Introduction to Complex Biological Systems

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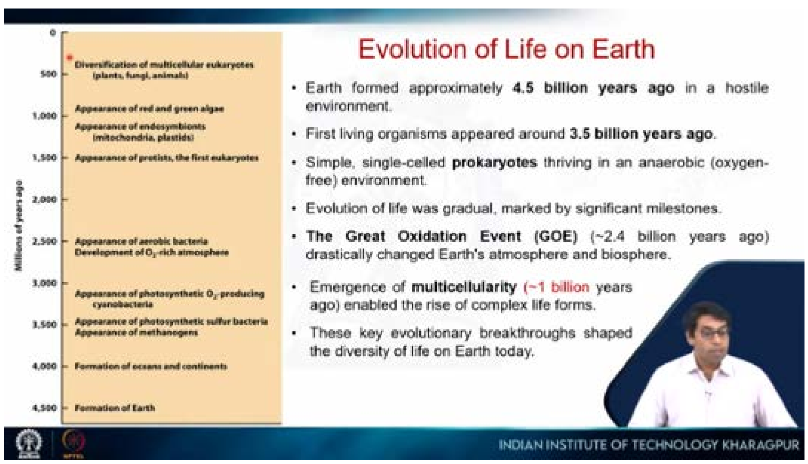
Lecture 36
Evolution of life on earth

Welcome to week eight of the course Introduction to Complex Biological Systems. So this week, I will discuss a very important concept in biology called evolution. You can imagine or consider evolution as the history of life. So today, I'm going to give a basic introduction to this history of life.

Then, in the next few weeks, I will take up more specific topics. So here is a timeline of our evolution. The Y-axis gives you millions of years. So that's the timeline in millions of years. The top part, which says zero, is today, the present day.



So 4.5 billion years ago, which is 4500 million years ago, the formation of Earth took place. 4000 million years ago, the formation of oceans and continents happened. 3500 million years ago was the appearance of the first photosynthetic bacteria. These were sulfur bacteria and also methanogens. These were bacteria that could trap solar energy and convert it into chemical energy.

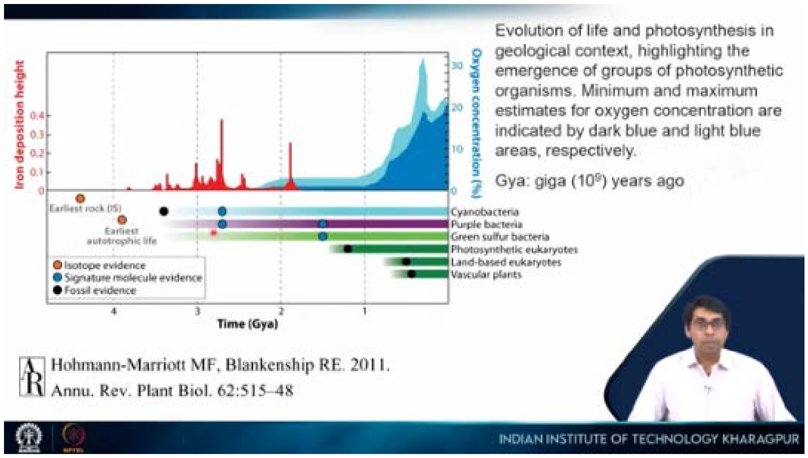
So that was the appearance of life that we understand and then there was the appearance of photosynthetic, oxygen-producing cyanobacteria. So we will see these bacteria in more detail in the coming slides. 2500 million years ago was the appearance of aerobic bacteria. Now, these were anaerobic bacteria, so you can imagine that maybe something similar to glycolysis would happen, where these high-energy molecules would be converted only up to a certain point. So the energy efficiency was not that great, but once these cyanobacteria appeared, they were able to use water as the electron source and one of the byproducts was this oxygen. So we will see that over a period of time, the atmospheric oxygen increased. So the Earth changed a lot in this region. I will discuss that in great detail. So the oxygen increased because of these bacteria, which would produce oxygen as a byproduct and that led to something very interesting called the Great Oxidation Event. So the level of oxygen, which was much, much less than 1% in the atmosphere, went up to the current levels, which is around 20% to 21% and that led to certain catastrophic events where almost all life forms became extinct and then slowly again, this life came back.

So I will talk about that in more detail in the coming slides and then around 1.5 billion years ago, the appearance of the first protists and the first eukaryotes occurred. So now more complex organisms are appearing, but these are still single-cellular organisms.

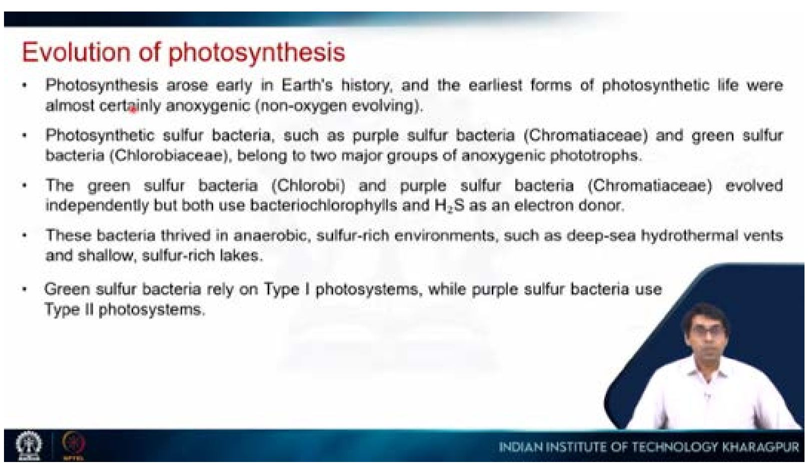
This is something that I discussed in the previous week, and I will discuss it again, where the appearance of these endosymbionts. So these eukaryotes will engulf some of the bacteria, some of the primitive bacteria, resulting in the formation of organelles like mitochondria and plastids and then that further helped in their metabolism and energy production. So then there was the appearance of red and green algae and then almost 500 million years ago, something interesting happened, which is called the Cambrian explosion.

