who are born with a defect of the enzyme that converts pyruvate to lactate (lactate dehydrogenase, LDH). These poor people cannot do much more than walk. Anything more and they will deplete their ATP, causing severe cramps.

If this energy system were to run at 100% power, you have about 40-50 seconds before the lactic acid builds up too much and forces your muscles to shut down. That's great if you're a 50 free specialist, but this is a problem for all other races. We will talk more in depth how the body deals with lactic acid later, but one solution to our problem is to get more ATP from a more efficient system that does not make acid at all.

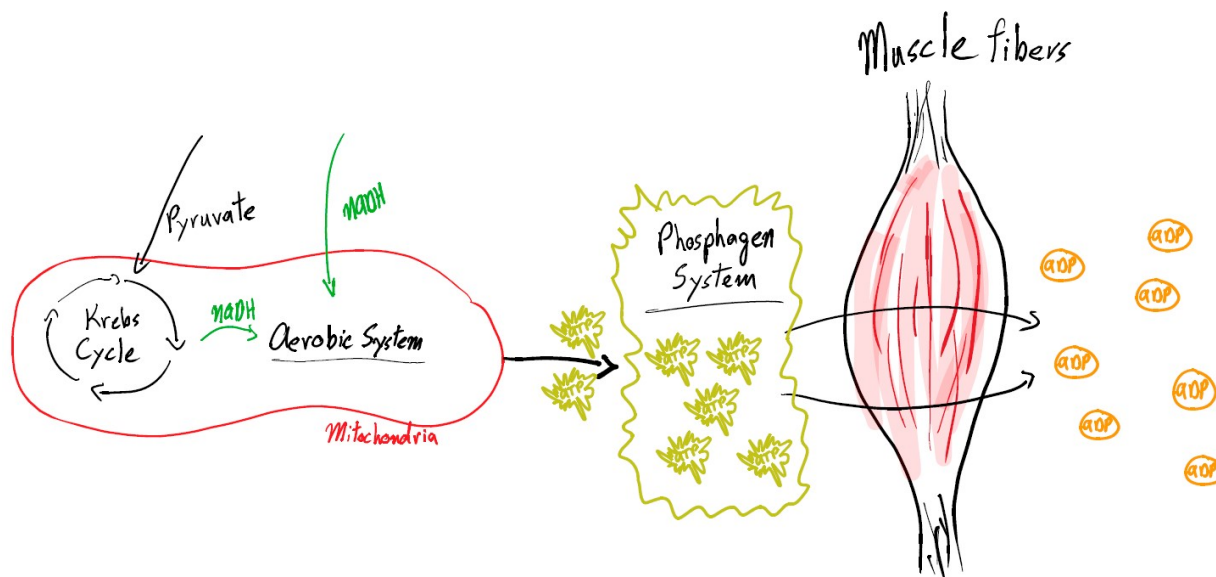
Aerobic: Efficient, but Slow Burning

The last energy system is the **aerobic system, which means “with oxygen”**. The other name for this system is oxidative phosphorylation (bless those biochemists). But it says a lot. Oxidative means “adding an oxygen”, phospho- means “phosphate” and lation means “to add.” So the translation-ish is “adding a phosphate to something by using the energy from adding an oxygen to something else” (you got all that...right)?

