PHOTOSYNTHESIS - Curated Transcript of BBC In Our Time podcast
https://www.bbc.co.uk/programmes/b0435jyv
Last On Thu 14 May 2020 21:30 BBC Radio 4

This transcript was created by downloading the podcast from the BBC website and passing it to Assembly AI V2 (https://www.assemblyai.com/) and then manually editing the resulting raw transcript to assign voices, to correct spelling, and to introduce occasional time stamps. Edits have also been made to better communicate the factual content of the podcast, rather than capturing all the details of the audio record. Such edits are indicated in the transcript.

Comments and corrections are welcome, and sincere apologies are made for any substantial inaccuracies in the following transcript.

(Credits from the BBC Website)

In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

Nick Lane
Reader in Evolutionary Biochemistry at University College London

Sandra Knapp
Botanist at the Natural History Museum

John Allen
Professor of Biochemistry at Queen Mary, University of London.

Producer: Thomas Morris

Transcript:

[Melvyn Bragg] Hello. Three and a half billion years ago, this planet was a hostile and barren place. The atmosphere was toxic and contained no oxygen and life on Earth was restricted to a variety of unsophisticated ... single celled organisms which lived in the sea. But then a new type of organism emerged, one with an amazing new capability. It could harvest energy from sunlight and use it to fuel its own activities. This phenomenon is known as photosynthesis, and it's almost certainly the most important chemical process on Earth. Plants and some other organisms depend on it for their energy, and almost all life is ultimately reliant on it for its survival. It's responsible for the food we eat and the air we breathe. And without it, Earth would still be sterile rather than, as it is, teeming with life. With me to discuss photosynthesis are Sandra Knapp, Botanist at the Natural History Museum, Nick Lane, Reader in Evolutionary Biochemistry at University College London and John Allen, Professor of Biochemistry at Queen Mary, University of London. Sandra Knapp, would you give us some idea of what photosynthesis is and why it's so important?

[Sandra Knapp] Photosynthesis is one of those things that you always read about, you hear about at school, but actually, when you look at it carefully, what it is is it's a very simple, elegant chemical reaction which involves an organism taking water and carbon dioxide and with the help of light, turning those into glucose and oxygen. So it's water and parts of the air turned into sugar and a really important part of the air for us. And the reason it's so important is because without photosynthesis, that blue and green ball that you see from space would look like Mars.

[Melvyn Bragg] And can you just develop that a bit of the importance of it and how it changed things?

[Sandra Knapp] Well, when organisms were able to create their own food, to create something from light, that then allowed other organisms to feed on them, so you have autotrophs, which are organisms that make their own food. So plants are autotrophs. Anything that does photosynthesis is an autotroph. We are completely hopeless. We're heterotrophs, we depend on other organisms for our food. So without these photosynthetic organisms, we would have nothing to eat and nothing to breathe. And so all of life really depends upon autotropes. It's also true, I think, that if you look at photosynthesis, it seems that's the sort of simple end but you look at the structural diversity of life on earth, sort of that we have rainforests and we have deserts and we have all these different types of habitats depends upon the different types of autotrophs which are in those habitats which then drive the development of communities that are in all the different biomes on Earth.

[Melvyn Bragg] What are the basic raw materials for photosynthesis? What does a plant, for instance, need in order to photosynthesize?

[Sandra Knapp] Well, first of all, it needs water. It needs carbon dioxide. There needs to be light, and there also need to be a few really important minerals.

[Melvyn Bragg] Of these three is the most important light?

[Sandra Knapp] Of these three..? Light is the most important, I would think. Water is also very important, and carbon dioxide can be in varying concentrations, and that makes a big difference, and I'm sure my biochemical colleagues will be able to tell us about that. But it also needs sort of a few other things as well. Plants need nitrogen and phosphorus to make the enzymes which drive the reactions of photosynthesis. And they also need an element - a mineral - called magnesium, which sits like a spider at the center of the chlorophyll molecule, which is one of the light harvesting pigments in leaves.

[Melvyn Bragg] So we're talking about photosynthesis as part of ... a central part of ... a little laboratory, really, isn't it? An engine room?

[Sandra Knapp] It's an engine room. It's an engine room. It's essentially plant power is what it is. Yes.

[Melvyn Bragg] Yes...Nick Lane, if we think about ... let's stick to plants, let's stick to plants all the time. What are the structures in the plant cell that make photosynthesis possible? You don't have to rush. We'd all like to know in detail...

[Nick Lane] Okay, well, it all goes on inside a special compartment inside the cell, which is called the chloroplast. Now, the chloroplasts, in fact, are ... were once bacteria in their own right. They were free living bacteria; we know them as cyanobacteria now. And they became captured probably something in the order of 1 billion to one and a half billion years ago by more complex cells. And they became responsible for photosynthesis. They continued to do what they were doing before

[Melvyn Bragg] You say became captured. That sounds terrific, but people like me don't know what you mean...