So in this phase, it seems like the organisms suddenly experienced an explosion. A huge explosion of different species evolved and before that, something interesting happened, which is the multicellularity of eukaryotes. So up to this point, we had single-cellular organisms. So here multicellular organisms appeared and then diversified very rapidly.

So in a few million years, we had all these different species and now we are here, in the present day. So let's look at these events in more detail. So this is the level of oxygen. So you can see that the oxygen concentration in our atmosphere is plotted on this side and this is the height of iron deposits. The X-axis plots the timeline. So this is the present day and as we go towards the left, it is in the past so one is the present. GYA, so GYA is giga years ago. So that is 1 billion years ago so 1 billion, 2 billion, 3 billion, 4 billion. So Earth formed somewhere here, 4.5 billion years ago and you can see that the level of oxygen was very low.



Then, over time, there was this buildup of oxygen, and now it has reached this 20-21% oxygen concentration and here, you see the appearance of all these different organisms. So cyanobacteria, purple bacteria, and green sulfur bacteria evolved or appeared at all these different time points and then, finally, the multicellular organisms appeared here. One of the most interesting things that happened is the evolution of photosynthesis because photosynthesis is directly related to all living organisms.



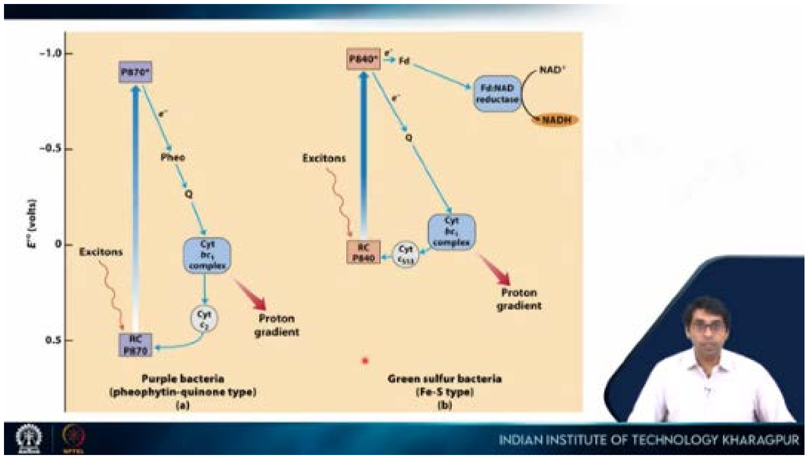
As we saw in the previous lectures, sunlight is the major source of energy and photosynthesis is the process that traps that energy. So, over time, photosynthesis became more and more efficient. We saw the emergence of more and more complex organisms, organisms that can harness this energy in a better way.

So photosynthesis arose early in Earth's history, and the earliest form of photosynthetic life was almost certainly anoxygenic. Anoxygenic means that they did not produce oxygen and that is evident here that all these organisms were not producing oxygen. Hence, the atmospheric oxygen was quite low. Photosynthetic sulfur bacteria, such as purple sulfur bacteria and green sulfur bacteria, belong to the two major groups of these anoxygenic phototrophs.

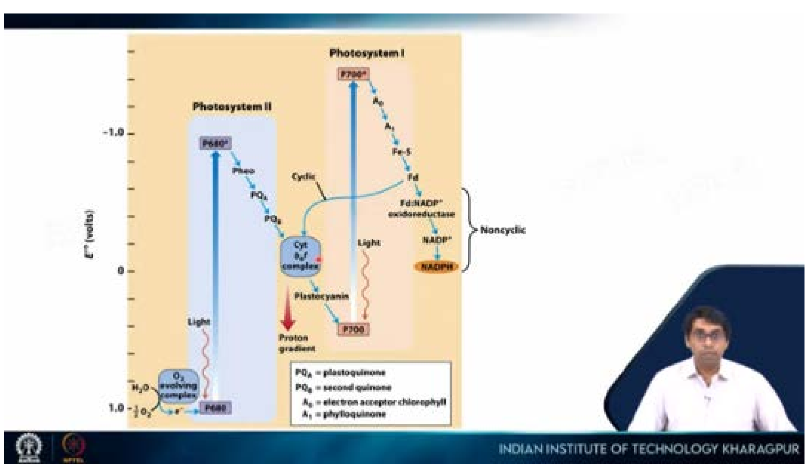
The green sulfur bacteria and purple sulfur bacteria evolved independently, but both used bacteriochlorophylls and hydrogen sulfide as the electron donor. So, they were not using water, which is H_2O, as the electron donor. They were using H_2S as the electron donor. Now, these two bacteria are postulated to have evolved independently and this is something that we will see again and again in evolution.

So, this is called convergent evolution. So, the same solution is arrived at from different sources. So, we will see that in the case of organisms, and we will see that in the case of proteins also. These bacteria thrive in anaerobic, sulfur-rich environments such as deep-sea hydrothermal vents and shallow, sulfur-rich lakes. Green sulfur bacteria rely on type 1 photosystems, while purple sulfur bacteria use type 2 photosystems.

So, these are shown here. So, this is your green sulfur bacteria, which uses this type 1 photosystem and the purple bacteria use type 2 photosystem. So, these are the reaction centers. They trap energy.