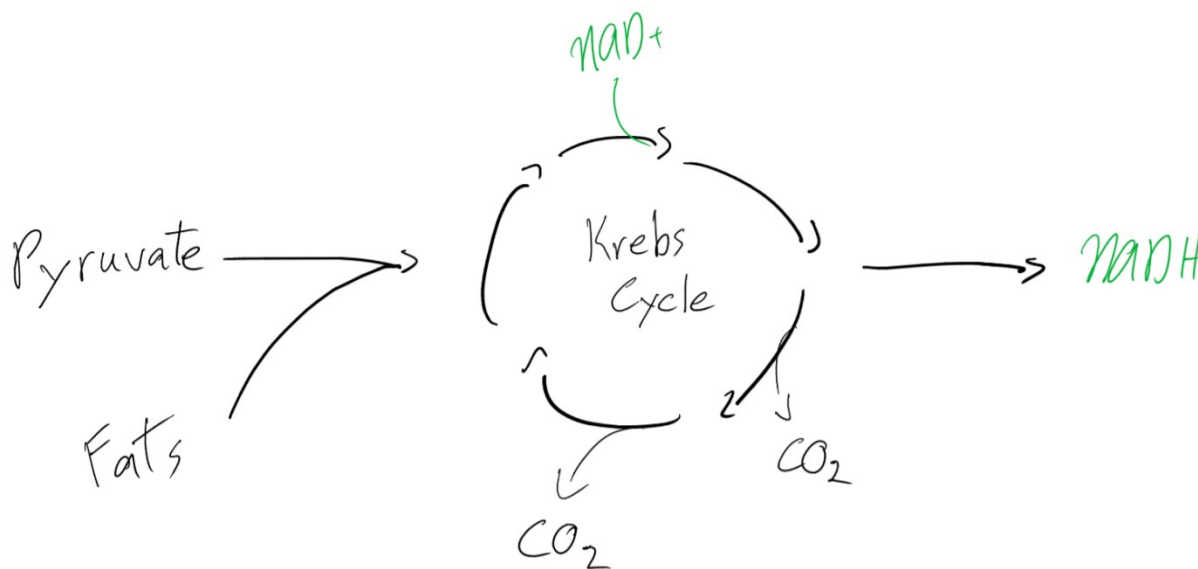
Here is the system in all its complexity. Notice this energy system involves many enzymes, multiple cycles, reactions that occur both inside and outside the mitochondria, and many membranes that must be crossed in both directions.



This complicated series is designed to extract every ounce of energy from the fuel sources entering in. **But all those steps and membranes slow everything down and efficiency comes at the cost of time.** So while this energy system is efficient and produces no lactic acid, even in fully trained elite athletes, this system's ATP/minute generating capacity is much less than that of glycolysis.



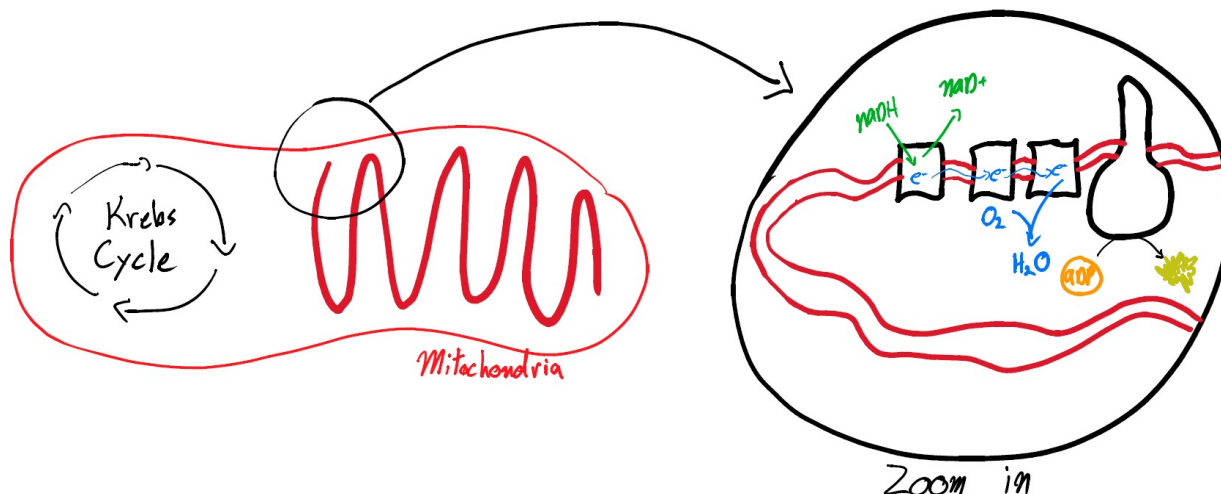
Let's start where we left off, pyruvate. Let's say we are now swimming a workout or a long distance race (at least 2 minutes). Now that the muscle has time, it will **shunt the pyruvate into the Krebs cycle** (aka the tricarboxylic acid cycle...aka the citric acid cycle...aka the bane of every biology student).



