

BAE 204: Introduction to Environmental and Ecological Engineering

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Preface

This is the first attempt at a textbook for BAE 204. It will be updated as class proceeds.

Chapter 1

Aerobic and anaerobic respiration

1.1 Generating energy: transfer of electrons

Us humans have the freedom to go about as we wish. All we need is to eat, drink, breath, and eliminate what we do not need. We could take our automobile cars as another example of bodies able to move about as long as they are fed some fuel. A lot of energy is realized from combustion of fuel or wood. In fact, provided that this energy be funneled into some very smart mechanical systems (e.g., combustion engines), and the energy power delivered is largely superior to any power any human could output. However, the energy consumed is also phenomenal and much of it is lost through heat. Life has found a way to be a lot more parsimonious with energy spending, which makes living organisms to be a lot more energy efficient than combustion in the long run: the *respiration* process.

But in both the cases of combustion or of respiration, energy is liberated or transferred to ATP, respectively, when **electrons are transferred** from an **electron donor** to an **electron acceptor**. Not surprisingly, life and its diversity as we know it, has been able to develop on our planet because primary producers have been able to transfer and store solar energy into a chemical energy, where electrons are effectively stored onto organic molecules, and, because dioxygen O₂, the most powerful electron acceptor, is freely floating in our atmosphere.

But, then if we ourselves are nothing but a lot of organic matter, therefore a very large source of electrons, and if we leave in an oxygenated environment, how come we are not going into combustion? Obviously this applies to all living organisms. Some of you might think that it is because of the water. But then why would not a very dry piece of paper, or leaves, not automatically catch on fire? The answer lays in two words: activation energy.

Electrons do not readily transfer from an electron donor to an electron acceptor because of the activation energy barrier which must be overcome. Activation energy is the level of energy necessary to be overcome for a reaction to carry on. On the figure below borrowed from Wikipedia, the energy difference between the peaks and the final energy level corresponds to the activation energy E_a

In normal conditions, this energy is preventing a reaction to proceed. This is why wood or most organic matter do not go into combustion or decomposition on their own. Nitroglycerin is notoriously unstable and the activation energy for electrons to be transferred to O₂ is very small, hence its propensity to explode and its danger. However, the activation energy can be overcome with enough heat brought near an electron donor in the form of a flame or a spark. Not much heat is necessary for natural gas (CH₄) for combustion to take place, i.e., for transfer of electrons from the carbon to oxygen, releasing twice the volume of gases:



hence the explosive nature of this reaction.

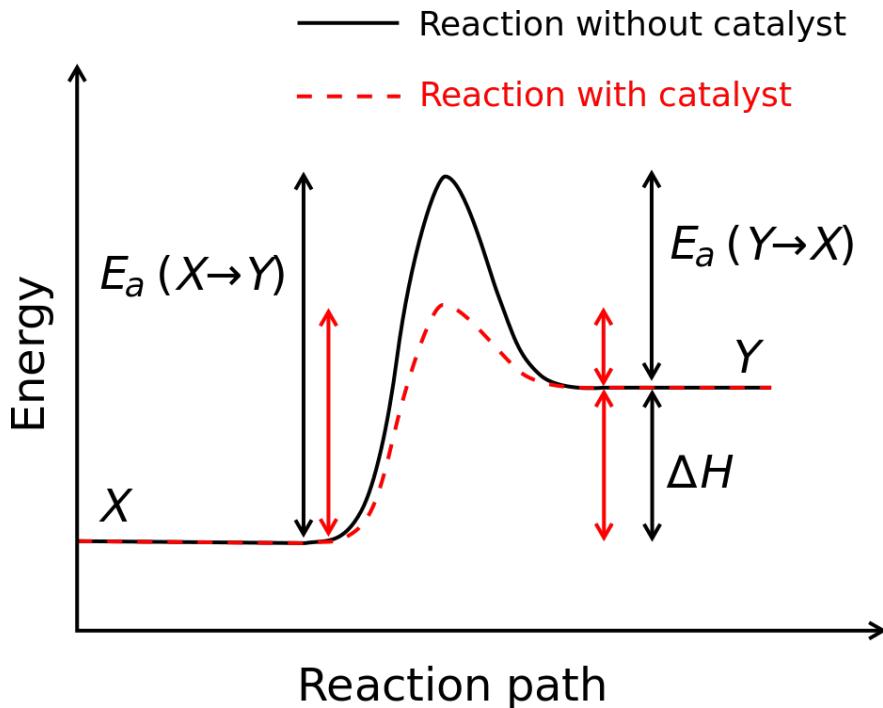


Figure 1.1: Activation Energy (E_a) needed for a reaction to proceed. (E_a) can be lowered thanks to a catalyst, and in the case of the respiration chain of living organisms, many of them. Figure borrowed from Wikipedia, Copyrighted free use, <https://commons.wikimedia.org/w/index.php?curid=779552>

1.2 Generating energy without combustion

Now because none of us and all the living organisms with us, *burn* to generate energy, there must be other systems to manage to liberate energy, and, there must be ways to have much lower activation energy. Life has found several mechanisms to optimize the transfer of energy from organic matter to the a magic molecule: ATP or Adenosine TriPhosphate.

1.3 ATP or the energy currency of the cell

There are many ways of transferring energy. To heat a house in the western world, we most often have a centralized heating (and sometimes cooling) system, where the heat is generated, e.g., in a furnace, and then transferred to the rest of the house via pipes and the like. The equivalent system might be for mammals the blood that gets re-oxygenated with the lungs, before it delivers oxygen throughout the body.

At the cellular level, however, ATP or Adenosine TriPhosphate is created throughout the cell near the equivalent of the little furnaces: mitochondria. Needless to say, there is no combustion with the mitochondria, and yet transfer of electrons and energy delivered. The energy is transferred from the organic matter to ATP, and ATP being a relatively small molecule, can easily reach all metabolic processes, usually operated by proteins, which need energy to proceed (to overcome the activation energy mentioned above).

The key to storing energy is in the bond between the phosphate, which are often referred to as high-energy bonds. High-energy phosphate bonds are pyrophosphate bonds, acid anhydride linkages formed by taking phosphoric acid derivatives and dehydrating them. As a consequence, the hydrolysis of these bonds is exergonic under physiological conditions, releasing energy. As ATP releases its energy by the break of the pyrophosphate bond, ATP thus becomes ADP (Adenosine Diphosphate) and releases a phosphate in the

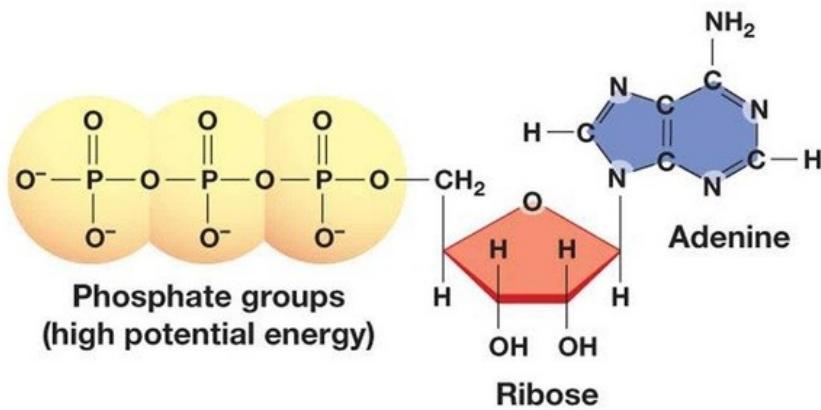


Figure 1.2: ATP molecular structure containing adenosine (= adenine + ribose) and the three phosphate linked together with a pyrophosphate energy rich bond. Copyright Pearson Benjamin Cummings

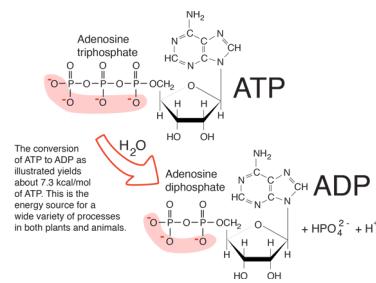


Figure 1.3: Release of energy ATP hydrolyzed into ADP. <http://hyperphysics.phy-astr.gsu.edu/hbase/Biology/atp.html>

meantime, like in figure 1.3. A common representation of this reaction is $ATP \Rightarrow ADP + P_i$ with the P_i referring to as a phosphate.

Now that we have allocated electrons on atoms and molecules, you easily understand that the number of electrons on the outside of the triplet $PO_3 - O - PO_2 - O - PO_2$ is huge. In his fantastic book, Degens (1989) suggests that

- because of the plethora of electrons on the triphosphate part of ATP,
- because the tetrahedral phosphate molecules are linked together by one of the corners of each tetrahedron (figure 1.4),
- and because of the π electron bonds (double bond) which tends to repulse each other (Degens, 1989),

the triphosphate molecule can only be in constant movement, which ‘maintains the animated world’ (Degens, 1989).

1.4 The ATP manufacture

If ATP freely releases energy for a reaction to proceed in the cell, as ATP becomes $ADP + P_i$, there must be energy at one point to ‘manufacture’ or recharge the ATP molecule in the first place. We have seen that much of the energy in the cell is transferred thanks to the ATP molecule. So could we just make ATP from

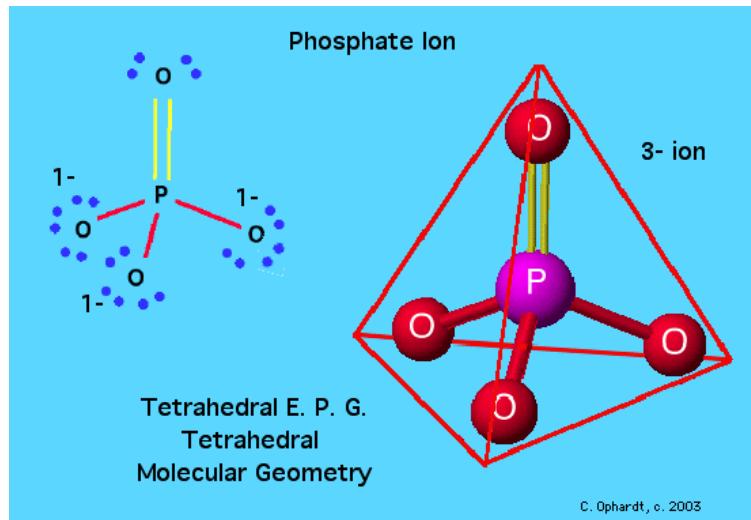


Figure 1.4: Tetrahedral configuration of each of the phosphate molecule which when linked together supposedly are in constant movement

the energy liberated by ATP??? The answer is no, obviously... The energy to create ATP has to come from elsewhere, otherwise it just cannot work....!!!

Life has found a wonderful way to do that thanks to proton flows. Yes, that is correct, a proton flow. ATP is literally formed from an ADP and a phosphate and assembled thanks to a protein called ATP synthase, or ATPase, which seems to be activated or powered almost mechanically, very much like a water mill, by a proton flow (Figure 1.5). The ‘head’ of the ATPase, which looks a bit like a ‘mushroom hat’, referred to as the F_O region, rotates as a result of the proton flow and allows the phosphorylation of ADP. It is thus fair to call the ATPase a ‘proton mill’. You may want to look at this very nice concise document on ATP synthase on Wikipedia, which provides more detailed information and shows quite nicely how the mechanical force of the H⁺ flow is thought to allow P_i to be attached to an ADP. This part of the energy recovery is referred to as **phosphorylation**.

So, this mechanical force is what generates the synthesis of ATP from ADP, or again **phosphorylation**. So this solves that part of the ATP synthesis. Now, another mechanism must be responsible for the formation of the proton flow.