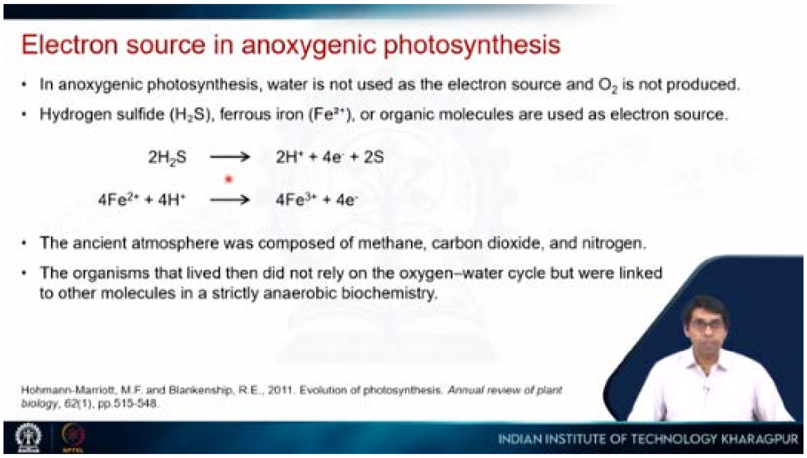


The reaction center's energy goes up, and then there is charge separation. So the electron is ultimately deposited, and then that creates a proton gradient across the plasma membrane and then that proton gradient is used to synthesize ATP. Now, these two bacteria had these two different photosystems or the reaction centers, and in the current organisms. So in current eukaryotes, we have seen that both these photosystems are incorporated. So light is absorbed twice, and the electron, which goes up in energy, loses, so there is a proton pump done here, and then again it is raised by absorption of another photon in photosystem one, and then again it comes back and more protons are pumped. Either it produces this high-energy molecule, or it goes back into this cytochrome B6F complex to create this proton gradient. So over time, these two photosystems, which evolved separately or independently, got incorporated together into these higher organisms. The electron source in this anoxygenic photosynthesis as I mentioned earlier, was not water.



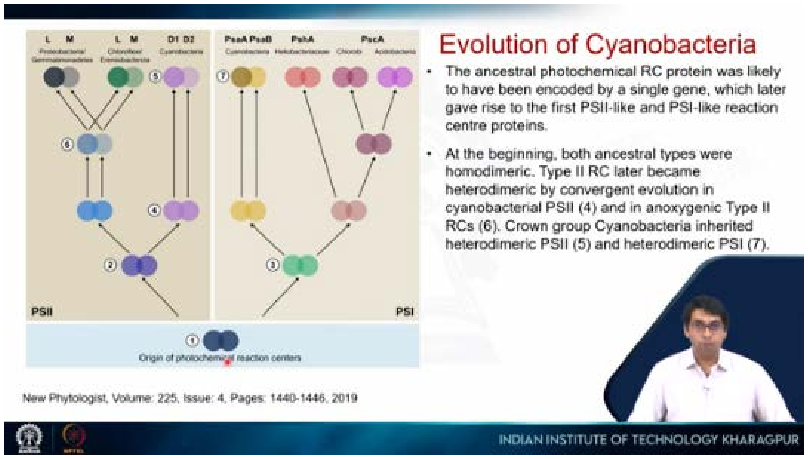
So it was not water. Hence, oxygen was not produced. Instead, hydrogen sulfide or ferrous ions or some other organic molecules were used as the electron source. So the reactions can be written like this. Hydrogen sulfide gives up a proton.

Electrons are released. Hydrogen sulfide gives up protons. Four electrons are released and sulfur is formed. Similarly, ferrous gets oxidized to ferric and electrons are released. The ancient atmosphere was composed of methane, carbon dioxide and nitrogen.



So there was not much oxygen. So these oxygen that lived then did not rely on the oxygen water cycle, but were linked to other molecules in a strictly anaerobic biochemistry. So we can imagine that one of the earlier organisms where this photochemical reaction center evolved, it was most probably a single gene. So one protein and it produced two copies. So it was a dimer that single gene was the original photochemical reaction center and then over time it accumulated mutations. So it got changed into all these different photochemical reaction centers. So at the beginning, both ancestral types were homodimeric. So you see that these two ancestral types are homodimeric. That is denoted by the same color both are the same color and then they diverge, but they are still homodimeric. Now, at this point, maybe some mutations accumulated in this gene, not this gene. So the gene duplication happened. Now, some mutations happened in this gene, and it changed this protein. So even though the overall protein remains the same, the architecture and everything remain the same, but they become slightly different. The same thing happened here. The same thing happened here.

The same thing happened here or maybe this is the same. So the same thing happened here.



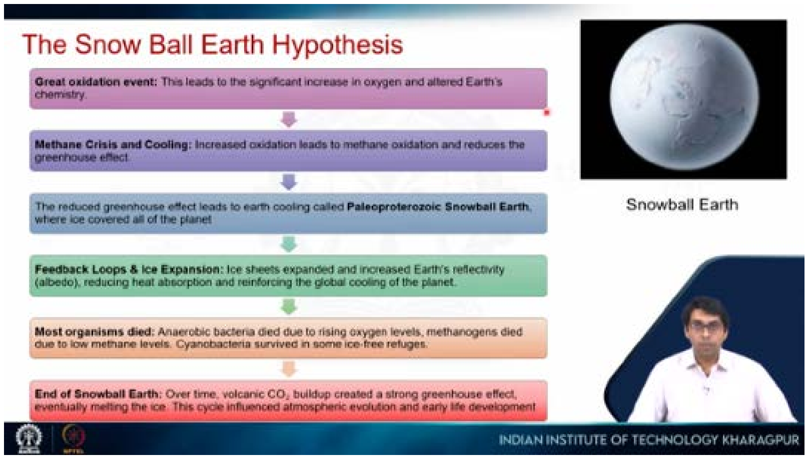
So, like this, this ancestral protein kept accumulating mutations that resulted in slightly different versions of these proteins, which would perform slightly different functions and finally, this crown group of cyanobacteria inherited this heterodimeric photosystem II, which is this, and the heterodimeric photosystem I, which is this. So, it got both these two photosystems and combined them like we saw in the previous slide. So now, these cyanobacteria were producing oxygen and that led to something which is the accumulation of oxygen over time. That is called the Great Oxidation Event, a pivotal transformation in Earth's history. So, this is almost 2.4 billion years ago. It was characterized by a dramatic and permanent increase in atmospheric oxygen levels.

So, this was primarily driven by cyanobacteria, which are capable of oxygenic photosynthesis, which means that they release oxygen as a byproduct of splitting water molecules. So, instead of withdrawing electrons from hydrogen sulfide, these bacteria were withdrawing electrons from water, and in that process, they were producing oxygen, which means that the atmospheric oxygen levels were slowly going up. Oxygen-producing microbial mats thrived in shallow seas and they were using this water source generously. Now, dissolved iron in the oceans reacted with this oxygen.