[Nick Lane] Well, they were simply engulfed by a larger cell and effectively put to work, not quite as slaves, but they did what they always did. They continued to photosynthesize; they continued to take electrons from water, put them onto carbon dioxide, and make sugars that way. And so the host cell, which had captured them, gained those benefits of getting a free lunch, you might say.

[Melvyn Bragg] Is the throwaway analogy that I said to Sandy a few moments ago ... is the idea of it being an engine room. Does that make any sense? Is that useful for people to think?

[Nick Lane] No, I think absolutely. It's an engine room.

[Melvyn Bragg] So can you tell us what's happening inside this engine room, then? Just tell it again.

[Nick Lane] Well, we have a series of membranes they're call the "thylakoid membranes", and there's ... enormous complexes of proteins. I mean, this is one of the difficult things to try to get across, because I say enormous complexes, but this is all microscopic, of course. But if you take yourself down to the size of a small molecule, say, the size of an oxygen molecule. These complexes, it's like being in some kind of huge industrial complex. So they're really enormous and they sit there in the membranes, and all they do at a chemical level is really amazingly simple. All they do is they extract electrons from water and they pass them down a kind of a chain, and eventually they push them onto carbon dioxide to make the sugars. Now, it sounds at a chemical level, it's very simple. At the biochemical level, it's enormously difficult. And these complexes...

[Melvyn Bragg] Why?

[Nick Lane] Well, it's not easy to get electrons out of water in the first place. So... the largest storms, crashing water against a sea cliff is not going to break water down into its component parts, but light can do that. Now, light doesn't normally do that; certain wavelengths, so UV light can split water, but by and large, it requires a biochemical skill which we can mimic, but with great difficulty actually, and plants just simply do it. They simply extract these electrons, they pass them down and they push them onto CO_2.

[Melvyn Bragg] They must have evolved to do it over a long period of time.

[Nick Lane] We don't know...

[Melvyn Bragg] Why did they want to do it?

[Nick Lane] Why did they want to do it? That's always a difficult question in the evolution. Essentially, water is everywhere. If you can crack that, then you've got your raw material that you need in the oceans; it's surrounding you. The other materials that could be used, things like hydrogen sulfide gas or just dissolved iron, for example - if you have no oxygen around you can use iron - but they're far less common. Water is the perfect fuel.

[Melvyn Bragg] The process, as I read from my notes - I'm making a lot of attention to my notes on this program - can be separated into two separate chemical reactions. Can you tell us what those two are?

[Nick Lane] Well, they're known as the light and the dark reactions. And really, ... at its simplest, the light reaction is driven by the absorption of photons of light and it's simply dragging, stripping electrons from water. So what's essentially what's being powered by the light reaction, is the removal of electrons from water. The waste of this is oxygen, which is just a waste product of photosynthesis. It's just let go, it accumulates in the atmosphere.

[Melvyn Bragg] Oxygen is a waste by product?

[Nick Lane] Yes. [laughter] So then the dark reaction, you take those electrons and you force them onto carbon dioxide. Now, that doesn't require light at all. So it used to be called the dark reaction. They changed the name recently to non light reactions, I think, but I prefer the old term the dark reaction. It can happen in the dark.

[Melvyn Bragg] It gets more and more mysterious, and the simpler you make it, the more mysterious it also gets. John Allen, at the heart of this process is this molecule called chlorophyll. Now, what's so specific about that? What's so special about that?

[John Allen] Well, it's interesting to follow Nick. Oxygen is not just a waste product, it's a toxic waste product. We don't think of it as toxic. We may come back to that...

[Melvyn Bragg] Can you tell us why now? You can't tease us like that. I mean - why is it toxic?

[8:57]
[John Allen] Well, 2.4 thousand million years ago, as you said in the introduction, the whole biosphere was working fine without free molecular oxygen. This was dangerous stuff to have around. It's chemically, highly reactive. 2.4 thousand million (equals billion) years ago, this trick was discovered by accident of taking electrons from water [and] producing this by-product. This was a big shock to the system. There's never been an equivalent environmental catastrophe for life that existed before that time as the production of oxygen.

[Melvyn Bragg] As the production of oxygen?

[John Allen] A poison gas, actually, which nevertheless ... doing that trick had such immense value. Again, discovered by accident. It wasn't that they wanted to do this. I know that you were speaking metaphorically there. This ... had such benefit that they had to learn to live with this poison gas and learning to live with it...

[Melvyn Bragg] Who's they? The organisms..?

[John Allen] Pretty well everything that had to deal with oxygen as it came along. There are still environments today where oxygen doesn't permeate and there is still anoxic life without oxygen. There was a relic of this former time which ...