1.5 Creating a proton gradient as a source of proton flow

Until now, I have not even mentioned where all this takes place. We are about to see where this happens. But first, let us take an analogy to better understand the proton flow responsible for the synthesis of ATP. Flow of matter just does not happen on its own, it only happens as a result of a **gradient** between a compartment and another. Using the water mill analogy, the reason why there is release of energy in the form of kinetic energy of the water is because there is a drop in elevation, and therefore in potential energy between the ‘compartments’ upstream and downstream the mill. To increase the hydraulic gradient, men throughout the world have built dams to create compartments and increase the hydraulic gradient between upstream and downstream the mill. So in the water mill analogy, the hydraulic gradient is maintained thanks to the dam which creates compartments, and to the continuous arrival of new water upstream and to the leaving of water downstream. So three things are necessary for the release of kinetic energy (which in the end is going to power the rotation of a mill wheel, and in the old days would grind wheat or corn grain):

- a system to compartmentalize water,
- a supply of water, and,

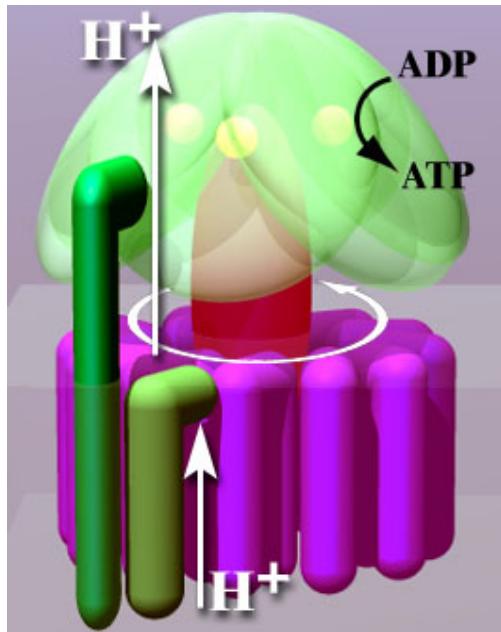


Figure 1.5: Artist representation of the ATP synthase powered, almost mechanically by proton flows. By The original uploader was Asw-hamburg at German Wikipedia - Transferred from de.wikipedia to Commons by Leyo using CommonsHelper., CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=8993938>

- an outlet for the water so that it does not accumulate.

By analogy, the formation of ATP corresponds to the grain grinding; the proton flow corresponds to the water flowing that activates the mill wheel, and in our case the proton flow activates the ATPase. We now need to address the three parts of the system needed to have a proton gradient and flow:

- a compartment system,
- a proton supply system, and,
- a system to use protons so the gradient is maintained.

1.5.1 A compartment to accumulate protons

We saw earlier that the double phospholipid layer made the cell membrane. Well if you close a membrane on itself you will make a compartment or a balloon. It turns out that if you look at a typical prokaryotic cell and at organelles in a eukaryotic cell (Figure 1.6), there are compartments formed between a cell wall and the plasma membrane for prokaryotic cells, and between two double layer phospholipid membranes for the eukaryotic cells. So in reality, it is a bit as if one were to create a space between two balloons.

At the end though, there exists for prokaryotic cells and mitochondria (and most organelles for eukaryotic cell) an inter-membrane space, which effectively creates compartments to accumulate ‘things’. The double phospholipid membrane is so strong and so tight that it is *proton-tight*. In other words, if somehow protons accumulate in this inter-membrane space, protons cannot leave through the membrane, they can only leave through designated areas. And yes, you guessed right, the designated area for protons to leave the inter-membrane space is the ATP synthase! So to take another analogy, you can imagine an inner tube full of air under pressure, air can only leave through the valve. And if you were to put a little fan in front of the valve as you are releasing air, the fan would rotate. Imagine that this is essentially what happens: the ATPase is both the valve and the fan as it literally rotates with the proton flow.

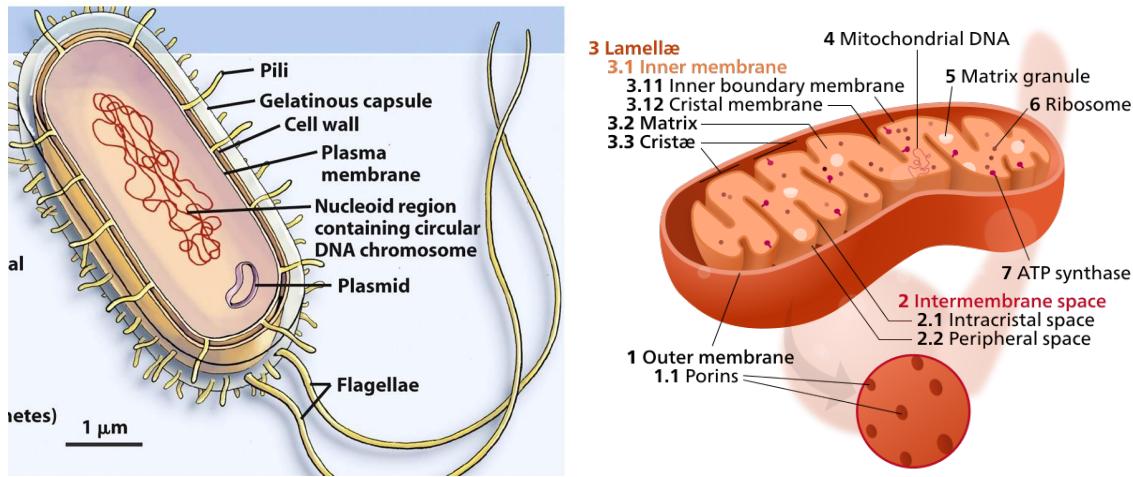


Figure 1.6: Artist representation of a prokaryotic cell and a mitochondrion from a eukaryotic cell showing the intermembrane spaces: between the cell wall and plasma membrane for the prokaryotic cell, and, between the outer and inner membranes for the mitochondrion. <https://micro.magnet.fsu.edu/cells/animals/animalmodel.html> and By Kelvinsong - Own work, CC0, <https://commons.wikimedia.org/w/index.php?curid=27715320>

1.5.2 A supply of protons for the intermembrane space: proton pumps

Now, the next natural question is that in the case of an inner tube, somebody pumped some air into the tube to put it under pressure. Similarly, there must be a system that pumps protons into the inter-membrane space. And yes indeed, you guessed it right, there are proton pumps that do the job. But again, these pumps must be powered by some sort of energy.

Let us pause for a second. We have seen in section 1.1 that generally speaking, energy is generated from the transfer of electrons. But until now, we have not even mentioned electrons: only ATP and protons...? This is where electrons come in: **energetic electrons transported onto electron transfer molecules are the ones that power the proton pumps!** It is time to take a bird's eye view again. Energy liberation exists when electrons are transferred from an electron donor to an electron acceptor. Life has found a way to capture this energy in the form of ATP, which allows transportation of energy to the needed places in the cell. So the energy transfer in the cell does not have to be totally instantaneous like combustion would be, and it can be spent exactly where it needs to be spent.

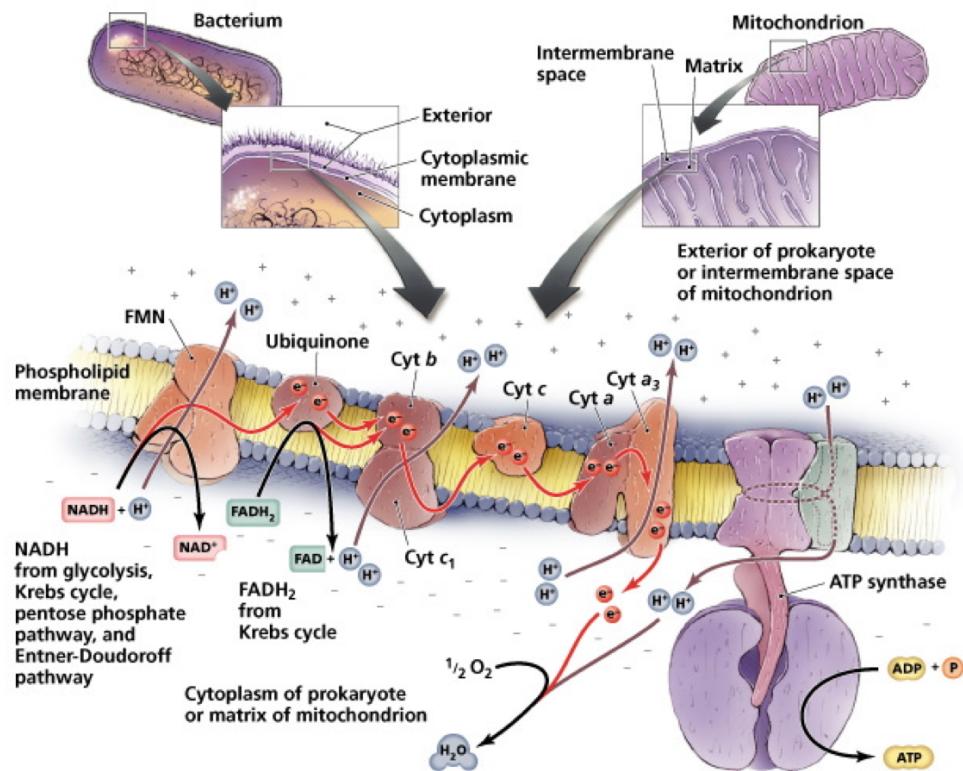
Yet, the production of ATP is in fact generated by an electron transfer, but indirectly.

- No, electrons are **NOT** transferred from organic matter to ATP.
- Yes, electrons are *ultimately* transferred from organic matter to an electron acceptor, which in the case of aerobic respiration is O_2 .

But just like the generation of ATP is indirectly linked to the electron transfer, the transfer of electrons from organic matter to the ultimate electron acceptor is also indirect. A set of molecules called **electron transfer molecules** are intermediate carrier of electrons and are the ones which power the proton pumps as represented in figure 1.7 below.

1.5.3 Electron transfer molecules that power the proton pumps

The two main electron transfer molecules in the respiration process are called NAD (Nicotinamide Adenine Dinucleotide; figure 1.8) and FAD (flavine adenine dinucleotide; figure 1.9). These two nucleotides have the



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Figure 1.7: Artist representation of the ATP synthesis powered by a proton flow, itself powered by a proton gradient, itself produced thanks to proton pumps powered by energy rich electrons carried by electron transfer molecules. Obtained from 2006 Pearson Education

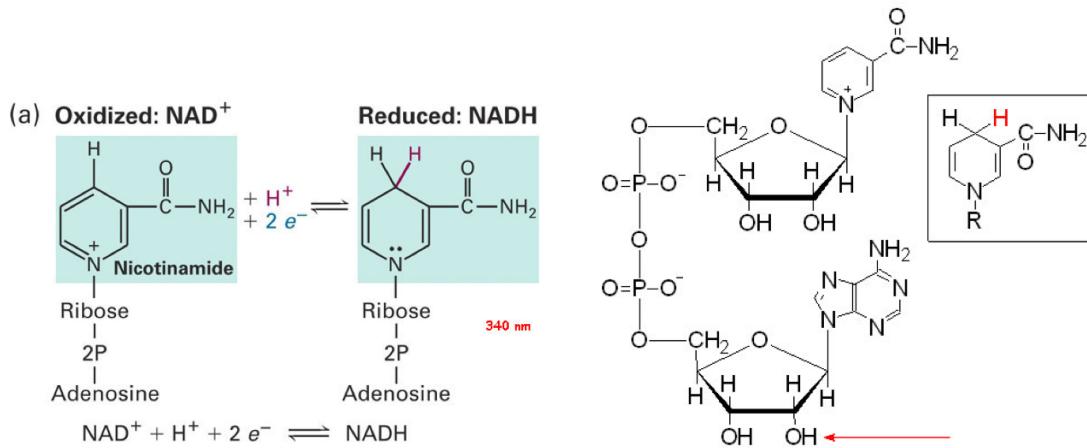


Figure 1.8: Molecular formula of Nicotinamide Adenine Dinucleotide (NAD) in both oxidized and reduced states

ability to be reduced (= gain electrons) and oxidized (= lose electrons), and because they are mobile, to carry electrons from the cell (bacteria) or mitochondrion (eukaryot) cytoplasm to the proton pumps.

1.6 Transfer of electrons from the Organic Carbon to an electron acceptor

So this answers the question of how the proton pumps are powered, but it is now time to look at the global fate of electrons: where do they come from and where do they end up? Actually, we already know the global answers to these questions: the electrons are stored unto the C, N, and S of organic molecules and they are eventually accepted by an electron acceptor; in the case of aerobic respiration, O_2 is the ultimate electron acceptor.

Before there might be any confusion, in the aerobic respiration process that involves organic molecules as electron donors (we will see that inorganic molecules can also be electron donors), strangely enough, the only atom which donates electron is **carbon** while the nitrogen and sulfur atoms keep all their eight electrons. Specialized microbes, called *lithotrophs*, literally ‘feed on stone’, which means that their source of electron is from an inorganic molecule, have the ability to use ammonium and hydrogen sulfide as electron donor (8 electrons available for ‘donation’) in their aerobic respiration chains. So all this to say that in aerobic respiration that involves organic matter, **only** the carbon atom donates its electrons. The organisms which use organic matter as electron donors are called *organotrophs*. We, as mammals and humans, are *organotrophs*.

