An Introduction to Evolutionary Biology

Prof. Sutirth Dey

Biology Department, Population Biology Lab

Indian Institute of Science Education and Research (IISER) Pune

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Origin of Life: Part 2

Hi, so in our last discussion, we looked at the Oparin-Haldane hypothesis. which provided a series of steps by which simple non-living molecules under prebiotic conditions could have given rise to life. Now, as I said, this is one of the biggest and most fundamental questions in the whole of biology. And therefore, people have spent a lot of time and effort to validate, you know, each component of those steps. And you know, countless experiments have taken place over the last 100 years or so. So, we do not really have time to go into it in great detail, I mean it can easily, you know, be taught as a full one-semester course or maybe more than that. So, what we are going to do is have a quick bird's-eye view of some of the key insights. and some of the key experiments that have shaped our understanding of how life originated. So, the first step, if you remember, is that under the conditions of primitive Earth, organic monomers—what do we mean by that? Amino acids, nucleotides, sugars, etc., can really be formed. Now, what are the conditions of primitive Earth that we are talking about? Now, we obviously do not have any direct evidence of what those conditions were. but we have some circumstantial evidence from, for example, what happens when there is a volcanic eruption. What kind of gases come out of that? The other major thing we have is that if these molecules formed, you know, In the open, directly in contact with the atmosphere, because at that point you do not really have membrane-bound organelles. So, under those conditions, if the atmosphere had as much oxygen as we have today, Then there were good chances that these, you know, reactions—these monomers—would not even have been formed.

How do we know that? Because of the properties of those monomers. Therefore, it is generally thought that the early atmosphere was reducing and obviously had much less oxygen. And, more importantly, the source of energy was different. So, today for living molecules, the primary sources of energy, you know, are coming from photosynthesis or ATP hydrolysis and so on. But at that point in time, these molecules are not there; these pathways are not there.

Therefore, the primary source of energy will be in the form of electric discharge. That are happening in the atmosphere, such as lightning, etcetera, during thunderstorms and heat. Heat from where? Remember, Earth is still a young planet, so it is still very hot. So, a lot of you know that heat is directly coming from the surface. Now, as far as the electric discharge and heat are concerned, People are reasonably confident that you know that is how things were.

In terms of the reducing property of the atmosphere, there is some disagreement among the scientists. about whether it was strongly reducing, weakly reducing, or whatever. So, different people have said different things. But it is generally understood that the level of oxygen was definitely less than it is today. So, the main question is, can organic monomers be formed under such a situation? And a very famous experiment that first tackled this question showed rather nicely that it can happen was this one due to Stanley Miller and Harold Urey? So, although this is known as the Miller-Urey experiment, it is generally acknowledged that the idea And the entire execution was due to Stanley Miller, who at that point in time was a PhD student with Harold Urey. Urey was already a Nobel laureate and extremely famous, but this was entirely, you know, Miller's game. And frankly, Urey more or less has recognized throughout his life that it was Miller who did all the work. And in fact, if you look at the paper, you will see I am showing you the reference over here. You can see that the paper only carries Miller's name, but somehow you know this is referred to as the Miller-Urey experiment.

So, what exactly was done? So, Miller was trying to simulate the prebiotic conditions. So you have two major components: the ocean and the atmosphere. So, in order to simulate the ocean, what he does is take a glass flask, put some water in it, and then heat it using a heat source. What happens? This will lead to the water becoming vapor, right? That is what happens even today. You have sun rays falling, and water turns into vapor. Then this vapor goes up, and in the context of the setup, This goes up through this tube, and then it enters the atmospheric component over here. What is an atmospheric component? It is another big glass flask, and in that flask, he put things like ammonia, methane, and hydrogen. Now, why did he put in these chemicals? Because this was his best guess at that point in time in 1952 about what the atmospheric composition would have been like. Then, in order to simulate lightning, he puts in two electrodes and uses an electric connection. Basically, you know, it creates a continuous spark between those two electrodes.

So, as a result of this high source of energy, these gases plus water. There is a reaction that is happening in this simulation of the atmospheric component. And then this stuff condenses, and then it comes down over here. So, here he puts a condenser to cool the whole thing, and this is essentially analogous to rainfall. And then this comes over here, comes down, and he puts a trap over here, so that from here he can take samples and analyze them. There is one more trap over here to understand what is happening in this part of the oceanic component. And then he sets this up and just lets it run for one week. So, I have a very nice video that shows you quickly, you know, the same stuff, 3D animated. Just to show you how the components rotated or moved from one part of the setup to the other.