So since they were producing this oxygen, it means that dissolved oxygen in the seas was also increasing and that was reacting with this dissolved iron and started forming iron oxide, which is this red precipitate rust and that formed these iron oxide precipitates. So this process initially delayed atmospheric oxygen buildup, but it created geological evidence of oxygenation. So if you dig in certain places, what you can see is layers of iron oxide deposition and that gives us geological evidence of this event, that is, the Great Oxidation Event. Free oxygen reacted with reduced sulfur and also carbon compounds so gradually saturating these things. So these sources of hydrogen sulfide and also methane were gradually depleting. A marked transition from a reduced atmosphere to an oxidizing one happened, which enabled aerobic respiration.

However, it created a really toxic environment for anaerobic bacteria. So, most of these anaerobic bacteria would actually die because of this Great Oxidation Event. But since aerobic metabolism evolved because of the presence of oxygen, which results in the production of more energy, as we have seen in the previous lectures. So, more energy utilization means that more complex functions can be done. So, the stage was set for the evolution of more complex life forms.

So one of the things that happened because of this great oxidation event is the rapid cooling of Earth, and that led to something which is called the snowball Earth hypothesis. So it is imagined that Earth formed a snowball like this, where it was completely covered with ice. So the great oxidation event led to a significant increase in oxygen and altered Earth's chemistry. Now, because of this increase in oxygen, a methane crisis happened. So methane would react with this oxygen. Increased oxidation led to methane oxidation and reduced this greenhouse effect. So you lose methane, which has a greenhouse effect, meaning that it traps heat in the Earth's atmosphere. So now that heat is lost. So the temperature of the Earth's atmosphere will gradually decrease because of the loss of this methane.



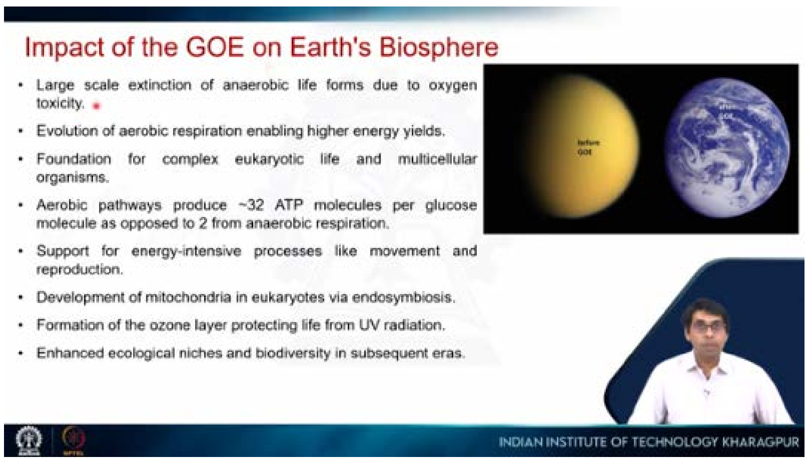
The reduced greenhouse effect leads to Earth cooling and this is called the Paleoproterozoic snowball Earth. You can imagine it looked something like that, where ice covered the entire planet. Now, feedback loops and ice expansion so one thing led to another.

Ice sheets expanded, increasing Earth's reflectivity. So if it is white like this, the solar energy that comes in will be reflected off. So less heat energy was absorbed by the planet. So that led to further cooling. So this reduced heat absorption and reinforced the global cooling of the planet.

As a result, most organisms died so this is also called the oxygen catastrophe because it was triggered by this oxidation event so anaerobic bacteria died due to the rise in oxygen levels. Methanogens died because methane was also captured due to low methane levels, cyanobacteria survived in some ice-free refuges.

So most cyanobacteria would die, but there were some pockets where some of these cyanobacteria would survive. Then over time, volcanic eruptions and the buildup of carbon dioxide created a strong greenhouse effect, which eventually melted the ice and this cycle influenced atmospheric evolution and early life development. So this event sort of made the transition from anaerobic to aerobic respiration for these microorganisms. So again, this is the summary, and we have reached up to this point that these aerobic bacteria are now thriving after this great oxidation event.

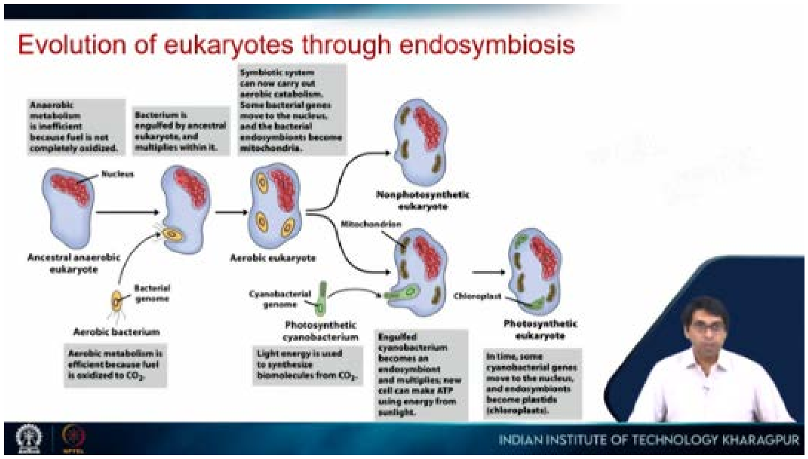
So, what was the impact of this Great Oxidation Event on Earth's biosphere? Large-scale extinction of anaerobic life forms due to oxygen toxicity. That happened. The evolution of aerobic respiration enabled higher energy yields because now oxygen could be used to oxidize molecules further, resulting in greater energy output, the foundation of complex eukaryotic life and multicellular organisms.



Since energy could be utilized more efficiently, more complex life forms evolved. As a reminder, aerobic pathways produce 32 ATP molecules per glucose, whereas anaerobic respiration produces only two. This higher energy production resulted in more complex functions. Support for energy-intensive processes like movement and reproduction was enhanced because organisms could now utilize energy more efficiently. The development of mitochondria in eukaryotes via endosymbiosis also contributed.