[Melvyn Bragg] Is this ... down in the clefts of the ocean.

[John Allen] Yeah. And under...in the rocks in the lithosphere. Yeah.

[Melvyn Bragg] And we're back to chlorophyll.

[John Allen] I wasn't evading the question.

[Melvyn Bragg] No, I know you weren't. I just got interested by oxygen being ... toxic waste - makes breathing an entirely different experience.

[10:31]
[John Allen] Well, not to us, of course. That's the...
Chlorophyll. Well, this is one of the time honored tradition of giving things Greek names. It simply means "green leaf" chloro-phyll. It's a chemical substance. It's an organic chemical substance. The structure of which I can describe very briefly. If you ... Sandy was right about this magnesium atom at the middle of the spider's web. The spider's web is um...built up of essentially four carbon atoms. If you imagine them being linked in series 1234 and then you add a fifth atom, which is not carbon, but nitrogen, and you fold that around to make a circle. It's a five membered object - pentagon actually. That is a simple circular molecule which is one of the building blocks. Now,there are four of these. It's called a pyrol is the technical term. There are four of these in the basic head group of chlorophyll, and these are 1234 also arranged in a series. And you fold that around to make a circle. And at the center of that with the nitrogen atoms pointing inwards is the magnesium atom. And that's really chlorophyll. Except you just have to add the fact that there's a hydrocarbon tail attached to one of these rings, which gives chlorophyll the property of being completely insoluble in water but soluble in organic solvents. And also its preferred location is within biological membranes, which are fatty waxy, oily compartments.

[Melvyn Bragg] And this is what's special and essential about it? Is it?

[John Allen] Well... special and essential? I mean, the first thing there really is there's nothing magical about it. You know, in the history of biology, people have always wanted to be focusing down on what's the smallest thing that we can say is alive. And people got very excited about chlorophyll. It seemed to be a very special molecule sustaining life on Earth. But in fact, it's just a chemical. In fact, it's been synthesized by synthetic organic chemists in Harvard University in the 60's or 70's - from scratch. You can make the whole thing - a tour de force of organic chemistry. Plants do this by a biochemical pathway.

[Melvyn Bragg] I'm told that there are two separate sets of chlorophyll involved in this reaction. Is that right? What do they do? How do they do it?

[John Allen] Well, that's correct. They do essentially the same thing... Nick talked about this chain of electron carriers, and a great insight was provided - in 1960 in fact, by Hill and Bendle, a paper published in April 1960. They said in this ... first of all, there is a chain of electron carriers. Secondly, there are two points in that chain of electron carriers where the electrons wouldn't go unless they were given a push by some energy input. And that push is provided by light energy acting on chlorophyll. One of the fates of the energy when the chlorophyll molecule has absorbed light is for it to lose an electron. That's the beginning. That's the push that drives this electron transport chain. That special chlorophyll that loses its electron to start the chain is just one of 300 chlorophyll molecules approximately. All the others take the absorbed excitation energy and pass it amongst each other until it arrives at this special one. And that sets the whole process going and sustains life on Earth, as we've heard before.

[Melvyn Bragg] Sandy, now, that we've been talking about for the synthesis as if it were a single process. But there's more than one type. Can you tell us about that?

[14:36]
[Sandra Knapp] Sure. Photosynthesis is most plants are what's called C-3 photosynthesizers, and it's called C-3 because the first thing that happens to the carbon dioxide when it gets split up is it turns into a three carbon molecule. But there's a whole set of flowering plants, and it happens all over flowering plants, which are called C-4 plants. And what they do is the first reaction is slightly different, and the carbon goes into the carbon dioxide, gets broken up into a four carbon molecule, and then the photosynthesis happens in two different places, two different types of cells. Normally it just happens in one part of the cell. But in C-4 photosynthetic plants, what happens is the CO2 is sort of stored. It's sort of packaged into special... They're called bundle sheet cells, and they're around the vasculature, so they're around the veins. If you think about a leaf, it has it has a set of veins in it, and that's where the water is is running up and the sugars are running down. And these, these special bundle sheet cells is where this carbon dioxide is stored. And C-4 plants are much more efficient at photosynthesis at high temperatures. So oftentimes, things that grow in deserts and in very hot places are C-4 photosynthesizers. And there's a third kind, which is called crastulacian acid metabolism. So CAM plants and because it was first discovered in a sedum, in one of those little rock plants that you grow in rock gardens, which are in the family crassulaceae, and so it's called crassulase and acid metabolism. And in those plants, what happens is the stomates -- the stomachs are like little holes in a leaf. So if you take a hand lens and look at the bottom of a leaf very carefully, you see tiny little pits. And those little pits are pores in a leaf, which have two guard cells around them, almost like a mouth that can open and close, and the CO2 goes in through these pores. So crassulacian acid metabolism plants keep their stomates closed during the day. All other plants open their stomates during the day, so this can all go on in the

light. Crassulacian acid metabolism plants keep those closed during the day and open them at night when it's not so hot. They do all the business of taking in the CO_2 at night and then store it. And so CAM plants can idle, so they can store up all the components for photosynthesis and kind of do it later, which is really useful if you live in a desert. So many CAM plants are things like cacti and orchids and the kinds of plants that live in very hot, dry, stressful environments.