So, I will just try to play this game. So, that blue arrow that is showing you the path of the, you know, water—water vapor, actually. So, this is, as I said, the oceanic component. So, this is being heated, and then you have the formation of water vapor, as shown by these bubbles. And this water vapor rises and then, through this tube, it reaches the, you know, simulation of the atmosphere.

So, in this component, you have the electrodes that are continuously sparking because of the chemical reaction that happens. The condenser cools the whole thing down, and then this comes back over here again. So, there is a continuous circulation happening. And as this says at the end of one week, as much as 10 to 15% of the carbon was now in the form of organic compounds. And so, these are the people who made that excellent video, and the results from this experiment were absolutely astounding.

So, after a week, the solution had turned deep red and turbid. Remember, this is 1952, so analytical techniques are still not as good as they are today. So, at that point, Miller had to do paper chromatography to figure out what the various things were and he identified. Five amino acids prove that the monomers of proteins can be formed from inorganic, organic, and pre-life molecules. So, it does not end here.

So, this happened in 1952. So, somewhere around 2007, Miller retires, and when he retires, it turns out that There were several samples that had been created from, you know, experiments done during that time. Not the 521 later experiments, and these samples had actually been sealed by Miller and kept. So, when he retires, this goes to the group of, I think his name was Jeff Bada. And Bada then takes these things and ends up reanalyzing the samples.

But since he was doing it in 2007, he used more modern techniques like High-performance liquid chromatography and time-of-flight mass spectrometry. And when he does that, he figures out that the same samples actually contained 23 amino acids and 4 other amides. So, the yield was actually much greater and more diverse than What Miller had actually ended up identifying was his primitive technique. So, this was a massive thing in the history of the origin of life research. And this conclusively proved that the fundamental building blocks of life could indeed arise from nonliving matter.

Now this was primarily about amines and amino acids. What about the other kinds of molecules? You need a lot to create life. So his research over the last 100 years has shown that almost all the biological monomers that you know are needed for life. All of them could have formed on the prebiotic Earth. So here is a video review that I am giving you the reference for which essentially discusses the various molecules and the conditions under which they were synthesized. Very, very comprehensive review. So now that you have the monomers, remember that all this is happening in the ocean, which is huge. So the concentration of these compounds, even if they are being formed, is going to be very, very low. And even if a lot of time passes, they are still not going to become too high.

And if you have to go from monomer to polymer at some level or at some point. The concentration needs to become high; otherwise, polymerization reactions do not take place at some level. So, how will that concentration happen, or how did that concentration happen? So, in order for the monomers to come together to form polymers, you need a mechanism by which they will come together. So, it turns out that there are multiple possible ways in which this could have happened. I am just talking about three such possible solutions; there are many more.

So, by the way, when I am talking about possible solutions, these are not mere hypotheses. These have been explicitly shown by people to work in order to create polymers from monomers. So, for example, there are many kinds of clay, and the most well-studied example is this substance called Montmorillonite. I hope I am pronouncing it correctly. So, if you have clay, then what happens is two or three things.

First of all, the clay, you know it is an adsorbing material. So, it can adsorb various kinds of monomers onto it, which obviously increases the concentration. The second thing that happens is that many of these clays act as catalysts, and in particular, they can catalyze. The phosphodiester bond, which is very important in the formation of polynucleotides, DNA, and RNA precursors. So, that is one thing that people have nicely shown again and again: you know, clay is one of the major ways in which many monomers can be concentrated to form polymers Many monomers can polymerize; basically, forget concentration; they can actually polymerize. The second huge candidate that people have is the hydrothermal vents. So, you know that these are vents typically at the bottom of the ocean where continuously heat is coming out. The chemistry near these hydrothermal vents is absolutely fascinating. I am not an expert on it, but when I look at it, I can see that there is a lot of, you know, complicated stuff going on over there.

Now, apart from the chemistry, you also have a very peculiar structure in these hydrothermal vents, which are kind of like Porous kinds of structures wherein people have shown that all these, or many of these, monomers can actually attach. Just like they can attach, you know, on the surface of the clay, they can also attach over there and thereby. Form local high concentrations, which can obviously be good for polymerization. The other thing over there is that the chemistry is such that people have shown, you know, empirically and theoretically, that That chemistry is extremely conducive to many of these polymerizations. That is why many scientists believe that the initial polymerization led to the origin of life might have happened, you know, at these hydrothermal vents. And the third major thing that people have shown is that, suppose you have a mudflat or a tidal pool. So, what happens? You know water comes and then it evaporates, but when it evaporates, obviously the concentration increases. After some time, it becomes dilute again and then evaporates again. So, if this keeps happening again and again, then, The concentration of the monomers is going to increase over there, which might end up promoting polymerization.