There are a few important things to know about the famous Krebs cycle. Number 1, it produces more NADH and other electron carriers that go on to be fuel for the mitochondria. Number 2, it is **the only place where CO₂ is created** (and no... the "O₂" in CO₂ is NOT the same oxygen you breathe in). Number 3, the Krebs cycle is the beginning of fat burning. Glycolysis does not use fat. **Only the aerobic system can use fat as a source of fuel.**

Alright, finally we have everything we need to make a lot of ATP. All those electron carriers (NADH mainly) go to the mitochondria and are funneled through multiple very big complexes and though a long and tedious process create ATP and creatine phosphate!

Tangent: Any blockage of oxygen getting to the mitochondria will cause the cell to use glycolysis instead. The resulting increase in lactic acid can then be measured in the blood. This is also where cyanide works, by preventing mitochondria from using NADH. Makes you appreciate all your mitochondria do for you, right?



At the end of this long chain of events, there is a poor little electron... drained of all energy. **This electron is captured by the oxygen we breathe and is combined with hydrogen to make water.** Yup, that's what oxygen is used for, picking up the garbage. And yeah, that may be why you have to pee so much during workout even though you are sweating and not drinking much, because as you burn energy, all the oxygen you breathe in turns into water, and that has to get out somehow.

Tangent: Remember, CO2 that you breath out is made by burning something, sugar, fat protein, wood...yeah, same combustion reaction you see at a bon fire. (What?! Weight loss through breathing... kool). The O2 you breathe does not become CO2, it becomes water.

So, how much ATP we talking about here. From pyruvate to CO2 and H2O is 32 ATPs. From sugar to the end, that's 34 total ATP (2 from extra from Glycolysis). That's a lot. But remember what we said before... efficiency of ATP production does not account for the time it takes to make that same ATP. **In reality, the aerobic system only produces about 60% of the ATP/minute when compared to glycolysis.**

Fat can only be burned in the mitochondria and is even more efficient than sugar, producing over 120 ATPs per molecule of fat! But it's **even slower at making those ATPs than when using sugar.** This has a big part in how you feel at the end of a two hour workout (will discuss soon) when all your sugar is out and all you are running on is fat.

Tangent: Some people are born without the ability to utilize fat as an energy source. These people usually end up with major developmental delays by their first birthday and eventually die very young due to heart problems because nerves and muscles depend so much on fats for ATP generation.

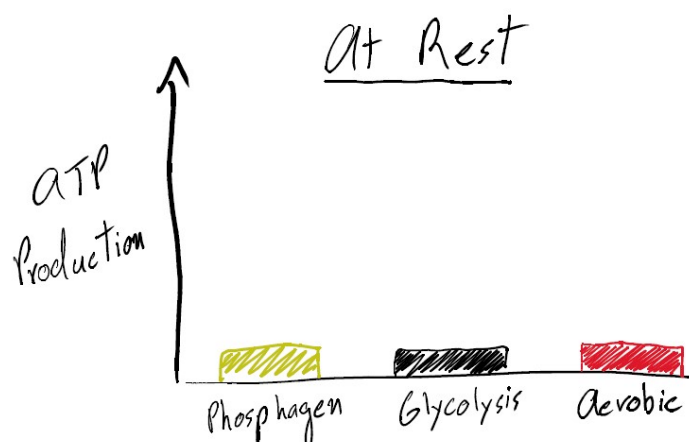
A swimmers ability to perform is mainly based on how well their mitochondria work. It takes a lot of yards to get these ATP factories up to scratch and we will talk more about how training physically

changes these energy systems for the better (BOS- II), but for now let us see how these systems work together during workout and different races.

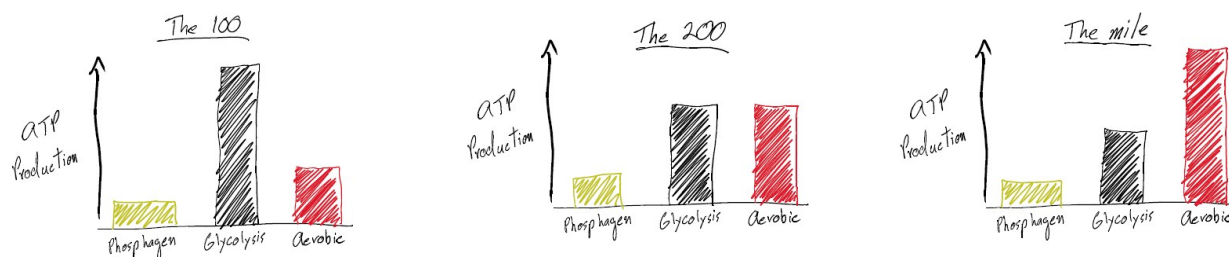
Tangent: Blood cells don't have mitochondria. They want to transport blood, not use it up.