Another byproduct of the increased oxygen levels was the formation of the ozone layer, which protected life from UV radiation. Finally, enhanced ecological niches were created, leading to greater biodiversity in subsequent eras. We can imagine that before the Great Oxidation Event, our planet looked something like this due to sulfur and iron. After the Great Oxidation Event, it looked something like this. This is something we have already seen.

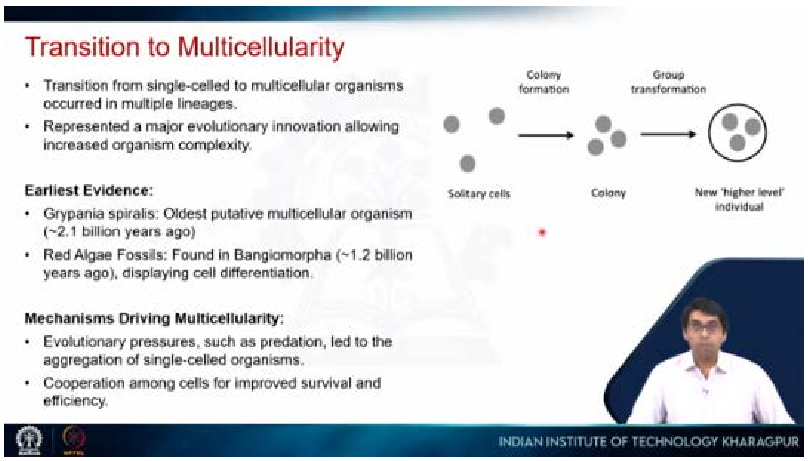
So by this time, eukaryotes have evolved, and something interesting happened, which is called endosymbiosis. So this is the ancestral eukaryote. So it has the nucleus. Now, this ancestral eukaryote engulfs one of these bacteria.



So this is an aerobic bacterium. So it engulfs this bacterium. Once the bacterium is inside the eukaryote, it finds this very rich environment. So it also multiplies, survives, and multiplies there. Now, this bacterium over time transfers some of its genes to the nuclear genome while it retains some and this bacterium gets converted into mitochondria, so this is a modern eukaryote, which is non-photosynthetic. Now, this eukaryote would capture a cyanobacterium, and again, some of the genes would get transferred to the nucleus, and it would retain some other genes, and then this cyanobacterium would eventually get converted into a chloroplast. So now this becomes a photosynthetic eukaryote because it can capture light energy and convert it into chemical energy. So eukaryotes evolved, now, they have mitochondria, they have chloroplasts, so they can do these reactions much better.

Something more interesting happened over time, which is the transition of these single-cellular organisms to multicellular organisms. So, these organisms were single-cellular like this, but over time, it was advantageous for the cells to cluster together like this. So that helped in their survival, etc. etc. We will see that. Then they can form a higher-level organism where these individual cells don't remain exactly the same, but they change and now they can become a higher-level organism. So we will see the mechanisms. The transition of single-cell to multicellular organisms occurred in multiple lineages. So it happened in many different ways. That is why we have so many different organisms. So it represented a major evolutionary innovation, allowing increased organism complexity. So we have all these different types of organisms and species. What are the evidences? One of the early evidences is this.

So it's the oldest putative multicellular organism. So it seems to have evolved 2.1 billion years ago. Red algae fossils have also been found and they are known to be 1.2 billion years old, displaying cell differentiation, which means that in the same cluster, you will find different types of cells. So what are the mechanisms?



Evolutionary pressures such as predation. So if they are alone, they can be engulfed by other organisms but if they form a cluster or a colony like this, then the chance of survival increases. So you will have any mutation that favors this will survive.

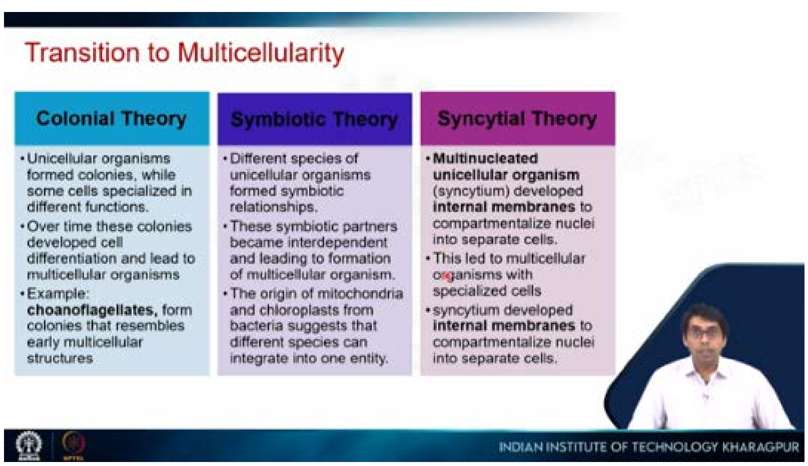
So this led to the aggregation of single-celled organisms, cooperation among cells for improved survival and efficiency. So once they are grouped like this, they can exchange materials, genetic materials, and other organic materials, which also help in the better survival of these organisms. So eventually, any processes or mutations that would help will give a survival advantage to those organisms. So there are several theories of multicellularity.

I will discuss the three major ones. The first one is the colonial theory. So, unicellular organisms formed colonies, while some cells specialized in different functions. Over time, these colonies developed cell differentiation and led to multicellular organisms. So, you have a cluster of cells.

Now, some cells will develop some mutations or gain some mutations so that they will change their characteristics and this will eventually provide them some survival advantage. So, this differentiation will ultimately lead to multicellular organisms.

So, an example is this: Choanoflagellates. So, they form colonies that resemble multi-multicellular structures. The second mechanism or theory is the symbiotic theory. So, it says that different species of unicellular organisms form symbiotic relationships. So, here they are the same species. These are different species.