Now, please appreciate one thing: these are just three of the many possibilities. B: Nobody is saying that these are mutually exclusive. It is entirely possible that all these things you know worked simultaneously, and you know. Some of the reactions happened on one kind of surface; some of the other reactions happened on another kind of surface. So, this is how one can go from monomers to polymers.

But now polymers are just molecules, right? But somewhere there has to be a function; otherwise, life will not work. So, in order to understand how you go from polymers to functions, let us go back to the definition of life. The NASA definition of life that we had discussed in our previous discussion. So, if you remember, the definition was that life is a self-sustaining chemical system that is capable of Darwinian evolution.

Now, let us unpack this definition. You have a chemical system, and you have Darwinian evolution. So, obviously, if you have a chemical system, then that chemical system has to be doing something. It has to be performing some roles; there has to be, you know, some catalysis or some kind of reactions happening. But more importantly, if you are talking about Darwinian evolution, remember natural selection. And remember, I had said that in order for natural selection to happen, you definitely need inheritance of information, right? So, any self-sustaining chemical system that can undergo natural selection will need a chemical structure that will be capable of Encoding complex genetic information, and that complex genetic information will need to be transmitted to the next generation.

So, there has to be a way to make copies as well. Without this, the whole thing will not work. So, we have two major kinds of molecules here: proteins and nucleic acids. Now, proteins do, you know, under normal situations, which are present in biological systems. The proteins carry out all the metabolic reactions through catalysis, including the reaction of making copies. So, DNA polymerase is a protein, right? However, the issue with proteins is that they cannot store or pass information to the next generation.

So, protein does part of the work. What about the nucleic acids? The nucleic acids, as we know, store information that can be used to make proteins either directly or via mRNA. But the issue with them is that they cannot catalyze reactions, nor can they copy themselves, right? In order to copy the DNA into RNA or, you know, DNA to DNA, you again need protein. So, these two molecules, these two classes of molecules, are very, very tightly sub-functionalized. And hence the question is, how exactly are they, you know, or rather, which came first? Because it is a chicken-and-egg problem. In fact, many people call it the chicken-and-egg problem.

So, neither can reproduce nor function without the help of the other. So, if that is the case, how did the first one evolve? Whichever it is, either DNA or protein, came first. So, it turns out that this was a, you know, conundrum for some time. Before the conundrum was resolved somewhere in the 1980s, when two people, Thomas Cech and Sidney Altman, discovered That certain RNA molecules, which they called ribozymes, apart from carrying information, can also act as catalysts. So, this led or rather this implied that these two functions working as a catalyst and working as an information storage and replication molecule, Both these functions can actually be in a single molecule, and that single molecule, which can do both, is RNA.

Now, although this comes as a surprise, if you think about it a little bit more closely and if you look at, you know, What we have understood about RNA biology in the last 20-30 years is actually no longer a surprise to modern biologists. Why? So, because nowadays we know that RNAs play all kinds of roles in our body. So, for example, we talked about, you know, siRNA, piRNA, or non-coding RNAs. And their roles in gene expression and all kinds of other things, right? So, they do play a lot of, you know, regulatory roles, and on top of that, if you look at the ribosomes, okay. So, ribosomes are one of the most conserved molecules, or, you know, things in the whole tree of life.

Ribosomal proteins are among the few 30-40 proteins that are common across every single known organism. Now, if you look at the ribosomes and how a ribosome functions, you know what it does. It basically, you know, catalyzes the function of joining those amino acids to form the polypeptide, right? The catalytic function that is doing the joining is actually not done by a protein. So, although the ribosome structure contains many proteins, But the real job of the ribosome is actually performed by the ribosomal RNA, which is essentially a ribozyme. So, this straightaway tells us that, given the fact that ribosomes are extremely fundamental and extremely well conserved, This straightaway tells us that RNA did have a very important role in the catalysis of reactions.