[Melvyn Bragg] But if they do it in the dark, what do they do for light?

[Sandra Knapp] They they harvest the light as well. So it all gets it all gets stored up.

[Melvyn Bragg] Through the day?...But you've said they're closed up...

[Sandra Knapp] Well, the stonemates are closed up. The light comes in through the cells of the plants. The light doesn't come in....

[Melvyn Bragg] I see

[Sandra Knapp] The stomachs are what take in the gas. And so C-4 plants are very interesting because if you look at the distribution of C-4 and C-3 plants across flowering plants, many of our major crops, corn [or] maize, for example, is a C-4 plant. And this has been studied the most in the grasses. And these C-4 plants are highly photosynthetically efficient. And so one of the great holy grails in agriculture is to take a C-3 plant like rice or wheat and turn it into a C-4 plant, which would increase its efficiency and thereby perhaps increase its yield and its ability to grow in different parts of the world.

[Melvyn Bragg] Okay, Nick Lane, what does the plant cell do with the energy that it's converted? Can you explain that again?

[18:00]
[Nick Lane] Yes, well... I talked earlier about the flow of electrons. Now they do two things. You have essentially a current of electrons and that is used to drive protons - so the positive nucleus of hydrogen atoms - across a membrane. So you end up with a proton gradient across the membrane. Now, that's common to all ...

[Melvyn Bragg] Gradient? Like you mean slope?

[Nick Lane] Well, yes... Essentially, on one side of the membrane you have a large number of protons. On the other side you have very few, relatively few. So it's essentially like a hydroelectric power scheme with a reservoir on one side and a turbine in the membrane itself. So the turbine is an enzyme called the ATP-synthase enzyme. And that is powered by the flow of protons from the reservoir back to the side where there's downhill in effect and that produces ATP. Now, ATP is generally called the "energy currency of life". It's used by all living cells. In fact, the ATP synthase as well, which produces it is also are used by almost all living cells and that powers everything in the cell. You could think of it like a coin in the slot machine. Basically, all proteins to do any work at all, they change their conformation - and to change their shape requires splitting an ATP. So the current of electrons, which is flowing from water to CO_2, is driving all of this process. The second thing that happens is all those electrons end up on carbon dioxide, converting it into a sugar, and those sugars are then interconverted into all the rest - in autotrophic plants and so on - converted into all the rest of the organic molecules that we need to live - that they need to live, that we need to eat. So growth basically - both power and growth are coming from photosynthesis.

[Melvyn Bragg] Can you remind us again because this is more and more industrial, isn't it? But can you remind us again the size of these things, the size on which they're operating? Is there any way explaining it graphically?

[Nick Lane] It's kind of difficult to grasp, but the chloroplast itself is the size of a bacterium. It was a bacterium. So you can't really see it except down a microscope. Down a microscope, you can see them. Down a light microscope, you can see them quite well. So you could if you have a reasonable microscope at home, you could see them, but they're in the order of a fraction of a millimeter, something like a 10th of a millimeter or so in their length. This is the chloroplast, this is the engine house where all this is happening. Beyond that... within the chloroplast itself, you have these big proteins within the membranes themselves. Now, these are what I was calling the industrial complexes before. And if you shrink yourself down to the size of a molecule like oxygen, then then really it's like a city. Now, there are tens of thousands of these great industrial complexes within a single chloroplast. So it's very difficult to to grasp this scale that something so small is, in fact, practically a city in itself.

[Melvyn Bragg] Sandra Knapp?

[Sandra Knapp] I was just going to say that if you buy SpyroGyro, which is one of these health food things from the health food store, and then wet it up and look at it with a lens, they have really big chloroplasts and you can see them and they're like little green, little green oblong things. They're really rather beautiful - chloroplasts.

[Melvyn Bragg] John Allen, photosynthesis is just one of the chemical processeses in plants - another is respiration. Can you tell us how these relate to each other, please?