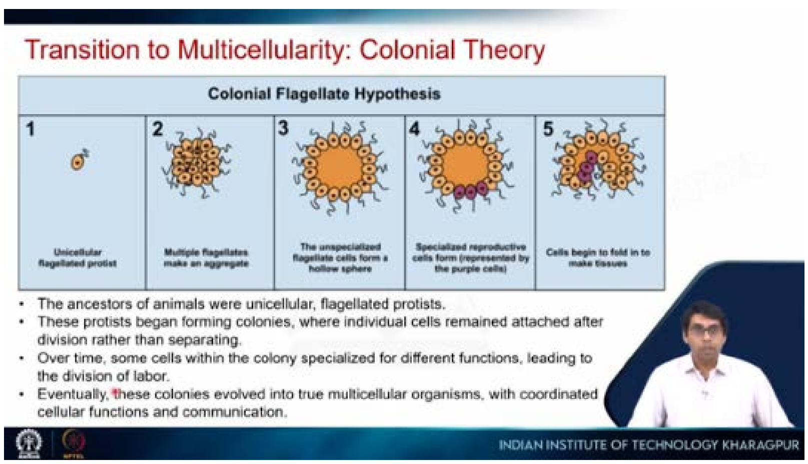
Now they form a symbiotic relationship. So they can exchange materials and help each other to survive. These symbiotic partners become interdependent, leading to the formation of multicellular organisms. The origin of mitochondria and chloroplasts, as we have seen, can be considered as an example. Syncytial Theory, so here, a multinucleated unicellular organism, you have one cell, but instead of one nucleus, you have multiple nuclei. So this develops inside the cell, and then internal membranes will occur, compartmentalizing these nuclei into separate cells. This led to multicellular organisms with specialized cells. So we will see an example of this in the next slide.



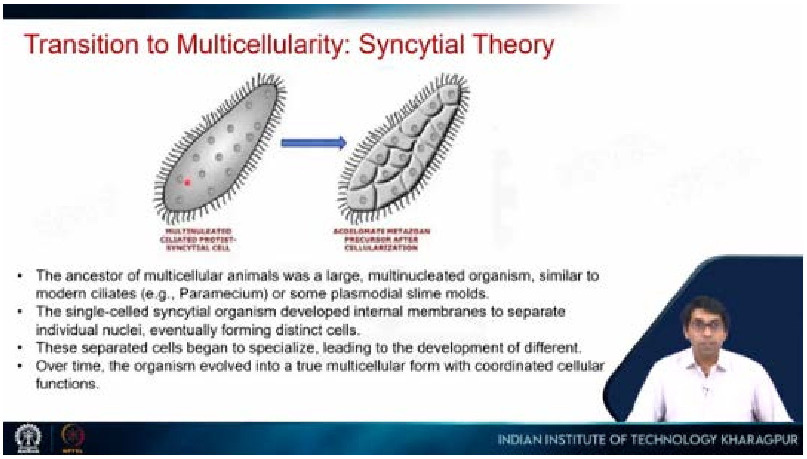
So this is the first one, the colonial theory. So what you have is a unicellular flagellated protist. So it is a single cell. So the ancestors of animals were unicellular flagellate protists like this. These protists began forming colonies where individual cells remained attached after division rather than separating.

So once this divides, instead of separating out, they will form a cluster like this. So over time, some cells within the colony specialize for different functions, leading to the division of labor. So some of these cells will gain mutations and become specialized cells. So they will perform certain other functions compared to these.

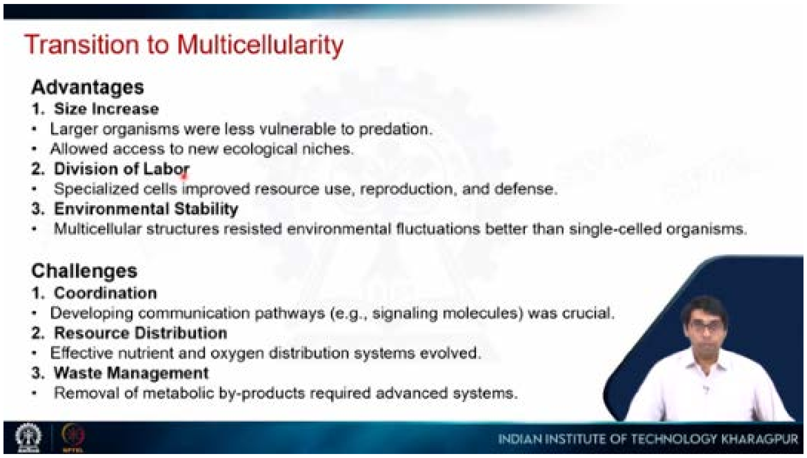
So this division of labor will eventually help in the survival of this colony of cells. Eventually, these colonies evolved into multicellular organisms with coordinated cellular functions and communication. So now these cells will start to fold. They will have a particular arrangement, and they will also evolve more cells with different functions and finally, they will become a multicellular organism.



So this is the third one, the Syncytial Theory. So this is a cell with multiple nuclei. So, a multinucleated ciliated protist, the ancestor of multicellular organisms was a large multinucleated organism similar to modern ciliates or some plasmodial slime molds. This single-celled organism developed internal membranes to separate individual nuclei. They will start developing internal membranes like this, where each of these nuclei will now get separated, eventually forming distinct cells. So this one will form one cell, this will form another cell, and this will form another cell. These separated cells began to specialize, leading to the development of different cell types.

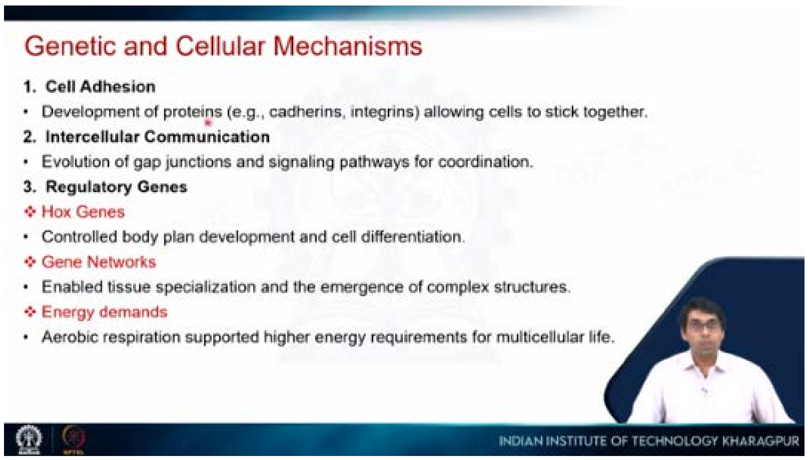


So now, if they start becoming different, you will have different cell types and functions. So over time, this organism evolved into a true multicellular form with coordinated cellular functions. There are several advantages when organisms transition from unicellular to multicellular. The first one is an increase in size. Larger organisms were less vulnerable to predation. So they can protect themselves better, plus this allows access to new ecological niches. Division of labor, since there are multiple cells of different types, specialized cells can be developed, which can use resources better. Cells can help in reproduction, and cells can help in defense.