The Race Chooses the Engine

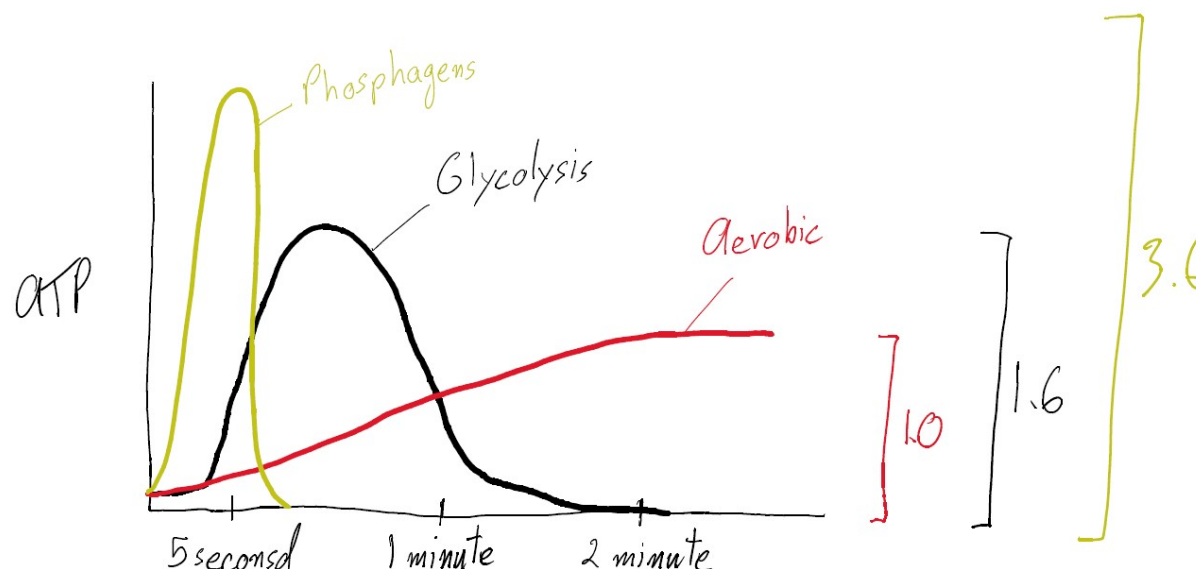
A big mistake would be to think of these three energy systems as separate and running one at a time. They are all turned on at the same time, all the time. Even now just sitting there reading this book your phosphagens, glycolysis and aerobic systems are working all together, if only at a minimal rate.



When you jump into the water for a race however, these systems rev up, just like a hybrid car's engines, except for the phosphagen system which doesn't change much because it is more of a bridge and storage battery for the other two systems. **The type of race you do determines how much of each engine the body revs up.** This is determined by the needs of the race.



If we made a ratio comparing the three energy system's maximum ability to regenerate ATP we would find a 1 to 1.6 to 3.6 ratio of aerobic to glycolysis to phosphagen system, respectively. This means that glycolysis makes 160% more ATP per minute than the aerobic system, and the phosphagen makes 360% more ATP than the aerobic system. It is also good to know that **each system takes a certain amount of time to reach that maximum ATP regenerating capability.**