1.6.1 Oxygen reduction

Let us start from the end of the process: the reduction of oxygen into H_2O , as represented on figure 1.7 above. As the NAD and FAD are powering proton pumps (which names include FMN, ubiquinone, cytochrome a, b, and c see figure 1.7), the electrons lose some of their energy and migrate within the phospholipid membrane from the proton pumps towards the ATPase. Because of the involvement of many different proteins involved in this transport, this is referred to as the **electron transfer chain**. Because the NAD and the FAD molecules are oxidized (they have given up their electrons), and because at the ATPase location, ADP gains a phosphate to become ATP, the whole process is referred to as **oxidative phosphorylation**. At the confluence between the ATPase and the cytochrome a_3 , the reaction (1.2) occurs:

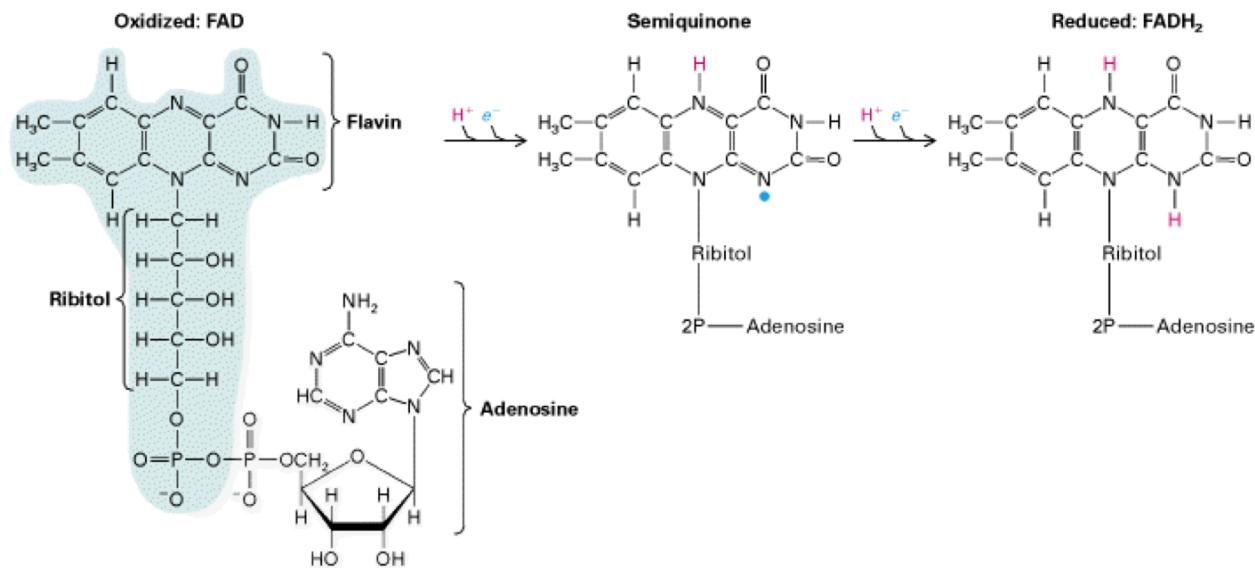


Figure 1.9: Molecular formula of Flavine Adenine Dinucleotide (FAD) in both oxidized and reduced states



This is the place where the electrons are accepted!!! So now you know exactly where all this is happening! Is not that wonderful? So the electrons are accepted by O_2 (remember on a molecule of O_2 , each Oxygen atom only has 6 electrons for itself, so each can accept two more), and these electrons reduce oxygen into H_2O . This has several consequences:

- the reduction of O_2 also consumes $4 H^+$, which solves the necessity for an outlet for protons as they flow out of the inter-membrane through the ATPase, which was the third condition to maintain a proton gradient
- the reduction of O_2 obviously consumes electrons, which also provides an outlet for the electrons. In other words, if no electron acceptors are available, then the electrons at the proton pumps have no outlet, so the proton pumps are stalled, which in turn halts the maintaining of a proton gradient, which eventually stops the production of ATP.

1.6.2 Electron fate from organic matter to electron transfer molecules

The fate of electrons from organic matter or glucose to the electron transfer molecules involves two processes called glycolysis and the Krebs or citric acid cycle. Biology majors have to learn in details all the steps and the name of the molecules involved in these chain reactions. This is beside our point for our class. Instead I want you to understand and know that these reactions involve

- transfer of electrons from organic carbon onto electron transfer molecules
- the release of carbon atoms which have lost all their electrons, therefore releasing C in the form of CO_2 .
- the hydrolysis of glucose molecules to pyruvate, a C3 molecule (a 3 carbon organic molecule) during the glycolysis, which then loses CO_2 as it enters the citric cycle
- the acetyl-coA, a co-enzyme is key to incorporate organic carbon in the Krebs cycle.

In figure 1.10 below which summarizes all the aerobic respiration pathways, you can see that most of the ATP is formed thanks to the proton flow, and that electron transfer molecules are involved in all steps.

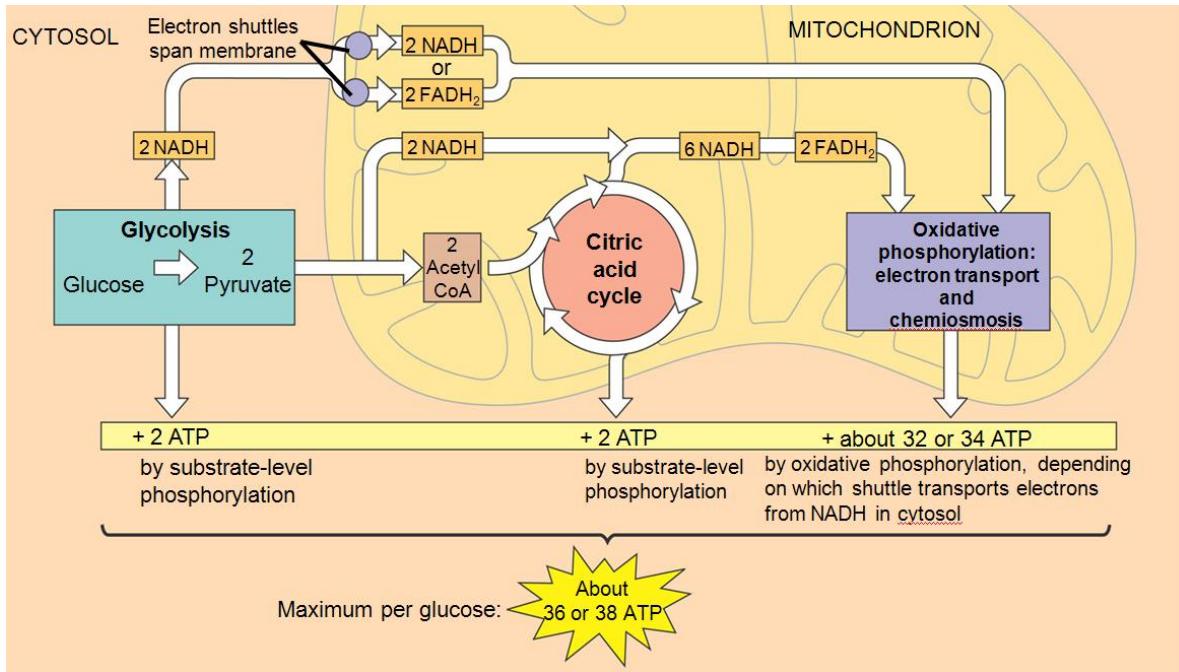


Figure 1.10: Summary of cellular respiration with the ATP and electron transfer budget. Obtained from <https://cdn.thinglink.me/api/image/847806852426104839/1240/10/scaletowidth>

This 1.10 diagram does not show where the CO₂ are produced so I invite to see, in addition to the notes given in class, that CO₂ is released as pyruvic acid enters in the figures 1.12 and 1.11 below.

1.7 Summary of respiration

We have purposely presented the molecular processes of respiration starting from the end and moving back to the beginning of the respiration chain. We can summarize the respiration process again in that order:

- the goal of respiration is to transfer energy initially stored as high energy electrons on organic molecules to ATP, the energy currency of the cell
- The production of ATP itself has to come from a different source of energy than that liberated by ATP itself
- ATP is synthesized by the phosphorylation of ADP by the ATP synthase, itself powered by a proton flow from the inter-membrane space to the cytoplasm space
- the proton flow is powered by a proton gradient between the inter-membrane space and the cytoplasm space
- This gradient is made possible thanks to
 - a proton-tight compartment corresponding to the inter-membrane space
 - a supply of protons from the cytoplasm to the inter-membrane space, fed by proton pumps
 - an outlet for the protons flowing out and powering the ATPase ('the proton mill'), which combined with the reduction of oxygen form water molecules
- The proton pumps are themselves powered by the oxidation of electron transfer molecules (NAD and FAD), which carry high energy electrons from the Krebs or citric cycle to the electron transfer chain
- The electron transfer molecules accept the electrons, or are reduced during glycolysis, before and during the Krebs cycle as organic carbon are oxidized or lose their electrons and release CO₂.

The other way to present respiration is to say that:

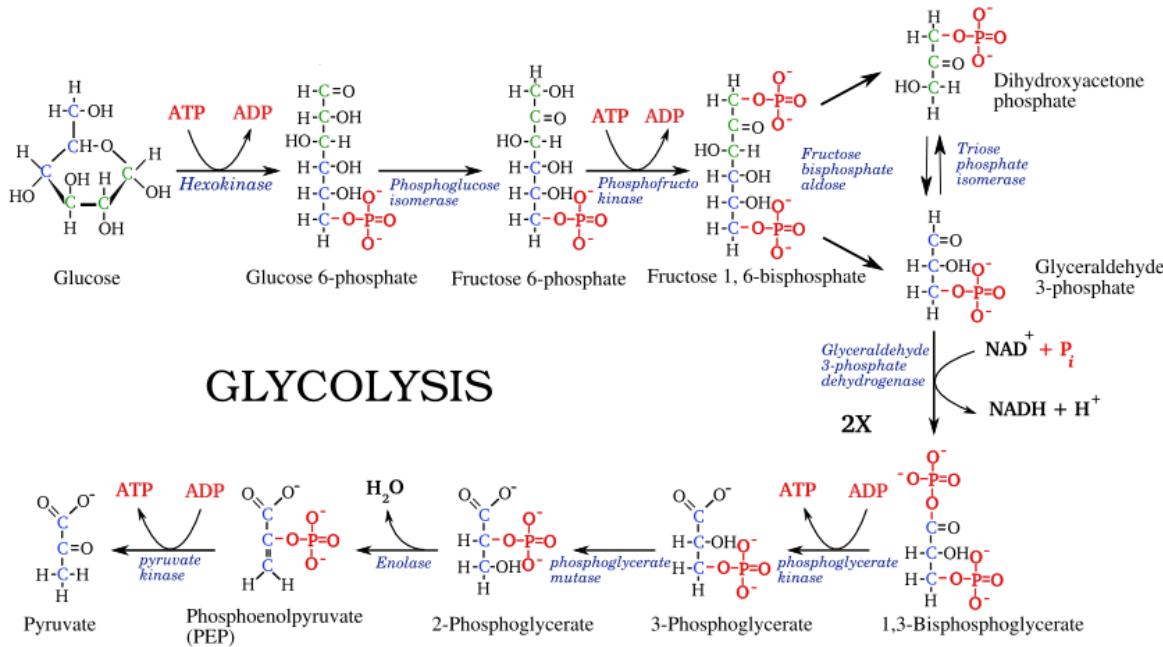


Figure 1.11: Glycolysis pathway. Image

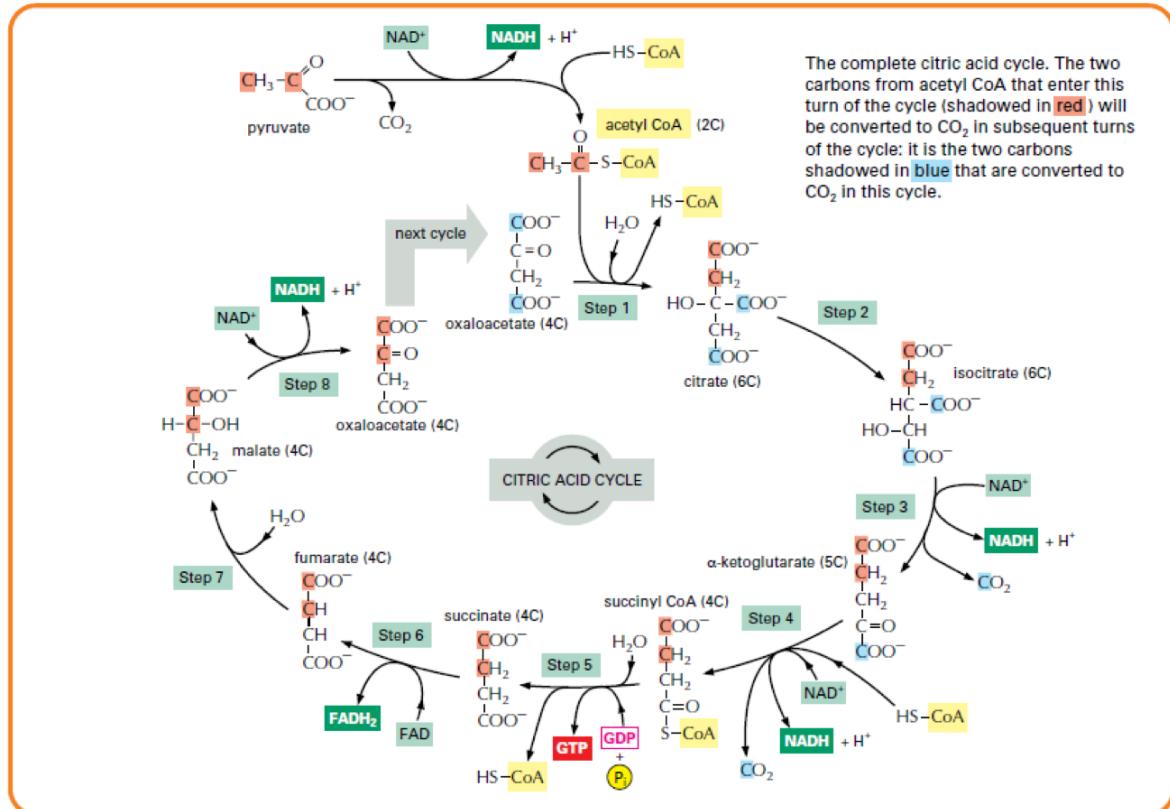


Figure 1.12: Krebs or citric acid cycle pathway.

- Energy rich electrons stored on organic molecules are transferred onto electron transfer molecules during glycolysis, before and during the Krebs cycle
- The high energy electrons thus transported power proton pumps placed in the inner membrane of the cell for unicellular organisms or of the mitochondrion for eukaryotic cells
- These pumps feed a supply of protons to the inter-membrane space which, because this space is proton-tight, and because protons outlets are limited to the ATP synthase, creates an accumulation of protons in this space
- The accumulation of protons creates a proton gradient between the inter-membrane space and the cytoplasm, which generates a proton flow at designated ‘holes’ in the membrane
- The protons flow out the inter-membrane through the ATP synthase which can be approximated by proton canals and almost mechanically turn the ATPase head which acts as a ‘proton mill’
- This proton mill catalyzes the phosphorylation of ADP into ATP
- The proton gradient is maintained possible because the protons flowing out of the inter-membrane space are combined with electrons reducing oxygen into water
- The electron flow is maintained thanks to the same oxygen reduction, which in turns allows electron transfer molecules to be oxidized so that then can take their ‘proton load’ again.
- Overall respiration consists in transferring high energy electrons from organic molecules to oxygen, and by doing so creating a proton gradient which in turn is the main driver for the formation of ATP in the cell.

Both summaries present the same story but have their own logic. Other important subtleties of respiration include:

- In the case organic molecules are the source of electrons, only the carbon atom donates electrons, the amine and thiol radicals being eliminated as a by-product DO NOT donate their electrons in this respiration system. This is admittedly a bit weird as the the amine and thiol groups still have 8 electrons to donate each.

1.8 Respiration electron flow schemes

1.8.1 Linkages between respiration and microbial processes

These few paragraphs and pages were necessary but we now need to connect them with some of the practical consequences that concern ecological engineering.

- The electron donors are the fuel for all microbial processes involved in the substrate of ‘treatment systems’.
- The byproduct of the loss of electrons originally stored on the electron donor will be a source of inorganic molecules that matter
- When the electron acceptor is O_2 , this results in an oxygen demand which may have consequences on the overall oxygen level and may lead to anaerobic conditions, where other electron acceptors come in play
- We try to take advantage of the anaerobic conditions to dissipate or strip excess nutrients, e.g. NO_3^-

1.8.2 Respiration schemes

So we thought we could provide a nice concise summary of respiration to highlight the points that matter for environmental and microbial considerations in the form of *respiration schemes*, still maintaining some of the important drivers of the formation of ATP. In the first respiration scheme in Figure 1.13 below, the transfer of electrons is represented by the *blue wavy line*. Electrons are transferred from an electron donor to an electron acceptor. The consequences of the transfer are represented in *thicker light blue arrows*. The first consequence of the transfer of electrons is the powering of proton pumps, which in turn create a proton gradient in the intermembrane space, which result into proton flow, which gives the necessary energy to

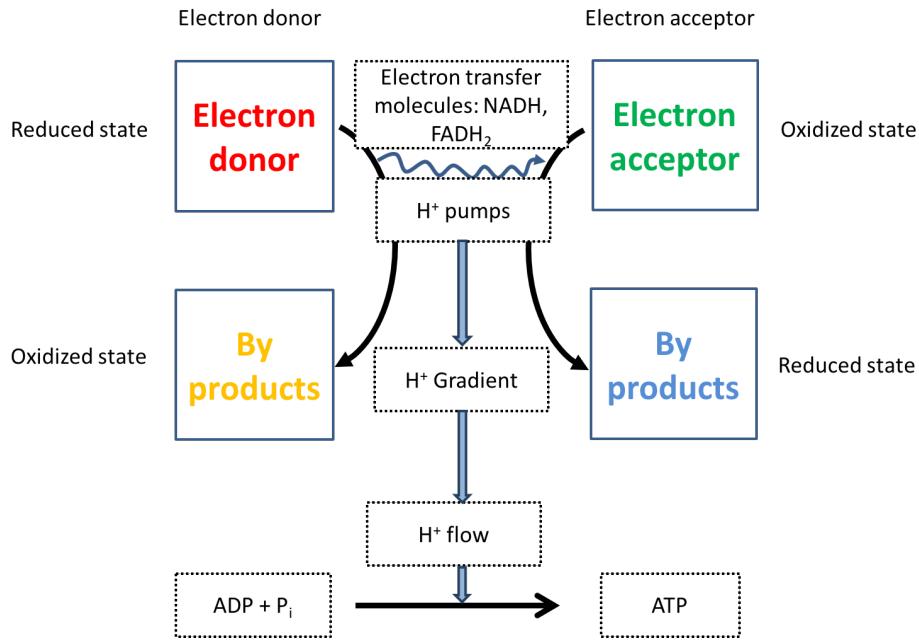


Figure 1.13: Generic respiration scheme illustrating the flow of electrons from an electron donor to an electron acceptor, the by-products of the respective oxidation and reduction, and the consequences on proton gradients and flow, which ultimately help catalyse the formation of ATP

catalyze the phosphorylation of ADP into ATP. The products of oxidation, reduction, and phosphorylation are represented in black arrows.

The respiration scheme is obviously an oversimplified representation of what happens as described above, but generally holds true. Some ATP are generated during glycolysis and in association with the Krebs cycle, but represent 4 out of a total of 38, or about 10% of the total. So it is probably fair to simplify things to represent the majority of the processes (here 90%). The beauty of this scheme is that it applies to just about all types of electron donors and acceptors.

In the next scheme, we take the example of aerobic respiration, where glucose is considered as the electron donor, and O₂ the electron acceptor. In this case (Figure 1.14), the by-products of glucose as the carbon loses all its electrons becomes CO₂. Water has also been added here, although technically in this very example all the Hydrogen atoms on glucose end up on the oxygen atoms originally from the O₂ molecule. But for more complex molecules, there always will be some H₂O molecules produced in the process, hence the addition here.

The third scheme (Figure 1.15), the generic term organic matter is used to show that in reality, not only glucose can be part of the electron transfer chain, but essentially all types of organic molecules, as represented in Figure 1.16. So the only difference with the previous scheme with glucose only, are the by-products of the catabolism of organic matter: CO₂, H₂O, NH₄⁺, HS⁻, and PO₄³⁻.

The important thing to notice here is that the N and S atoms, which possess 8 electrons for themselves, or are fully reduced, in organic molecules, stay reduced as byproducts of the respiration. This is odd as mentioned before, because there are electrons available for another oxidation. Lithotroph micro-organisms are specialized in taking advantage of these available electrons, as we shall see later.

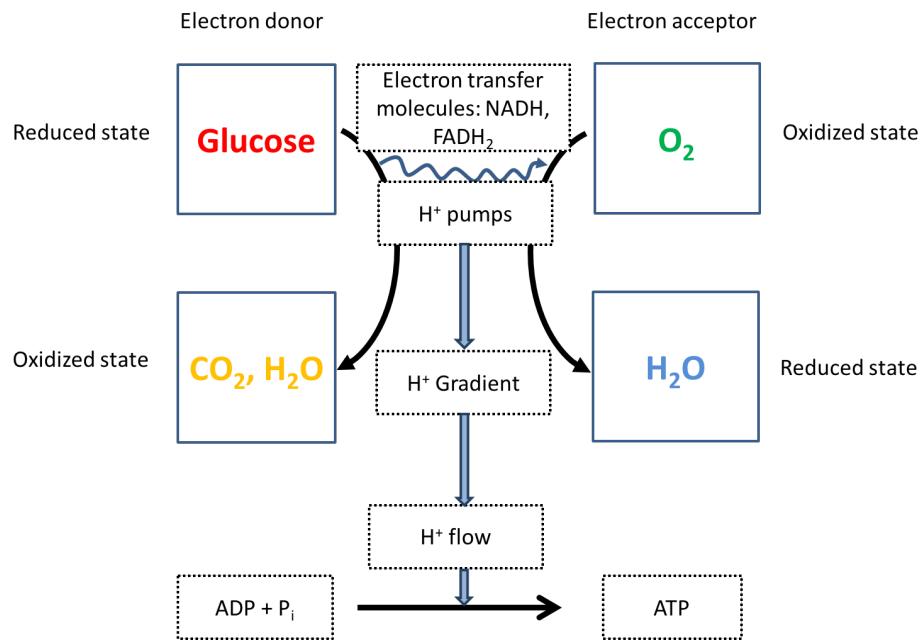


Figure 1.14: Aerobic respiration scheme illustrating the flow of electrons from glucose to O_2 , the by-products of the respective oxidation and reduction being CO_2 and H_2O , and H_2O . The consequences of the transfer of electrons on proton pumps, gradients and flow, which ultimately help catalyse the formation of ATP, do not change from the generic respiration scheme above

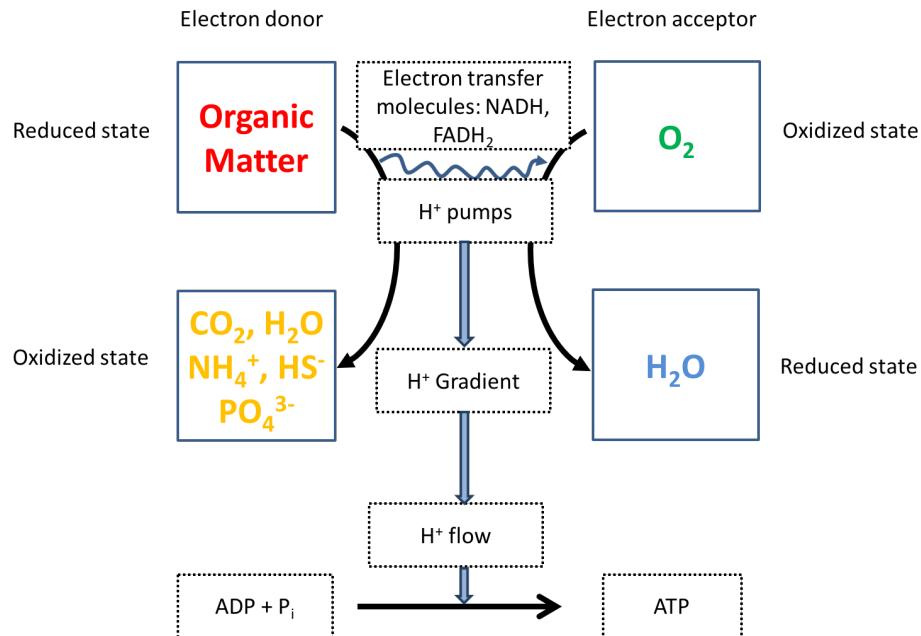


Figure 1.15: Aerobic respiration scheme illustrating the flow of electrons from organic matter to O_2 , the by-products of the oxidation of OM include ammonium, hydrogen sulfide and phosphate this time