So this type of division of labor will help in the survival of the organism. Environmental stability, so multicellular structures resist environmental fluctuations better than the single-celled organisms. Challenges, coordination, so developing communication pathways between the cells, which is signaling molecules.

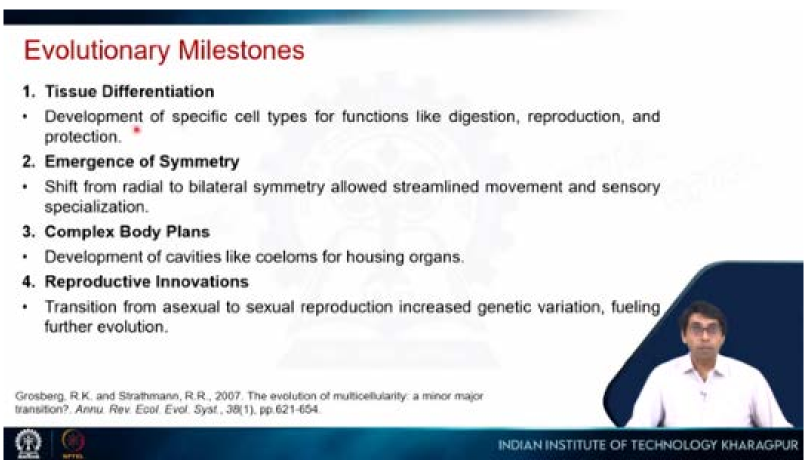
So these things were slow to develop, but these were some of the challenges. Resource distribution, so how do you distribute all the resources between different cell types so effective nutrient and oxygen distribution systems have to be evolved. Waste management so there is many byproducts that are formed and that have to be excreted out. So removal of metabolic byproducts required as advanced systems. Genetic and cellular mechanisms, so what were the genetic and cellular mechanisms which help these multicellular organisms to stay multicellular? The first one that is needed obviously is the cell addition.



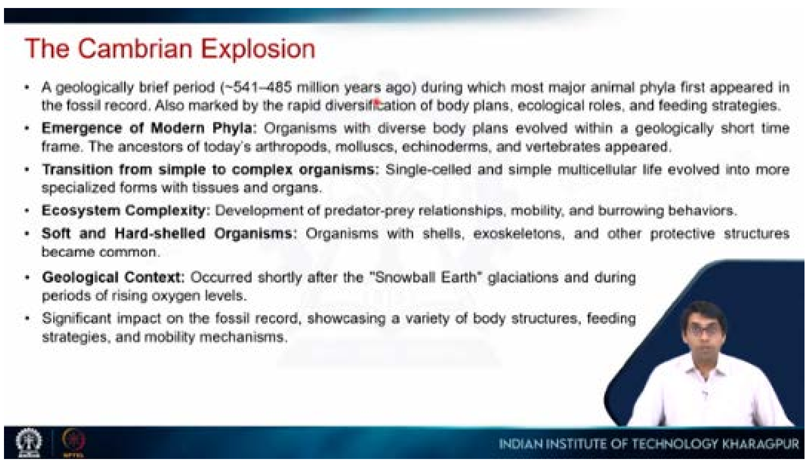
So these cells have to stick together. So for that, specialized proteins evolved, such as cadherins and integrins, which allow these cells to stick together. So these are like molecular glues. So that will allow these cells to stick together. Intracellular communication, so now these cells may have to communicate with each other via, again, more specialized types of proteins. So the evolution of gap junctions and signaling molecules occurred for this type of cellular communication and then, once these multicellular organisms evolved into more complex organisms with different body plans, more types of genes evolved, such as regulatory genes so one such regulatory gene is the Hox gene. So these are transcription factors that control body plan development and cell differentiation.

So starting from this single zygote, the cells, once they start dividing, which cell will form the head, which cell will form the torso, and which cells will form the limbs are decided by these Hox genes. So this type of specialized protein or gene evolved to determine the body plan of an organism. Gene networks, so these also evolved and they enabled tissue specialization. Emergence of complex structures, we have exactly the same number of genes in all the cell types, but different genes are expressed in different cell types, resulting in the formation of different tissues. So these gene networks evolved over time. Energy demands, aerobic respiration supported higher energy requirements for this multicellular life so multicellular life was supported a lot because of the evolution of aerobic respiration.

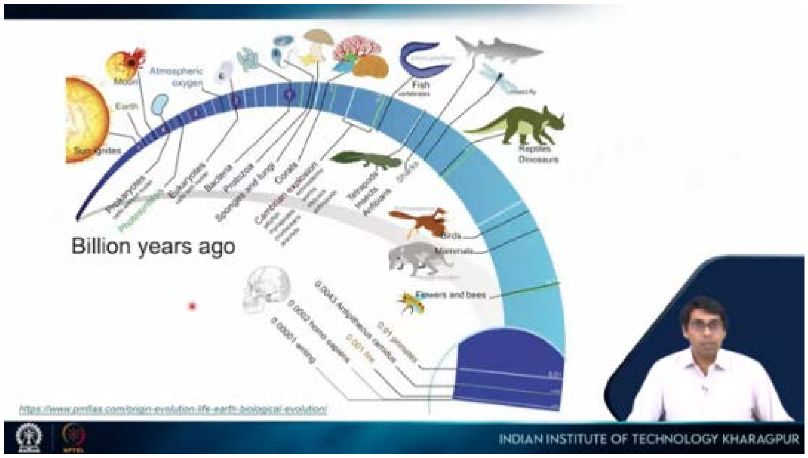
So what were these evolutionary milestones? Tissue differentiation, so now more complex organisms have evolved with different types of tissues. For example, we have all these different tissues: skin cells, liver cells, heart muscle, brain, and so on. So the development of specific cell types for functions like digestion, reproduction, and protection happened. So protection means immunity. Emergence of symmetry, so the shift from radial to bilateral symmetry allowed streamlined movement and sensory specialization. So if you see a starfish, that is radial but if you see yourself, we have this bilateral symmetry. So that shift happened as more and more complex organisms evolved and then complex body plans evolved so development of cavities like coeloms for housing reproductive innovations, transition from asexual to sexual reproduction. This increased genetic variation, fueling further evolution.