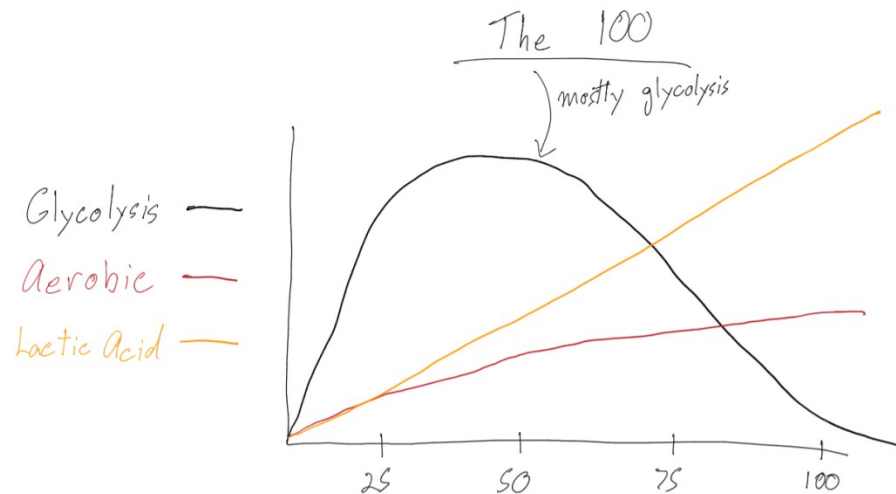
As you can see, the mitochondria take some time to get going, about 2 minutes of constant low level work. **That's one of the reasons for warm up!** Ever try to race a 200 free without warming up? What happens? You feel ok the first 50, but by the 150 your muscles are locking up, burning through the roof, and that last 50 turns into a struggle to survive. What happened was you never warmed up the aerobic system, so your body had to rely completely on glycolysis which makes a TON of lactic acid. In a race that is 2 minutes long, that's going to hurt...a lot.



What's the idea behind cool down? We will talk more in the Lactate Threshold chapter. For now, let's compare some races and see what happens inside your muscles cells. Also, let's assume you warmed up real good too.

The 100

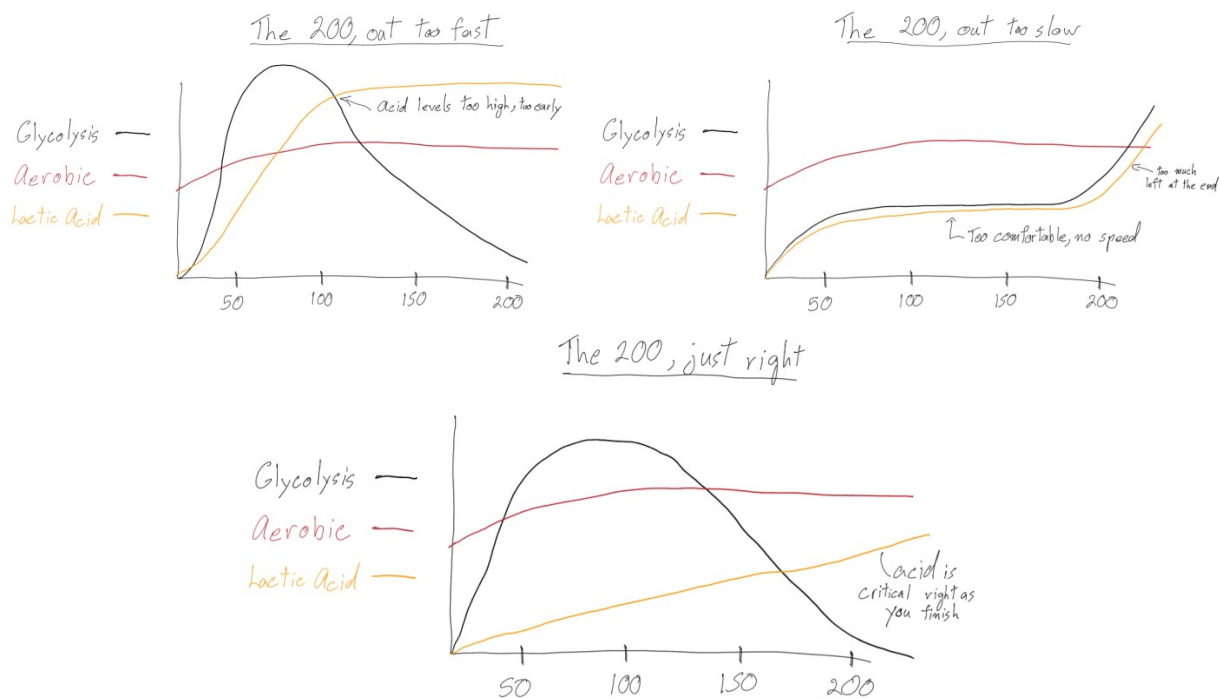
Phosphagens gets you off the blocks and you are going all out from the get go. The massive power requirements to sprint mean that **glycolysis is the main engine being used** in this race and at maximum capacity. By the first 25 you have used up all the available NAD^+ and glycolysis is about to shut down. But have no fear! At this point the newly made pyruvate is shunted away from the mitochondria and is used to produce lactate and regenerate the NAD^+ . Glycolysis continues this way until you reach the 75 mark. At this time, the lactic acid is building up to critical levels and has started to physically stop your muscles from functioning properly. This is why you slow down a little on the final 25 if you really have been going all out from the beginning.