Today, something which we almost exclusively tend to associate with proteins. But now the question is, okay, so if RNA can do both catalysis and information storage, how does this resolve our conundrum? So, the way it resolves the conundrum is through what is known as the RNA world hypothesis. Something that was proposed by Alexander Rich in 1962. So, what is this hypothesis? It is a multistage process. So, the hypothesis says that right at the beginning, it is RNA molecules that form and replicate.

Now, these RNA molecules—some of them, not all—develop catalytic abilities; these are the ribozymes. The most successful ribozymes facilitate their own replication and catalyze simple metabolic reactions. So, they do both the jobs of the protein and the DNA. And this is the stage; this is what is known as the RNA world, where RNA is the primary molecule. This eventually leads to the development of proteins and DNA, which are more efficient in their own specific tasks.

Why is that? Because if you have ever worked on the bench and if you have ever tried to isolate RNA for any gene expression work, You will realize that RNA is notoriously unstable. So, it is well; I should not say notoriously because we are able to work with it. But it is pretty unstable, much more unstable than DNA, for example. And the second thing is, if you look at how diverse an RNA sequence can be, there are just four bases, right? Whereas if you look at a protein, there are 20 amino acids, right? So, for the same length, the amount of diversity in structure is. Therefore, the amount of diversity in function that you can get in proteins is way, way greater than that of RNA.

So, because of this, by its very structure, protein is much better suited for catalysis and all metabolic functions. DNA is much better suited for the transfer of information across generations due to its stability. And therefore, at some point, although RNA initially did both, a sub-functionalization happens. Because of which these things, you know, these functions become specialized between these two molecules: DNA and protein. Now, there are several lines of evidence that are consistent with this view of the RNA world.

However, I will be the first to admit that not all questions have been appropriately addressed. There are quite a few things that we do not know. So, for example, sure, I mean it is a hypothesis that we went from an RNA world to a DNA plus protein world, but, How exactly did the transition happen? What caused the transition? We can see how it will benefit, but how exactly was the trajectory? We really do not know. The second thing is, yes, sure, RNA can do catalysis, yes, sure, RNA can store information, but how good is it? Was it good enough for you to know the whole thing to become sustained and well spread? We do not know. So, for example, for the longest time, it was known that although RNA can help in replication, it does not really do a good job of it.

It was definitely not as good as, say, DNA polyvirus. However, very recently, you know, in 2024, scientists have actually created a ribozyme. which can very faithfully replicate another ribozyme, which is itself a DNA-cleaving molecule. So, you have one RNA molecule that is acting like a DNA polymerase. and is able to replicate another RNA molecule that is acting like a protein.

But chemically, both are RNA. So, this is supposed to be one of the big, you know, breakthroughs in this field, and by no means is this the only breakthrough. There are several breakthroughs that keep happening in this field. Because it is a very happening field, and you know a lot of work is going on in these exciting new findings all the time. So, monomers can be formed, and polymerization can happen after polymerization to function, you know. If you go through RNA, then at some point, hopefully the RNA world gave rise to the current DNA and protein world.

However, we still have a problem. What is it? Which is that if you need to have a system, it will be. I mean, you need the system to have some way to separate itself from the exterior. So, if you look at our present living world, burning the viruses that are anyway somewhere in the boundary, Everything is enclosed in a membrane; everything is membrane-bound. And being enclosed in a membrane is actually extremely beneficial. Why? Because this enclosure allows for the creation of a unique internal chemical environment.

Why is that important? Remember I told you that you know initially when the molecules are formed outside, then they are going to be unstable. Simply because they are going to react with the gases, and you know pH and everything else in the ocean, in the open ocean. Whereas if you can create an enclosure, that raises the possibility of having a different pH. A very different, you know, oxidation or reduction environment inside, and so on. So, that essentially increases the ability of the system to do a lot more if you can have your own unique chemical environment.

And that is something that, until and unless you have some kind of enclosure, is not going to happen. The second thing is that many of these macromolecules, for example, RNA, are pretty fragile. So, if you are able to create that enclosure, you will be in a much better position to protect those fragile macromolecules. And that is very important if you want a stable inheritance to occur. I mean if your DNA is simply fragmenting before it can have a chance to reproduce, then there is not much life, right?

And thirdly, the formation of these kinds of enclosures can locally increase the concentration of the reactants. So, earlier we were talking about, you know, hydrothermal vents, clays, and so on and so forth. If you are able to put things inside a boundary, then you can keep increasing the concentration there. and have a locally high concentration of all these reactants. So, as I said, we already know that all living forms, minus viruses, are membrane-bound.