[21:42]
[John Allen] Well, that's a good question. You know, Sandy's definition of photosynthesis is release of oxygen and uptake of carbon dioxide. This is good. This is correct. This is what plants do. ... There is another view which maybe we will come to ... And if you take that [Sandy's] view, aerobic respiration, which is respiration that plants do and which we do - we're all doing it now - is the uptake of oxygen. You put electrons onto it to make water. So it's the reverse of taking electrons from water to re-liberate oxygen. We take up oxygen to take a deep... breath here. And we respire to make ATP by exactly the process that Nick just described. And in that process, we release carbon dioxide. So photosynthesis is release of oxygen, uptake of carbon dioxide. Respiration is uptake of oxygen, release of carbon dioxide, which we're all doing now. And all hetotrophs. We're all heterotrophs sitting around here respiring and getting our energy from ultimately from sunlight stored by photosynthesis. So from Sandy's point of view, respiration and photosynthesis are the reverse of each other. I'm just using this as a token for this entirely correct botanical description. However, if you look more deeply at the kind of level that Nick is describing, the process of energy transduction - we could say a power station is a good analogy. It could be a medieval

power station, like a watermill or something. We're converting energy from one form into a different form. The way in which that is done is universal in biology. And photosynthesis and respiration are two ways of applying that same fundamental mechanism. Electron transport, moving protons across a membrane to make a gradient, which is stored energy and used to make ATP. So in that sense, they're the same process, except that the chlorophyll in the photosynthetic reaction center gives the electron that initial push that it needs. In respiration, the electrons just sort-of flow where they want to go.

[Melvyn Bragg] Nick Lane?

[Nick Lane] Yeah, the source of electrons is really the major difference between photosynthesis and respiration. So in respiration, we need an easy source of electrons. That's food in our own case. And the food will react spontaneously with oxygen. It doesn't happen right now because there are barriers to it happening, but in terms of the thermodynamics, they want to react with each other -- and it will happen, and the enzymes in the mitochondria allow that to happen. What's happening in photosynthesis is that light is is providing that essential input of energy which flows, which starts electrons flowing from far more difficult places - so water in this case. So water really does not want to lose its electrons but the input of light through chlorophyll extracts electrons from it and sets them flowing in exactly the same way that they flow from food to oxygen in us. Exactly the same processes. The source of electrons differs.

[Melvyn Bragg] I'm still reading for this thing that's a 10th of the smallest thing I can properly think of has cities inside it. But on we go... Sandy Knapp, the plants and bacteria live in a wide variety of habitats. What are the limiting factors on ... are there any [limiting factors] on hotosynthesis and insufficiency?

[Sandra Knapp] There are certainly limiting factors. If there's no water in the environment, plants can't photosynthesise. Nothing can photosynthesize because water is one of those inputs. Same is true for carbon dioxide. Same is also true for light. But there are also limits in things like nitrogen and phosphorus, which is part of the reason that we fertilize crops, is to increase photosynthetic efficiency and thereby increase yield, that you need the nitrogen and the phosphorus to build the other enzymes that operate in this little factory. But temperature is a very important limiting factor for photosynthesis as well. At very high temperatures, photosynthesis doesn't happen particularly efficiently, and at very low temperatures, so there's an optimum range. And one of the things that's really interesting about plants is that people often think of plants as just sitting there. Plants just sit there. But plants behave it's just on a very different scale to our human behavior. And so if there's not enough water or if there's too much light, the stomates were closed, and thereby no carbon dioxide is taken in and photosynthesis go down. So plants regulate the degree to which they photosynthesize, dependent on various environmental conditions, the most important of which are probably water and carbon dioxide concentration, which is interesting in the context of climate change. It's interesting in the context of the differing carbon dioxide concentrations over the history of life on Earth.

[Melvyn Bragg] And John Allen, again, chlorophyll isn't the only pigment. That's the pigment that gives us green ... Are there others as important?

[John Allen] Well, there are others that serve to collect the light energy and ultimately deliver it to this special chlorophyll that loses its electron, which starts the whole process. There are carotenoids... these don't engage in this chemical reaction, but they absorb light and the energy is transferred into this sort of pinball game of chlorophyll molecules where it finally ends up in one special one. There are other pigment molecules, the cyanobacteria, for example, and red algae, which are eukaryotic, which are plants. These have pigments which absorb light energy, which is used for photosynthesis, again, essentially by chlorophyll. But these pigments are - I mentioned [earlier] these four rings [in chlorophyll] - these [other pigments] are linear tetrapyrols rather than cyclic tetrapyrols. So there's a whole range of different pigments that different photosynthetic organisms have sort-of latched on to and exploited if they're useful for capturing and concentrating light energy.

[Melvyn Bragg] Why is chlorophyll green?

[John Allen] That's such a good question. And, you know, I have to confess I don't know the answer. Lots of people have asked that question. Why is it green?

[Melvyn Bragg] They're rushing in - our colleagues...

[Sandra Knapp] It's not green. We see it as green because green is the only thing that isn't absorbed. Green is the only wavelength that isn't absorbed. So nothing really has color. We just perceive it because of the wavelength of light which is reflected off it...so... it's interesting...there's a concept called chlorophyllia, which is about the love of green things, which I think is a nice thing to be.

[Melvyn Bragg] I think John wants a little ..