Some pyruvate makes it to the mitochondria, but before aerobic engine fully kicks in, the race is over. **The only source of fuel for this race is sugar.** No fat, no protein, and no oxygen were burned during this race. If no oxygen was used, why are you breathing so hard? That's in the Lungs chapter, but the short answer is lactic acid basically makes more CO₂ which needs to be breathed out.

The 200

The balanced race. This race ends up getting **half the ATP from glycolysis and the other half from the aerobic system.** That's why it is so difficult to pace. Go out too fast and glycolysis will make too much lactic acid, shutting you down before the end of the race. Go out too slow and you will miss your opportunity to use the power of glycolysis to get ahead. If you do it just right, the amount of lactic acid will reach critical levels just as you are taking your last stroke. That means running glycolysis at just under maximum capacity, and running the aerobic engine at 100%.

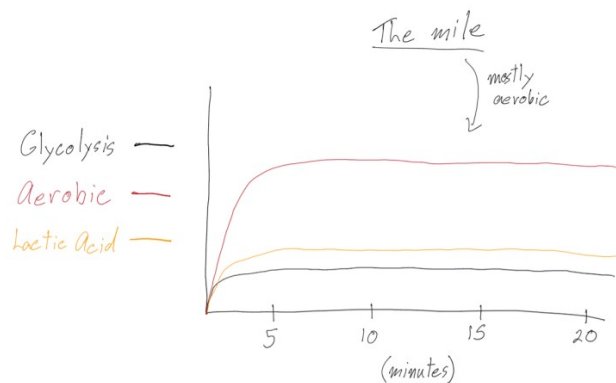


Again, the **main source of fuel here is sugar**. Fat burning may play a small role, but sugar will be the big player. Since we are using mitochondria to utilize oxygen, breathing in this race serves to both get rid of CO₂ made by lactic acid from glycolysis and to bring in oxygen for the aerobic system.

Because lactic acid and CO₂ go hand in hand, breathing out CO₂ is one of the ways the body deals with getting rid of lactic acid. That's why you need to breath early and often in a 200! The more you hold your breath, the faster the lactic acid will build up, and the sooner your body will end the race for you. We will touch on this again when we talk about Lungs.