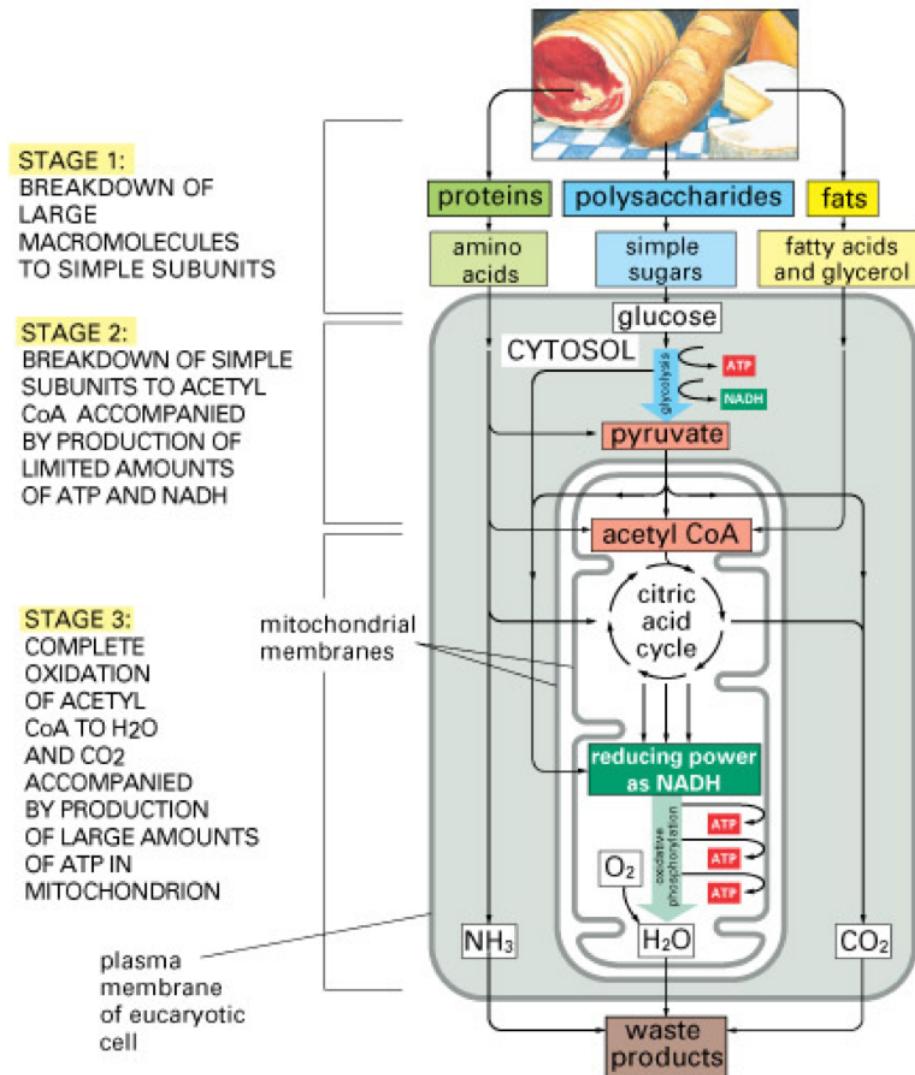


Figure 1.16: Oxidative phosphorylation of organic molecules of carbohydrates but of other molecular families as well. Figure obtained from Essential Cell Biology from Garland Science

Chapter 2

BAE 204 Glossary

This glossary is meant to assemble terms that we routinely use in Environmental Sciences and Engineering and which are expected to be mastered by students taking BAE 204 at NC State university. They are ordered in alphabetical list for better retrieval and look up.

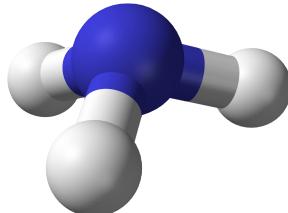
2.1 A

2.1.1 Aerobic respiration

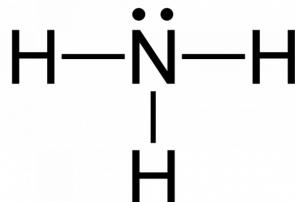
2.1.2 Anaerobic respiration

2.1.3 Ammonia

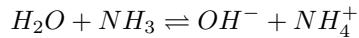
- Ammonia is a colorless gas with a characteristic pungent smell
- Formula: NH_3



- Ammonia 3D shape:

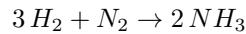


- Lewis dot structure:
- Number of electron N has for itself following electronegativity rule: eight
- NH_3 can only be an **electron donor**
- Because N has so many electrons to be potentially donated, ammonia is generally unstable in an aerobic environment. As a result, it tends to trace quantities in nature
- When dissolved in water, and depending on the pH of the solution, ammonia converts to ammonium following the reaction:



- Production:

- Because of its many uses, ammonia is one of the most highly produced inorganic chemicals. Dozens of chemical plants worldwide produce ammonia. Consuming more than 1% of all man-made power, ammonia production is a significant component of the world energy budget.
- In 2014, about 88% of the ammonia produced was used for fertilizing agricultural crops
- Modern ammonia-producing plants generally depend on the Haber-Bosch process which consists into reducing dinitrogen into ammonia



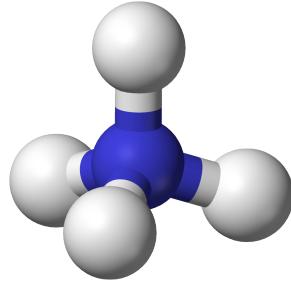
- Consumption:

- Ammonia is directly or indirectly the precursor to most nitrogen-containing compounds. Virtually all synthetic nitrogen compounds are derived from ammonia.
-

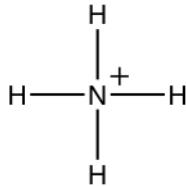
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2.1.4 Ammonium

- Ammonium is the most reduced inorganic nitrogenous cation (positively charged).



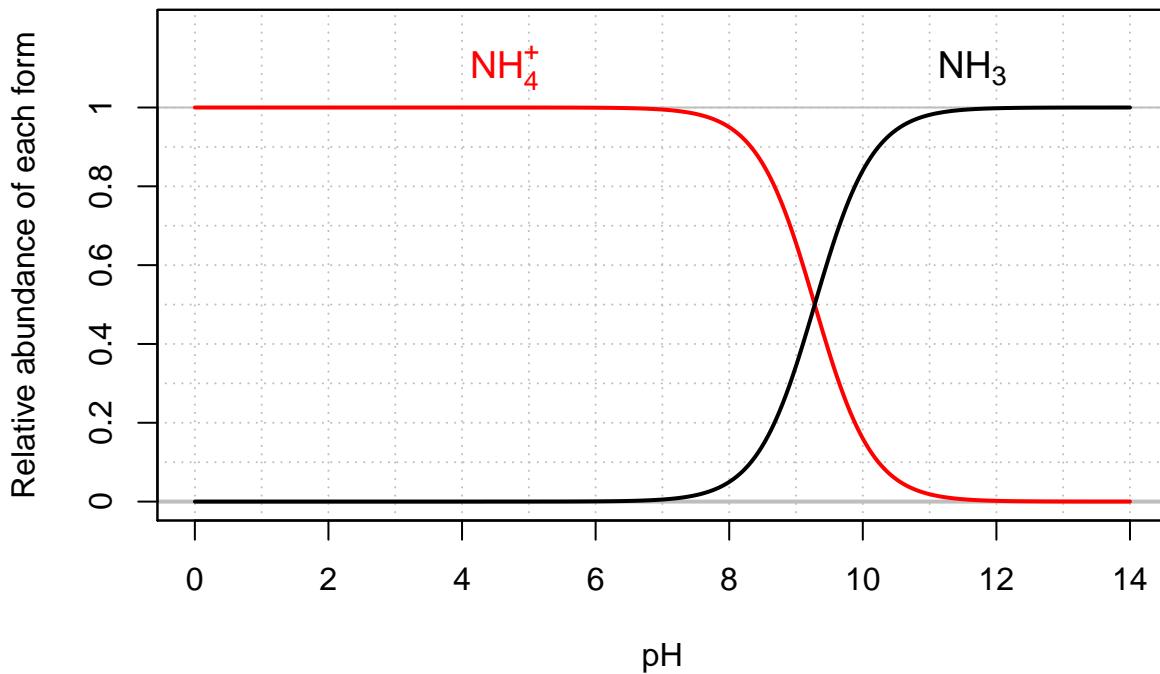
- Ammonium 3D shape:



- Lewis dot structure:
- Number of electron N has for itself following electronegativity rule: eight
- It is formed by the protonation of ammonia following the reaction:



- The relative abundance of ammonium vs ammonia depends on the pH of the solution. See figure below

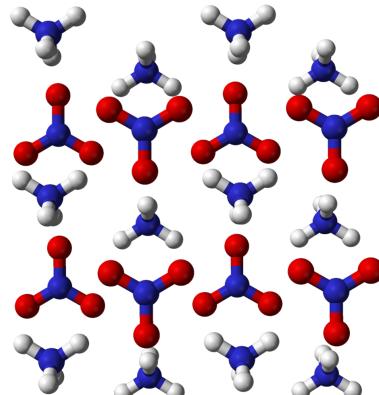


- Because in most natural aqueous environments, pH is below 8, ammonium tends to be the preponderant form.
- Production:
 - In nature, ammonium is a waste product of the mineralization of organic molecules
 - It is added as fertilizer on soils as ammonium nitrate
- Health hazard:
 - Ammonia vapor has a sharp, irritating, pungent odor that acts as a warning of potentially dangerous exposure
 - Exposure to very high concentrations of gaseous ammonia can result in lung damage and death
- Drinking water standard:

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2.1.5 Ammonium nitrate

- Ammonium nitrate is a chemical compound, the nitrate salt of the ammonium cation
- It is a white crystal solid and is highly soluble in water.
- Formula: NH_4NO_3



- 3D shape:
- It is predominantly used in agriculture as a high-nitrogen fertilizer
- Its other major use is as a component of explosive mixtures used in mining, quarrying, and civil construction
- Production:
 - Ammonium nitrate does exist naturally in mines of the Atacama desert in Chile but globally nearly all ammonium nitrate is now produced synthetically
 - Byproduct of all respiration processes. Ammonium ions are a waste product of the metabolism of animals. In fish and aquatic invertebrates, it is excreted directly into the water. In mammals, sharks, and amphibians, it is converted in the urea cycle to urea, because urea is less toxic and can be stored more efficiently. In birds, reptiles, and terrestrial snails, metabolic ammonium is converted into uric acid, which is solid and can therefore be excreted with minimal water loss.
- Consumption/utilization:
 - It is used as a fertilizer, because it tends to release inorganic nitrogen slowly in soil. Applied as a surface fertilizer, it penetrates the soil with rainfall infiltration. Highly soluble, the nitrate anion becomes readily available to plant roots, although it is susceptible to leaching below the root system into the shallow and deep groundwater. The ammonium cation tends to adsorb to soil particles and is thus not as susceptible to leaching. Ammonium can be directly taken up by plant roots, which thermodynamically makes sense, although because in most soils aerobic conditions are preponderant, nitrate tends to be the ion taken up most often. Soil bacteria in the aerobic zone of the soil will oxidize adsorbed ammonium into nitrate, which then becomes available for plant roots. The whole chain of events slows the release of inorganic nitrogen to crops and thus makes for more effective fertilizers.
- Health hazard
 - No direct known health hazard