[John Allen] Okay, why is chlorophyll green? Because it absorbs blue light and red light and doesn't absorb light in the middle of the visible spectrum, which is green. I mean, that's true, but that's just sort of stating not starting an argument here...I mean Melvin's question, if I may, could be rephrased. Why aren't plants black? Right? If they were black, they would be absorbing all visible.

[Melvyn Bragg] We could start again.

[John Allen] No, why are they green? I mean, why are they not making use of green light? They should really. If they were interested in getting the most energy, they would use the whole of the visible spectrum and would be black, and they're not. So that's a question still.

[Melvyn Bragg] Nick, have you got the answer?

[Nick Lane] No, but I have a small contribution. It's interesting that they use red light mostly. So the spectrum of light that chlorophyll is absorbing, which is taking the electrons from water and driving the whole process, is red light, which is not energetically, particularly strong. Blue light has far more energy in it than red light does. So you would have thought from first principles - nd actually, chlorophyll does absorb blue light as well, as John said, but it's not using that wavelength. And the reason is not clear. But it may simply be the destructiveness of UV and blue light - you know it can damage our own retinas and so on as well. There are issues with higher energy wavelengths of light. So I think it's ended up with red, partly because that's the wavelengths that chlorophyll absorbs, and partly because selection has adapted the wavelengths that chlorophyll absorbs to being the gentlest on the plant itself. It's less likely to do damage if you're absorbing light at that wavelength.

[Melvyn Bragg] Can we move on to a section on evolution if we could satisfy with you, Sandy. How has the need to photosynthesize influenced the evolution of plants in different sort of environments?

[30:49]
[Sandra Knapp] Well, because all plants need to photosynthesize to make their own food to live. And what's really interesting is plants in all kinds of places photosynthesize. So think about the back of caves. The back of deep caves have photosynthetic organisms in them, and ... so what has happened over the course of evolution is that plants that occur in particular areas have developed structural elements of how the leaves are, that you could say optimized, but they make photosynthesis possible. So think about a plant, for example, in the very dark rainforest, understory the light that comes in, there is mostly those very long wavelengths, the red wavelengths, but it only comes in sunflex[?] and many plants in the rainforest understory have a red layer on the underside of the leaves. And people for a long time wondered why this was. And it's actually very striking in in deep rainforest plants. And, and David Lee did some work in the 1970s and published a really nice paper where they showed that what happens in this anthocyanin layer is that it reflects light back into the chloroplast so that they get more of that of the little light that's coming through, they get a bit more. Anthocyanins are pigments that we see as red, so they're absorbing everything except the red but anthocyanins, so they're reflecting it back into the chloroplast in those rainforest plants, but they also protect chloroplasts from excess light in very high light environments. So plants do a huge number of different things with the pigments in their cells, and the structure of the cells which focus light in, that are all driven by evolution. Because if you think about it, what evolution is doing is it's maximizing the production of offspring. So if you are a plant and you photosynthesize well, grow well, produce lots of seeds - the genes that you have, the characteristics that you have, will be passed on to your offspring, which is how evolution gets driven. An individual plant doesn't necessarily evolve during its life. It's all done through reproduction to the next generation. And you think about the diversity, the diversity of structure in plants that's really driven by the ability to make food and grow in different kinds of ways.

[Melvyn Bragg] Nick Lane, what do we know about the evolutionary history of photosynthesis itself? When is it thought to have emerged?

[33:11]
[Nick Lane] Well, there's quite a lot of controversy. It arose probably the very first forms very early on, three and a half billion years ago. But those forms did not use water as the electron donor. They used things like hydrogen sulfide and iron. And the products that they produce.... so if you're using iron as an electron donor, what you're leaving behind is rusty iron, which precipitates out of the oceans, and forms banded-iron formations, which are the major sources of iron ore that we're using today. So some of the big mineral deposits derived from photosynthesis and are evidence that

photosynthesis was happening at that time. Oxygenic photosynthesis - so this is splitting water and releasing the toxic waste oxygen - probably arose between two and a half and 3 billion years ago. It's difficult to constrain that - there's arguments about it; the arguments are based on the ratios of different isotopes of different atoms; it's quite abstruse. And we have to assume that measurements taken in one rock, in one place are in some way representative of the whole planet, which is usually not true. So there's all kinds of difficulties with constraining. We know for sure it happened, as John said, by 2.4 billion years ago, because we see this tremendous catastrophe. So we have a snowball Earth at that time. The entire planet froze over ...

[Melvyn Bragg] That time. What time are we on now?

[Nick Lane] We're about 2.4 billion years ago. So there's been several episodes of these snowball Earths across Earth history. Probably what happened there was, as oxygen was being released, it oxidized the methane being produced by other bacteria, and methane is a greenhouse gas, and as it's stripped out of the atmosphere, the temperatures plummet. And the other thing we see around that time is the oxidation of rocks and so on on the continent. So we see what are called red beds, basically rusty iron everywhere.