The Mile

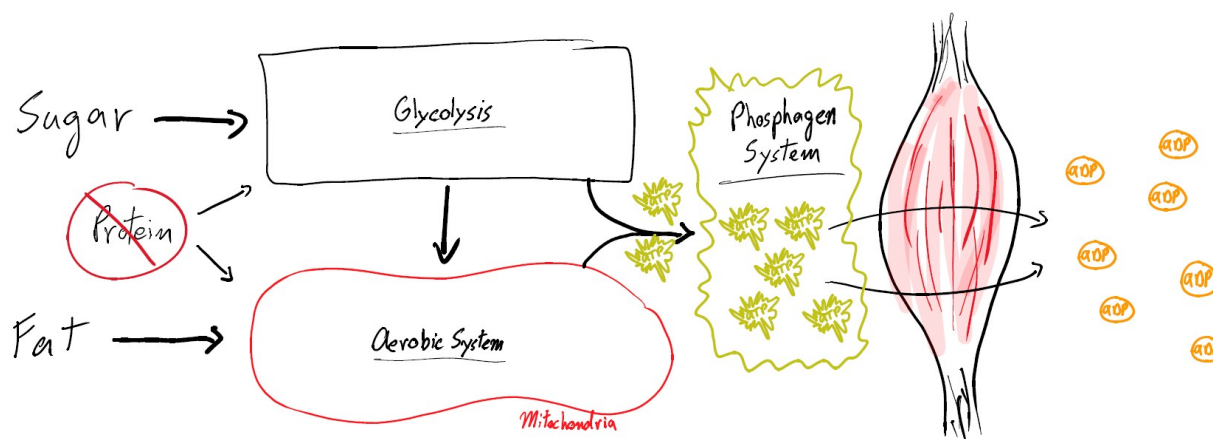
Excluding the end and beginning, **this race is mostly aerobic**. Sitting right on the Lactate Threshold (a whole chapter just for this) to get the most power for the least lactic acid. What this means is that there is a balance between making lactic acid (another way of saying using the glycolysis engine) and getting rid of it. **Because mitochondria don't make any acid at all and because this is a 15-20min race, it is the ideal source for regenerating ATP.**



Power for this race comes from the size and quality of the mitochondria, their ability to burn fat and sugar using oxygen and the supply of blood to the muscles (which we will talk about in the Cardio chapter). Here, you mainly breathe for O₂, and not to breath out CO₂.

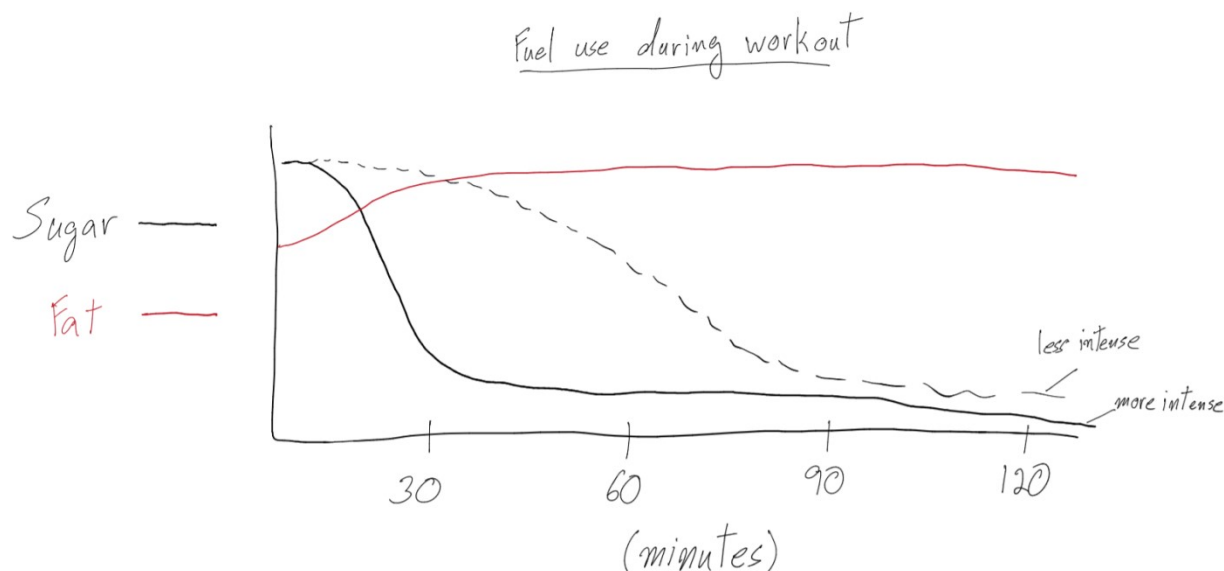
Fuel Supply for each Engine

Let's talk about what happens during a two hour workout. No matter what the work's focus is that day, sprinting or distance, the fact that you are training for more than about 40 minutes means you are using multiple sources of fuel to power both glycolysis and the aerobic system. **The two main sources of fuel in workout are sugar and fat.** Proteins are used...but it makes up such a small amount that it is generally ignored.