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2.1.6 Anoxic waters

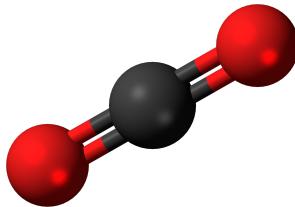
- Anoxic waters are areas of sea water, fresh water, or groundwater that are depleted of dissolved oxygen and are a more severe condition of hypoxia (Wikipedia)
- Anoxic waters result from an **IMBALANCE** between oxygen supply and demand

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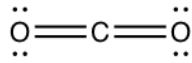
2.2 C

2.2.1 Carbon dioxide

- Carbon dioxide is a colorless gas which density is 50% higher than that of dry air.
- Formula: CO_2



- Carbon dioxide 3D shape:



- Lewis dot structure:
- Number of electron C has for itself following electronegativity rule: zero
- CO_2 can only be an electron acceptor
- Production:
 - oxidation of C in all organic molecules
 - Almost all respiratory processes on earth (some respiration does not involve oxidation of C)
 - Combustion of all Carbon-based fuel
- Consumption:
 - Photosynthesis
 - * Atmospheric carbon dioxide is **the primary carbon source for life on Earth**
 - Calcite precipitation in the oceans
- Ecological Significance:
 - Greenhouse Gas, which serves as reference for all other GHG
 - Concentration in the atmosphere ~380 ppm on the rise, or 0.38%, or a partial pressure of 0.38 atm

concentrations of carbon dioxide in the atmosphere from hundreds of thousands of years ago through 2015, measured in parts per million (ppm). The data come from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source (EPA, 2016)

- In reality, concentrations are not stable, and vary widely in time and in space at the next two videos nicely show.
- The next one results from the model simulations

Youtube video of CO_2 modeled seasonal variations

- The following one is the combination of both models and observations

Youtube video of CO_2 modeled and observed seasonal variations

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2.2.2 Carbonates

- After carbon dioxide dissolves in water, it will combine with water to form carbonic acid (H_2CO_3).

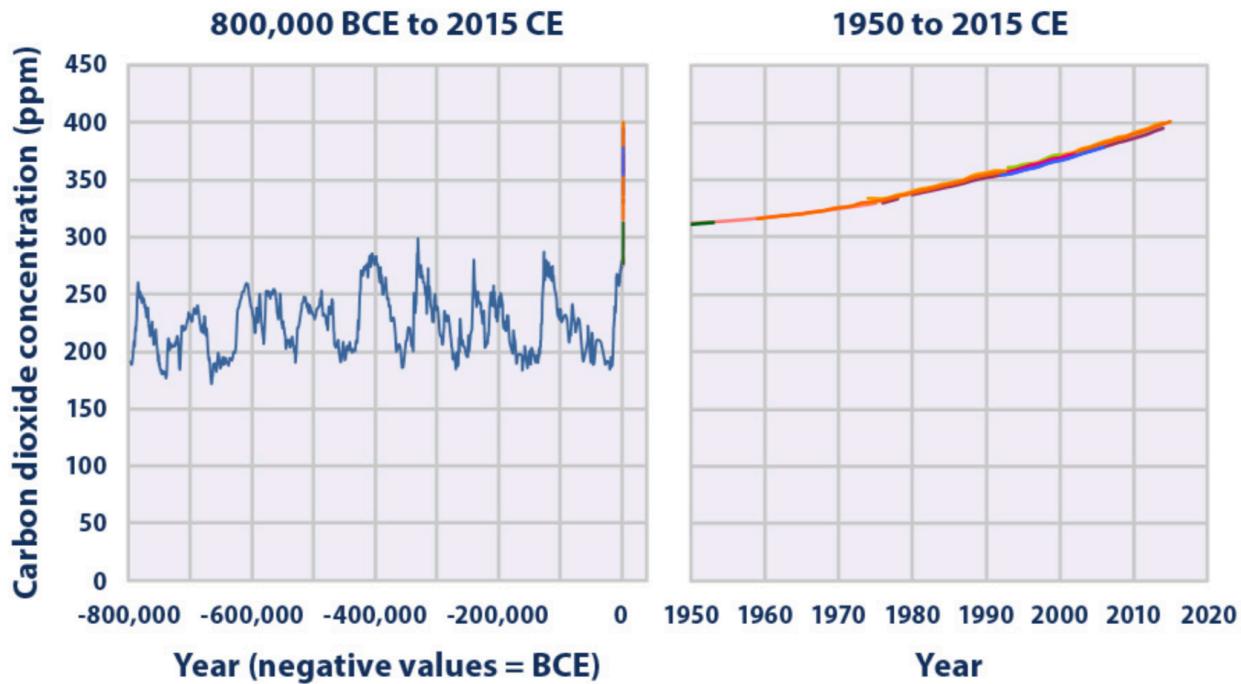
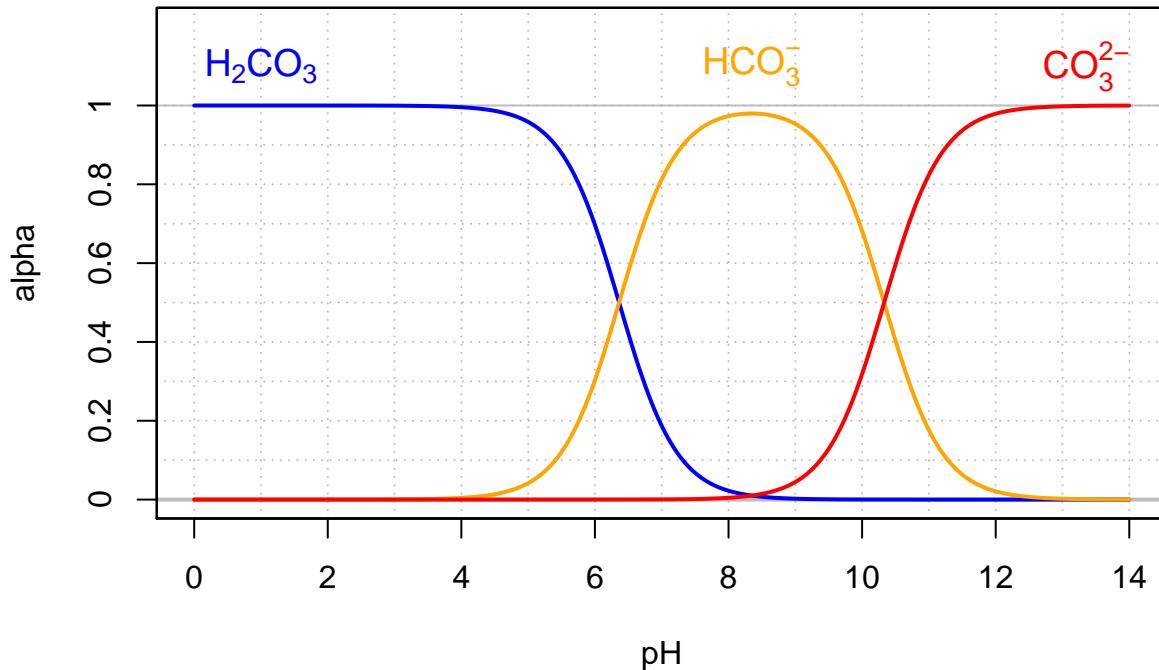


Figure 2.1: Carbon Dioxide variations through ancient and modern times

- Carbonate serves as **the carbon source** for aquatic vegetation
- Carbonic acid can then dissociate into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-})



- In an environment not open to the atmosphere (or where direct exchange with the atmosphere is very limited like in stream or wetland sediment), the preponderant form depends on the pH and can be calculated as illustrated on the graph below.



- In sea water, Carbonate can combine with Ca^{2+} to form Calcium Carbonate (CaCO_3), which precipitates out of solution. In other words, calcium carbonate formation is a sink for carbonate, and ultimately from CO_2 addition from the atmosphere to increased CO_2 concentrations in the atmosphere.
- Carbonates are thus a great pH buffer in aquatic environments

2.3 D

2.3.1 Dihydrogen sulfide

- see hydrogen sulfide

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2.4 E

2.4.1 Eutrophication

- Definitions:
 - ‘an increase in the rate of supply of organic matter to an ecosystem’ (Nixon, 1995)
 - ‘is the enrichment of a water body with nutrients, usually with an excess amount of nutrients’ (Wikipedia)
 - ‘the enrichment of water by nutrients, especially nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of water concerned’ (Anonymous, 1991b)
 - ‘the enrichment of water by nitrogen compounds causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of water concerned’ (Anonymous, 1991a)

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2.5 G

2.5.1 Greenhouse gases (*GHG*)

A greenhouse gas is a gas in an atmosphere that absorbs and emits radiant energy within the thermal infrared range. This process is the fundamental cause of the greenhouse effect. The primary greenhouse gases in Earth's atmosphere are **water vapor**, **carbon dioxide**, **methane**, **nitrous oxide**, and **ozone**. Without greenhouse gases, the average temperature of Earth's surface would be about -18°C (0°F), rather than the present average of 15°C (59°F). In the Solar System, the atmospheres of Venus, Mars and Titan also contain gases that cause a greenhouse effect. (Wikipedia)

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2.6 H

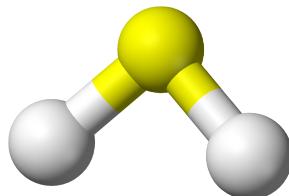
2.6.1 Haber-Bosch process

- Haber-Bosch process

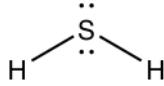
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2.6.2 Hydrogen Sulfide

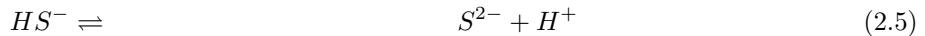
- It is a colorless gas with the characteristic foul odor of rotten eggs.
- It is very poisonous, corrosive, flammable and acidic in nature.
- Formula: H_2S



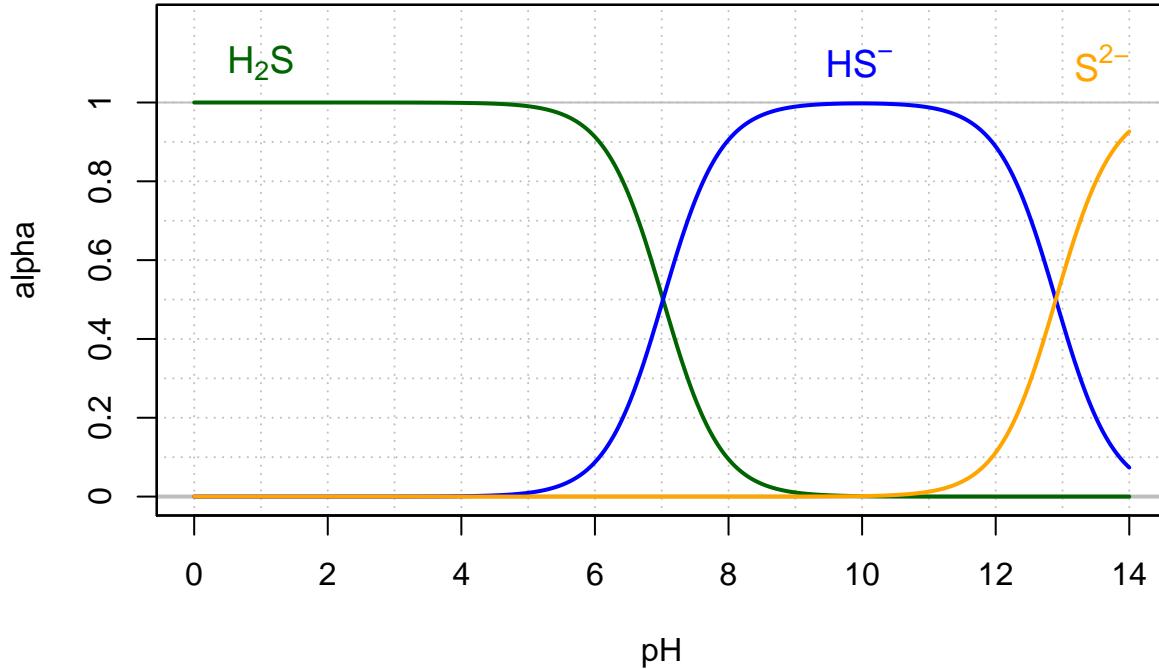
- hydrogen sulfide #D shape:



- Lewis dot structure: $\begin{array}{c} \cdot \cdot \\ \text{S} \\ \diagdown \quad \diagup \\ \text{H} \quad \text{H} \end{array}$
- Number of electron S has for itself following electronegativity rule: eight
- H_2S can only be an electron donor
- Unstable under aerobic conditions, will readily be oxidized into sulfate
- H_2S is a polyprotic acid which can lose up to 2 protons in water, depending on the pH.