[Melvyn Bragg] John Allen, can I come back to you again? I talked about the structures in plant cells known as chloroplast. In evolutionary terms, how did plants gain these structures and when?

[35:24]
[John Allen] Well, they they acquired them. It's sort of a question of mergers and acquisitions, and chloroplasts were cyanobacteria. A larger cell discovered that if it entered into an intimate partnership with a cyanobacterium, it had a free supply of food and also oxygen for its own respiration. I think there's really no doubt about that now. When I was an undergraduate student, this was regarded as a sort of slightly flaky left-field proposition, you know. But now, for all sorts of reasons, there's really no escape from the fact that the chloroplast originated as an endo-symbiont, a symbiont within the cell, and that symbiont resembled very closely what we know today as cyanobacteria.

[Melvyn Bragg] Are you giving us any date for this within a sort of 700 million year, something like that?

[John Allen] Well, I think Nick already said 1.5 billion, and I'd go with that. That's okay. Yeah. I mean, it's hard. There are no fossils of this kind of thing to date in rocks. But it must have happened. Various reasons for knowing, thinking it must have happened.

[Melvyn Bragg] Nick, can I stand up one of you? This is important for me, anyway. The emergence of the first photosynthetic organisms. How did it affect the development, the later development, of life on Earth?

[Nick Lane] Well, I mentioned the snowball Earth and the Great Oxidation Event and so on. After that, 10 or 20 years ago, we would have thought, or we did think, that once oxygen levels started picking up in the atmosphere, everything should have changed. But actually, it didn't - it got stuck in a rut for another billion years or so.

[Melvyn Bragg] The billion boring years.

[Nick Lane] The the boring billion, it's called. Yes. So nothing really happened. Actually, complex cells arose in that time. As John was saying, the acquisition of chloroplasts and so on happened in that time. But there's very little in the fossil record. We do see fossils, but we can't really constrain the sequence of events that happened. But then, at the end of this boring billion, we go into another global upheaval of more snowball Earths and so on. And then right on the back of that is the Cambrian Explosion and the appearance of animals really for the first time in the fossil record. Now, again, there's lots of debates about what was happening, but one thing we're fairly certain about is that oxygen was produced at that time by plants, terrestrial algae and so on, rather than just cyanobacteria. And that gave the animals the energy they needed.

[Melvyn Bragg] And that time is ...

[Nick Lane] Well, the Cambrian Explosion is just over half a billion years ago, 550,000,000 years ago.

[Melvyn Bragg] So we're getting closer...

[Nick Lane] Yes. It's remarkable, though, that for three, three and a half billion years of Earth history, you know, is bacteria and and very simple cells. And then suddenly, with the Cambrian Explosion, you see the first real, real animals.

[Melvyn Bragg] Sandy Knapp would you give us some sense of the place that photosynthesis has in ecosystems in general and that in the Earth as a whole?

[Sandra Knapp] Well, I think photosynthesis itself, as we said, drives life on Earth, essentially, so it drives ecosystems and it probably drives the ... composition of ecosystems as well. If you think of what an ecosystem is, it's all the organisms in a place and their relationships between them. And because so many heterotrophs depend upon autotrophs, which are these photosynthesizing organisms, for their daily lives and their food, and then other heterotrophs depend upon those. So we depend on ... we eat beef, which is a heterotroph, which is eating grass. So we actually are eating sunlight via this complicated sort-of

[Melvyn Bragg] It's a big like "On Ilkla Moor Baht 'at" isn't it, really?

[Sandra Knapp] Yeah, basically, sort of. But I think I think so...really, photosynthesis is driving structural complexity in plants because of evolving structural complexity, to be able to co-occur and harvest light, which is a resource. And then those relationships between things that live on those plants are also driven by that complexity of plants. So it's a tangled web, as Darwin said.

[Melvyn Bragg] John Allen, when did scientists first start to investigate the process of photosynthesis?

[John Allen] Well, you know, the great step in chemistry and biology was Joseph Priestley, about whom Nick has written in his book Oxygen. And in 1772, Priestly published a paper, an investigation of different kinds of air, because he knew some sort of air is necessary for life, and other sorts of air would extinguish life. And so the discovery of photosynthesis is, with good reason, ticked off to Priestly in 1772.

[Melvyn Bragg] And the mouse?

[John Allen] And the mouse?

[Melvyn Bragg] Priestly's mouse.

[Sandra Knapp] The mouse in the bell jar.

[Melvyn Bragg] The mouse in the bell jar.

[John Allen] I've got a mighty quote here. Do we have time for this?

[Melvyn Bragg] Well, we have to rush. Maybe you could one...