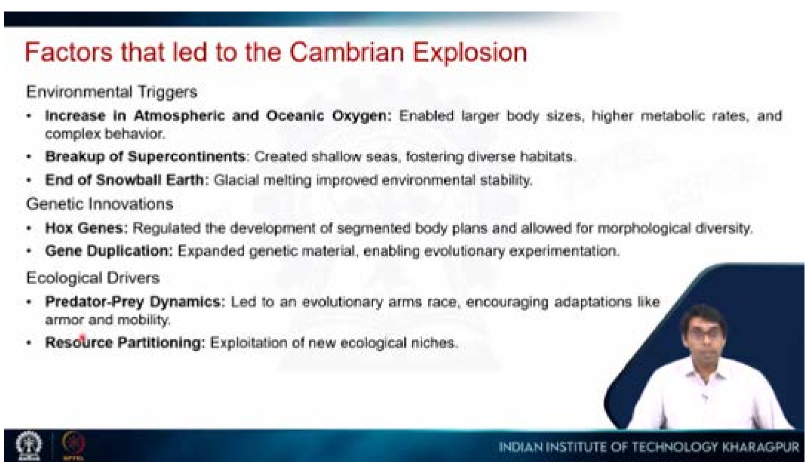
So again, this is the summary. We started from here and we have reached somewhere here and now this interesting event happened, which is the diversification of these multicellular eukaryotes, known as the Cambrian explosion. So the Cambrian explosion was a brief geological period, which is estimated to be almost 500 million years ago. So during this, most major animal phyla first appeared according to the fossil record. So it also marks this rapid diversification of body plans, ecological roles, and feeding strategies so all different behaviors and other things evolved in this time period so the emergence of modern phyla. Organisms with diverse body plans evolved in this very short time period transition from simple to complex organisms so single-celled and multicellular life forms evolved into more specialized forms with tissues and organs. Development of predator-prey relationships, mobility, so organisms started moving around, burrowing behavior, so digging holes and staying inside those. So all of these behaviors also evolved in this time period and then there were organisms with soft and hard shells.



So organisms with shells, exoskeletons, and other protective structures became very common. Geological context, so, this occurred shortly after the Snowball Earth glaciation and during the period of rising oxygen levels. Now, there are these significant fossil records which highlight this. However, there are several criticisms also. So, this is a summary of the evolution of life on Earth. So, the sun ignites the formation of Earth. Then we have this Cambrian explosion somewhere here, which is 500 million years ago. Then all these different life forms evolve, and we are somewhere here. So, what are the factors that led to this Cambrian explosion? Again, these are mostly speculation and hypotheses, but based on all the geological and fossil records, geological evidence, and fossil records. So first is, of course, this increase in oxygen levels. Wake up of supercontinents, so that also resulted in these isolated habitats that created different types of ecological systems. End of the Snowball Earth, so that helped in the formation of a stable environment. Genetic innovation, so Hox genes, which created these different body plans, gene duplication that, expanded the genetic material, resulting in this evolutionary experimentation of different mutations. We will talk about all these things in more detail in the next two lectures.

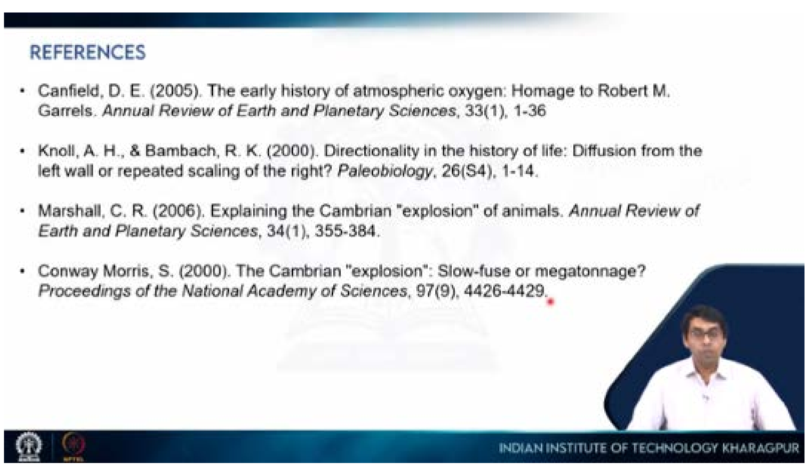


So that helped in the formation of diverse proteins and functions. Ecological drivers, so predator-prey dynamics, this led to an evolutionary arms race. So this resulted in a change in behavior, which was also and also resulted in the adaptation of certain mutations that would give them survival benefits. So anything that has armor, a hard shell, will survive better and anything that can move fast will survive better so all of these functions evolved because of this predator-prey dynamic.



Resource partitioning, exploitation of new ecological niches and all of these things led to this Cambrian explosion or evolution of all these different species almost 500 million years ago. There are, of course, controversies because these are all based on certain fossil records and mostly speculation. So there is a debate whether the Cambrian explosion was a true rapid event or an artifact of incomplete fossil records so corrupted fossil records can lead to wrong conclusions.

For example, organisms with hard parts or hard shells, their fossils will survive better compared to organisms that have soft bodies or soft tissues. So even though such organisms appeared before the Cambrian explosion, their fossils will not be there and hence we will not know about them. Now there is evidence from this Ediacaran period which suggests a longer timeline for the emergence of complexity. So what we have is the best guess of the evolutionary record of life on Earth. So I have already listed several references in different slides.



These are some of the additional references that you can look into. Thank you.