- The figure below suggests that at pH found in most streams (4.5 to 8), H_2S is either preponderant or corresponds to at least 20% of all sulfide forms. H_2S being a highly volatile product, it explains why we can easily smell and detect it in most conditions in streams.



- Production:
 - Hydrogen sulfide often results from the microbial breakdown, or mineralization, of organic matter in anaerobic conditions, such as may exist in swamps and sewers. When happening in sediment, this is referred to as sediment diagenesis
- Consumption:

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2.7 L

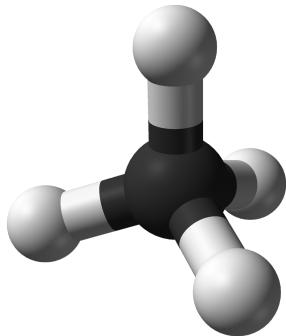
2.7.1 Limiting factor

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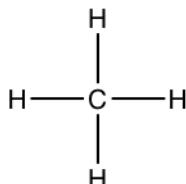
2.8 M

2.8.1 Methane

- Under normal conditions for temperature and pressure, methane is a colorless, odorless gas main constituent of natural gas, and the simplest alkane
- Formula: CH_4



- Methane 3D shape:



- Lewis dot structure of methane:
- Number of electron C has for itself following electronegativity rule: eight
- CH_4 can only be an electron **donor**
- Because methane has so many electrons to give, it will easily ‘burn’ in normal atmosphere (provided that ignition T°C be reached, e.g., by a spark), liberating large quantities of heat (55.5 MJ/kg). The electrons are transferred from the carbon to the oxygen atoms following two redox half-reactions to obtain the overall reaction:



(2.8)

(2.9)



- Production:
- Consumption:
- Ecological significance:

Concentrations of methane in the atmosphere from hundreds of thousands of years ago through 2015, measured in parts per billion (ppb). The data come from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source(EPA, 2016)

- Health effects:

2.9 N

2.9.1 Nitrate

- Nitrate is the stable inorganic nitrogenous anion in oxidized water
- Formula: NO_3^-

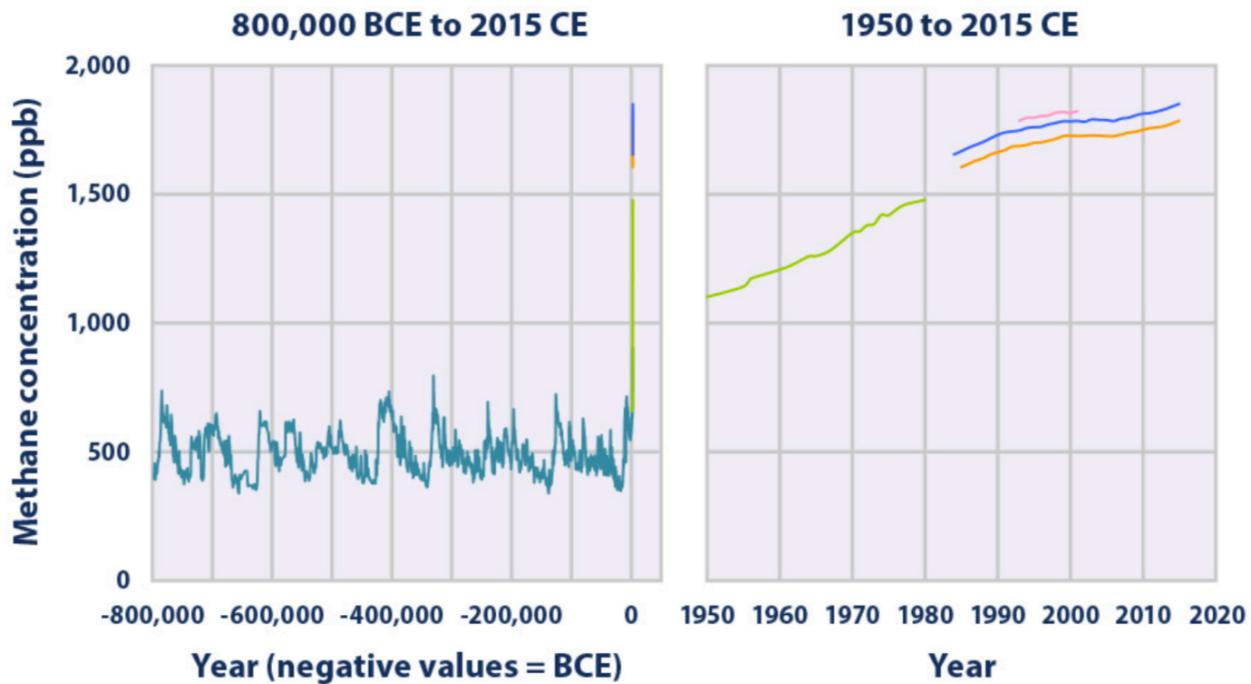
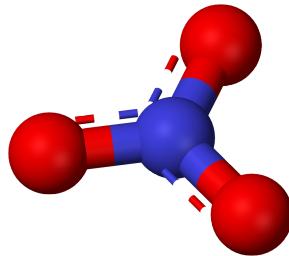
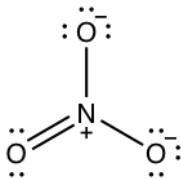


Figure 2.2:



- Nitrate 3D shape:



- Lewis dot structure of nitrate:
- Number of electron N has for itself following electronegativity rule: zero
- NO_3^- can only be an electron acceptor
- NO_3^- is technically the conjugate base of nitric acid HNO_3 , but the pK_A of the reaction is at a theoretical pH of -1.38. In other words, for the pH of most natural waters ($4.5 < \text{pH} < 8$), HNO_3 is totally insignificant.
- Production:
 - from the complete oxidation of inorganic nitrogenous molecules which include ammonia, ammonium, nitrite
 - from the mineralization and complete oxidation of amine radicals in organic molecules
- Consumption:

- **Uptake** from microbes, plants, and algae for their anabolism, which consists in building complex organic molecules from inorganic ones.
 - * Uptake, assimilation, anabolism, immobilization are all synonymous terms to express the fact that the N atom is immobilized, at least temporarily in organic molecules.
 - * Because N is assimilated in organic molecules during uptake/anabolism, and because N gains electrons in the process (it is thus *reduced*), we refer to nitrate uptake as **assimilatory nitrate reduction**.
- **Denitrification:** under anaerobic conditions, nitrate is used by facultative anaerobes as electron acceptor to generate ATP in their respiration chain. The two major end products of denitrification are gases, namely dinitrogen (N_2) and nitrous oxide (N_2O), which leave the aqueous environment. As such, nitrate is not assimilated by any bacteria and denitrification is therefore, as opposed to uptake, referred to as **dissimilatory nitrate reduction into dinitrogen (N_2) and nitrous oxide (N_2O).
- Ecological significance:
 - Because of assimilation and denitrification processes, the overall nitrate concentrations in rivers tends to diminish from the catchment headwaters to the receiving bodies such as estuaries and coastal areas. As a result, inorganic nitrogen has naturally been in very short supply in these coastal water bodies, and nitrate and traditionally been the nutrient limiting aquatic productivity there. Very much like with phosphate, algae have adapted to be able to grow in very low concentrations. Anthropogenic activities, and agriculture in particular, have largely increased the loads and concentration of nitrate reaching estuaries, to the point where nitrate is no longer the limiting factor. As a result, excess nitrate is one of the reasons for the global and persistent presence of algal blooms in estuaries and coastal waters.
- Health hazard:
 - There is a heated debate about the health hazard that nitrate might pose. Some argue that if anything, there might be beneficial effects, while others argue that there are evidence of cancers linked to excess nitrate absorption. Unfortunately, arguments on both sides might not be totally independent of militantism and lobbies.
 - The only consensus everybody seems to agree upon is the Blue Baby syndrome, or methemoglobinemia. Methemoglobinemia is an unusual and potentially fatal condition in which hemoglobin is oxidized to methemoglobin and loses its ability to bind and transport oxygen, hence the cyanosis (blue appearance) usually visible on fingers, toes, and lips. Nitrate reduced to nitrite in the body of humans and animals enters the body stream where it seems to directly oxidize oxyhemoglobin to methemoglobin-peroxide complex.



Picture of a Blue Baby from syndromespedia.com/blue-baby-syndrome.html

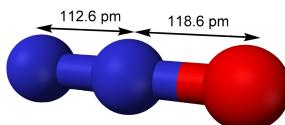
- Drinking water standards

- Although there is still a heated debate whether or not nitrate does have have detrimental health effects, the World Health Organization has provided maximum concentration guidelines of 50 mg/L as nitrate (World Health Organization, 2011). These guidelines have been enacted in hard laws in the US and in Europe. The 50 mg/L as nitrate equates 11.2 mg $NO_3\text{-N}/\text{L}$ and in the US, the drinking water standard is **10 mg $NO_3\text{-N}/\text{L}$** .

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2.9.2 Nitrous Oxide

- Commonly known as laughing gas
- Nitrous oxide has significant medical uses, especially in surgery and dentistry, for its anesthetic and pain reducing effects.
- Formula: N_2O



- Nitrous Oxide 3D shape:



- Number of electron N has for itself following electronegativity rule:
 - the first one on the left has 5
 - the middle N has 3
- N_2O can be both an electron acceptor and an electron donor
- Production:
 - N_2O is produced due to bacterial processes (over 90%) and anthropogenic processes such as burning of fossil fuel
 - * The two main bacterial processes are *nitrification* and *denitrification*
 - * Accounting that human activities have enhanced both nitrification and denitrification processes, it is estimated that overall, about 2/3rd of N_2O production is natural, and about 1/3rd is human enhanced
- Consumption:
 - Because of all the electrons stored on the two N atoms ($5 + 3 = 8$), nitrous oxide is a potential electron donor and bacteria can use it for their respiration processes
- Ecological significance:
 - Powerful Greenhouse Gas, 298 times that of CO_2 (EPA)
 - Concentration in the atmosphere ~ 0.0003 ppm or ~ 325 ppb on the rise

Concentrations of nitrous oxide in the atmosphere from hundreds of thousands of years ago through 2015, measured in parts per billion (ppb). The data come from a variety of historical ice core studies and recent air monitoring sites around the world. Each line represents a different data source)(EPA, 2016)

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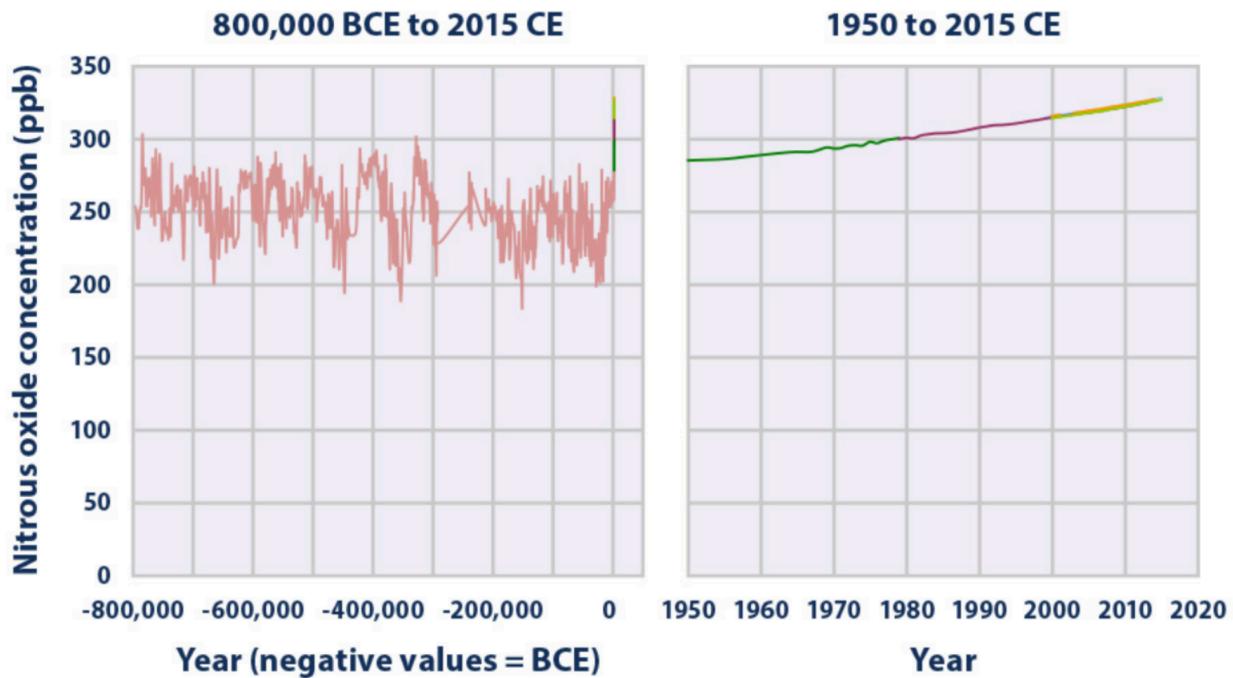