[John Allen] "I flatter myself that I have accidentally hit upon a method of restoring air which has been injured by the burning of candles, and that I have discovered at least one of the restoratives which nature employs for this purpose. It is vegetation. One might have imagined that since common air is necessary to vegetable as well as animal life, both plants and animals had affected it in the same manner. And I own that I had that expectation when I first put a sprig of mint into a glass jar standing inverted in a vessel of water. But when it had continued growing there for some months, I found that the air would neither extinguish a candle nor was it at all inconvenient to a mouse, which I put into it." That's the discovery of oxygen and the discovery of photosynthesis in one experiment.

[Melvyn Bragg] What a wonderful way to end. Thank you very much. You got it all in, John. Thank you very much. Very much to John Allen, Sandy Knapp and Nick Lane.

And the In Our Time podcast gets some extra time now with a few minutes of bonus material from Melvin and his guests.

[41:55]

[Melvyn Bragg] Did we leave anything essential out, John?

[John Allen] Yes, I think...you know ... I agree with everything everything said. I didn't mean to have an argument with Sandy. I hope that doesn't come over in that way.

[Sandra Knapp] No. It wasn't an argument. Just a different perspective. [laughter]

[John Allen] The point really is autotrophs, right? You're absolutely correct... but you did say early on, all photosynthetic organisms are autotrophic. They build themselves up. It's not true. Microbiologists would insist and in fact ...

[Sandra Knapp] Yeah, that's true. That's right.

[John Allen] That's for your ... I'm okay for banging on just a little bit.... Now we're off air, right?

[Melvyn Bragg] You must be told this little extra bit goes on as a PS in the podcast.

[John Allen] Okay, well, just I think they can just tell me if this gets boring. Look, there are two things you can ask.

[Melvyn Bragg] We can be been bored for a billion years, what's a few minutes?

[John Allen] There are two things you can ask about any living creature. Number one, where does it get its energy? Right? Is it a phototroph getting its energy from light? Or is it a chemotrough getting its energy from food it eats? Right? So that's energy...

[Sandra Knapp] So I'm just out of date?

[John Allen] No, you're not out of date at all. No, absolutely bang on. So that's the energy. Now, photosynthetic organisms are phototrophs, but they don't have to be autotrophs because they can get the energy and still eat food.

[Sandra Knapp] I think that might be too complex for a taxonomist. That's too much of a taxonomy trope.

[John Allen] I'm not trying absolutely not trying to pull... I would not wish to pull rank. I am humble before a plant taxonomist who actually knows and knows about plants, I do assure you. But the second thing you can ask about any living organism is where does it get its stuff that it makes itself from? Does it apparently get it from nowhere? Well, actually, we know pluck it from the air, it's then an autotroph, or does it get it from other living things? Heterotroph, other feeding? That's a possibility. We're all heterotrophs. No, there are photo heterotrophs that get their energy from light, but they still eat food. They need other organic compounds to assimilate. The other thing that we're almost there. The other obverse of that is there are also chemo autotrophs, which are organisms which not interested in light. They live deep in rocks.

[Sandra Knapp] Are those the vents?

[John Allen] The vents. They're chemo autotrophs that get their energy from chemical reactions, but they fix CO_2 and make carbohydrates, just like so that's a bit of a wider context, that's all...

[Sandra Knapp] But I think what that's what always amazes me is that life on Earth is absolutely incredible. The number of different ways in which organisms make their living - grow, survives.

[Melvyn Bragg] When I walk through London, I feel the same every time I look into shop window. Dr Johnson said that when people make a living...

[Nick Lane] It reminds me of the banking crisis, actually.

[Sandra Knapp] Nothing ever changes.

[Melvyn Bragg] Have we said enough about the sun and how fascinating it is that all the early civilizations, whether it's Ra in Egypt or the sun god in the Aztecs, they had it bang on from the beginning, didn't they? They knew what created life.

[John Allen] They had some immediate perception that the sun was the source of all life. Well, of course, when it rises, life begins. And the seasons, of course, away from the equatorial regions you worship the sun when it begins to appear and exert its strength in the spring, it's remarkable, isn't it? Yes, I think it's a human.

[Sandra Knapp] Well, the correlation between the sun and growth, especially in temperate zones, it's very obvious.

[Nick Lane] I mean, one of the things I don't think I quite got across is that, you know, you think plants produce oxygen, animals consume oxygen, but that's a complete balance, and so nothing changes. That's why you have that boring billion. It's only when... if we die and we're buried and we are not then kind of broken back down into CO_2 and oxygen again... and water again. If we're just buried intact as a fossil fuel, in effect, then the oxygen that would have oxidized you is left over in the air. And so the ... dynamic over evolutionary time is nothing to do with how much photosynthesis there is. It's to do with how much carbon is buried. So it's a geological process rather than really a biological process.

...