To complicate things further, it's not just what fuel you use that determines how you make ATP, but where that fuel comes from. **Sugar and fat stored inside the cell are almost immediately available** to be used in glycolysis and/or the aerobic system. **Sugar and fat that needs to be imported into the cell from the blood takes a longer path and can slow down the muscle's energy systems** by limiting how much fuel is available to burn.

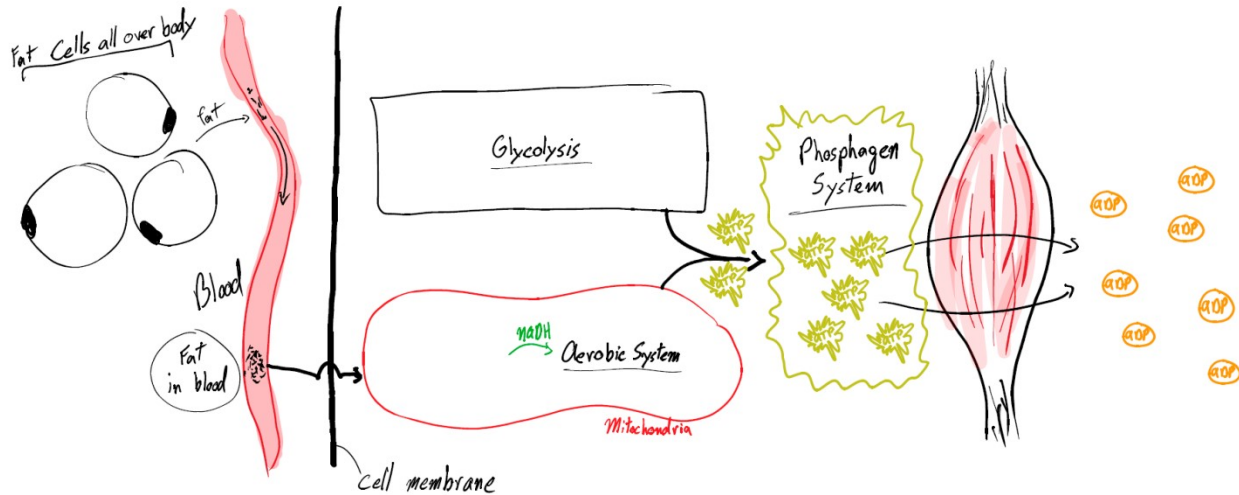
Why do you need to know this? Because the longer workout lasts, the more your muscle cells start to run out of fuel from inside the cell and begin to import it from the blood. This extra step dramatically reduces the amount of ATP that can be produced. This timing effect explains a lot about how you feel as a swimmer as workout goes on.



Notice what happens around 30-60 min into workout? The sugar inside the muscle cell runs out! This is why the water starts to get heavy after about 30 min of intense working out. At this point, the cell depends mostly on sugar from the blood and mitochondria burning fat to regenerate ATP. What this means is **at the beginning of workout you are mostly using glycolysis, but at the end of workout you will be relying mostly on mitochondria.**

Tangent: Carb loading is based on the idea of forcing your muscle cells to store more sugar inside them, allowing you to maintain glycolysis for a longer time. This is possible and it does work, but a real carb load actually takes about 10 days to perform and can triple the sugar levels in your cells!

Mitochondria can never match the ATP producing capacity of glycolysis, and that is why you feel so drained at the end of workout. **With no sugar left, you are now burning mostly fat to generate your ATP.** By this time, the fat fueling the mitochondria is coming from fat cells (called adipocytes, adipo= fat and cyte= cell). These fat cells are all over your body, and they all start secreting fat into the blood so your muscles can use them. Even in skinny people, there is basically an unlimited amount of fat to fuel muscles (about 30 days if you don't work out). And while you can't make much ATP per minute using fat, you can make it last for days on end, making it the major fuel source during long workouts, doubles, and hell week training.



*Tangent: So, will doing crunches burn the fat right above the muscle to give you a six pack?
Nope, it burns fat from everywhere, if at all. You're probably mostly burning sugar and using glycolysis anyway....making a lot of acid...that's why it burns!*

Swimmers need both a big, mean glycolytic machine and many well developed mitochondria to be fast in any race. How training develops these energy systems is the topic of multiple chapters to come, but for now I think we have talked about plenty.