Figure 2.3:

2.10 O

2.10.1 Oligotrophication

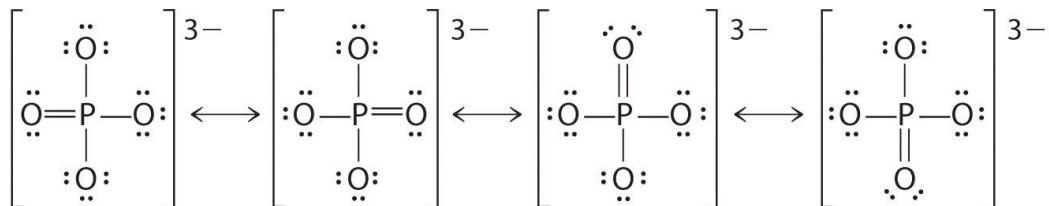
- ‘a decrease in the rate of supply of organic matter to an ecosystem’ (Nixon, 2009)

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2.11 P

2.11.1 Phosphate

- Phosphate is an inorganic chemical and a salt-forming anion of phosphoric acid
- Formula: PO_4^{3-}



- Phosphate is one of the anions of the polyprotic acid (i.e., which can liberate several protons H^+)
- The conjugate bases of phosphate are:
- All conjugate bases are related through the set acid-base chemical equilibria:

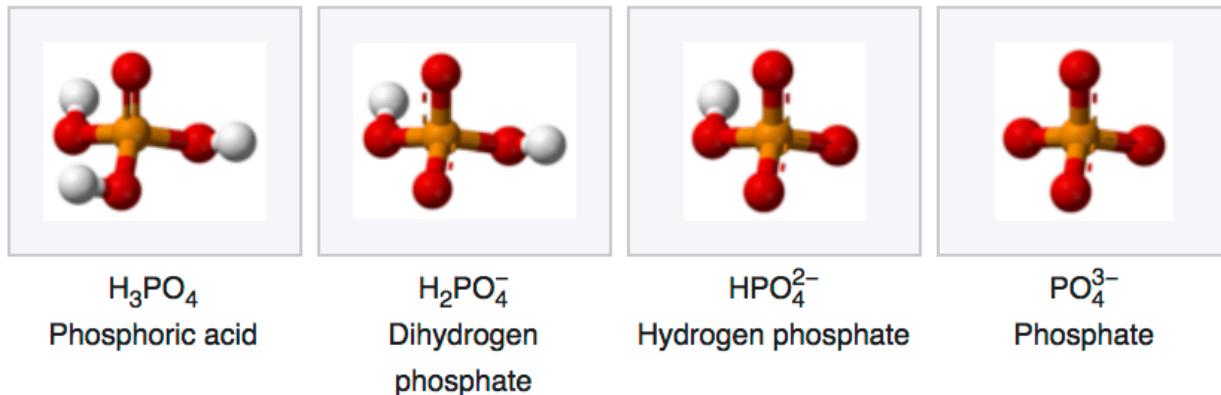
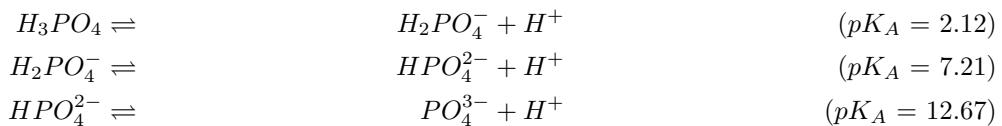
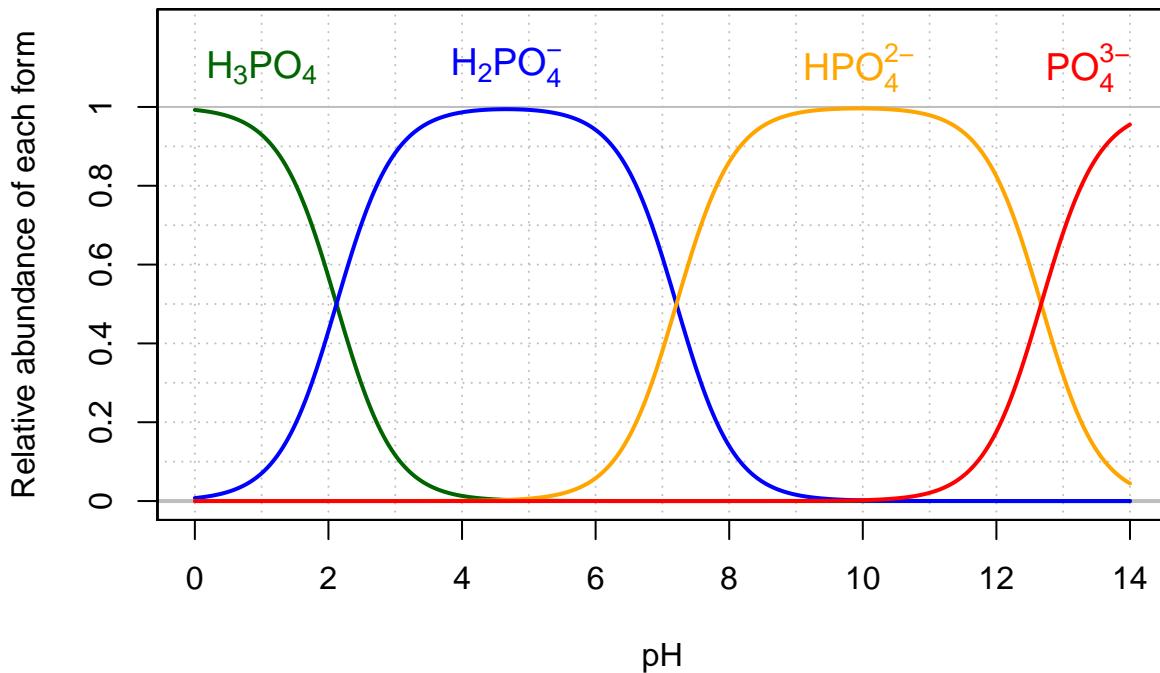


Figure 2.4:



- The preponderant form of phosphate in a solution also depends on the pH following this relationship:



- Production:
 - Phosphorus in general and phosphate in practice has remained one of the nutrients limiting the most plant productivity on our planet
 - Phosphates are the naturally occurring form of the element phosphorus, found in many phosphate minerals
 - Phosphate minerals are mined to obtain phosphorus for use in agriculture and industry
 - The largest global producer and exporter of phosphates is Morocco.
 - Within North America, the largest deposits lie in the Bone Valley region of central Florida, the Soda Springs region of southeastern Idaho, and the coast of North Carolina (near Aurora).

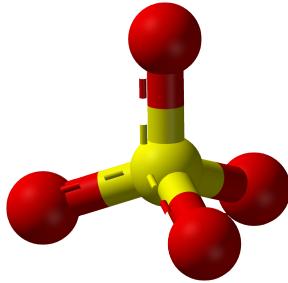
- Consumption:
 - Uptake from all primary producer including plants and algae
 - Phosphate can also be immobilized by bacteria
 - In food industry, phosphates help baked goods rise, they act as emulsifiers in processed cheese and canned soup, they add flavor to cola and color to frozen french fries. They also can be added to meat, poultry and seafood to help the protein bind more water, making it juicier after freezing and reheating.
- Ecological significance:
 - Phosphorus as phosphate naturally is the most limiting factor for primary productivity for land and aquatic plants. Because it tends to bind to particles, phosphates have accumulated with sediment particularly in coastal areas, where phosphate can become available again to algae through sediment diagenetic processes. As a result, phosphate is generally not considered the most limiting factor for algae in estuaries and coastal environment. However, it does tend to be the limiting nutrient in freshwater receiving bodies such as lakes and reservoirs.
 - Excess phosphate in freshwater receiving bodies has been shown to be the nutrient causing some major eutrophication problems throughout the planet

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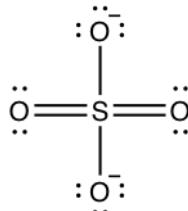
2.12 S

2.12.1 Sulfate

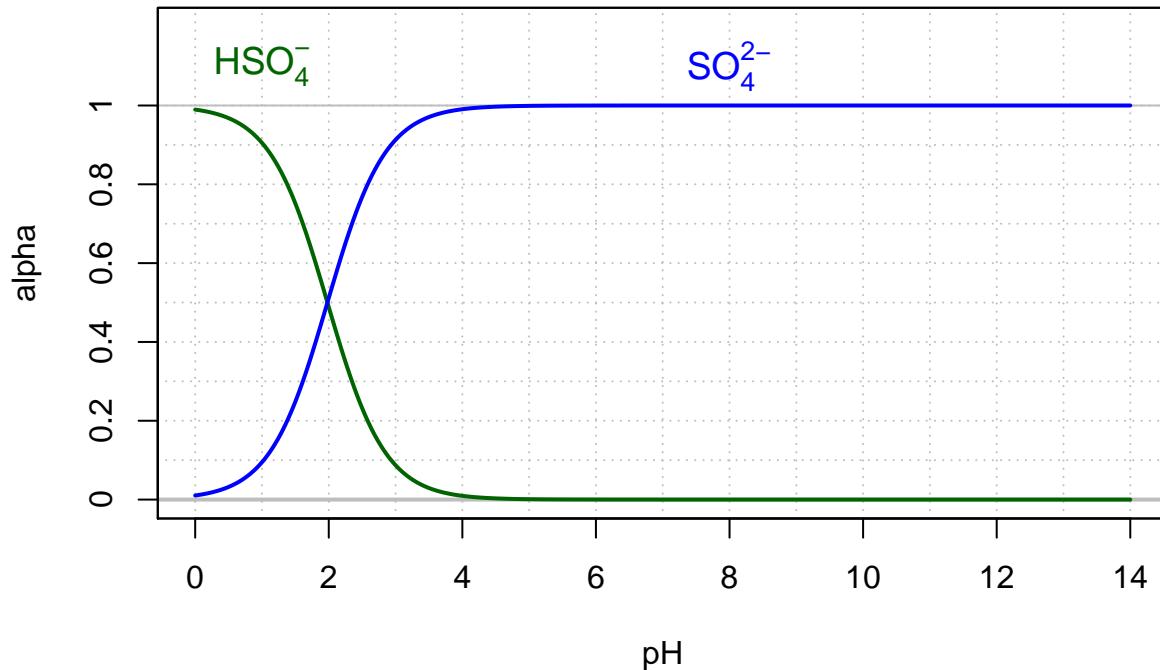
- Sulfate is the inorganic sulfur anion stable in oxidized water
- Formula: SO_4^{2-}



- Sulfate 3D shape:



- Lewis dot structure of nitrate:
- Number of electron S has for itself following electronegativity rule: zero
- SO_4^{2-} can only be an **electron acceptor**
- SO_4^{2-} is the conjugate base of Hydrogen sulfate HSO_4^- . The figure below shows that for pH normally measured in surface water and streams (4.5-8), SO_4^{2-} is the truly preponderant form. We therefore generally omit to mention HSO_4^- as a chemical form that plays any significant role.



- During their anabolism, primary producers uptake sulfate, but the sulfur atoms can be incorporated into amino-acids only after sulfur has been reduced, or gained 8 electrons to be in a thiol ($-SH$) form.
- Production:
- Consumption:
- Ecological significance:
- Health effects:

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