So how exactly could such enclosures or compartments form? Now Operin proposed that if you have organic molecules, they can form microscopic spheres, which he called coacervates. and these coacervates could then act as protocells. Nothing wrong with that; people have shown that coacervates can and indeed do form under many situations. However, there is another way in which such kinds of, you know, membrane-bound spheres can form. And that is through compartmentalization using what are known as amphiphilic molecules.

Now, what are amphiphilic molecules? So there are many molecules, the biggest example being fatty acids, which tend to have two parts in the molecule. There is typically a hydrophilic head, which means part of the molecule that likes water. You know it wants to be closer to water or orients itself toward water. And then there is another part that is typically called a tail, which is hydrophobic and wants to move away from water. Now this is the nature of the molecule; there is no willfulness or free will or anything over here; this is the nature of the molecule.

And as I said, the biggest example of this is the fatty acids, which can combine with many other molecules to form lipids. So we already know that lipids are the primary component or one of the major components of Almost all the membrane-bound organelles are known to you. So it turns out that if you put these fatty acids or even the lipids into water, then they can form different kinds of structures. So the simplest kind of structure that gets formed is these bilayered sheets. Now, why is a bilayer formed? Because remember, these are the heads; these are hydrophilic.

These are the tails; these are hydrophobic. So if they arrange themselves in a bilayer then the heads on both sides, This part over here and this part over here are facing outside; they are facing the water. Whereas the hydrophobic parts of the tails are facing inward, they are facing away from the water. So, as a result, this is a somewhat stable structure, and people have actually shown that. If you have proteins incorporated in them, then this becomes, or you know, even more stable. So now, if you have a bilayer structure like this, then this bilayer sheet itself can form different kinds of structures.

So the simplest structure that it can form is a sphere, a single-layer sphere which is known as a micelle. The other thing that it can form, you know, this bilayer thing, entirely can just go inside, you know, and have a cavity inside. And that is what is known as a vesicle or a liposome. Now the main difference between a liposome and a micelle is that the former is single-layered.

So you can see that you have the heads and you have the tails and that is it. So there is hardly any cavity; it is very small. But in this particular case, this entire bilayer, you know, folds in on itself to become the sphere. Because of this, you can have a large cavity in this internal part. And once you have that cavity, then in that cavity, you can have your proteins, and you can have your nucleic acids.

And you can have all your, you know, cell organelles, etc., which can form later. So, the basic point is that, A, you do not have to do anything; you just have fatty acids and lipids coming. And the moment you put them in water, these structures form. And more importantly, particularly these liposomes or the vesicles, they can grow by incorporating more fatty acids into the membrane. So this is not a static hard sphere; this is something that can potentially keep increasing its volume. By incorporating more molecules, that is obviously a very, very important thing both in terms of growth and in terms of forming another you know structure. So, if you have a large enough liposome, at some point it can simply bud off like this and, you know, become two things: liposomes. So, the structure and flexibility of the membrane allow it to do that. So, this is why it is a very crucial step in the formation of lipids. So, you have these things, these liposomes, and hopefully inside these.

You have various proteins, and you have various nucleic acids, and so on and so forth. So, that is what we call a protocell. It is not a cell; it is a protocell; it is going towards a cell. Now, from the protocell, we see these as the first lifelike organisms: the protocells. And from that protocell, you know we somehow need to come towards the so-called last universal common ancestor.

Why? Because I told you that all existing life forms, except viruses, are cellular. So, there are several lines of evidence that suggest that all the existing cellular forms have Arisen from a single common ancestral population, this population had certain properties. What are the properties? We will talk about that in a minute, but this single ancestral form is what is known as the last universal common ancestor. And this is, as I said, the hypothesized common ancestral cell population. which gave rise to the three existing domains of life: bacteria, archaea, and eukarya, or the eukaryotes and this LUCA, our evidence, you know, DNA sequencing evidence indicates arose about 3.5 to 4.3 billion years ago. So, this is just to show you the whole thing, you know, in the context of the tree of life. So, this is bacteria, this is archaea, this is eukarya, eukaryotes, animals, plants, fungi, etc. And all of these finally come from one root node, and that root node is the LUCA.

Now there are a few points to keep in mind here. It is a hypothesized entity based on biochemical evidence, very important. We do not have a fossil form to which we can point and say, "This is LUCA." It is coming from a hypothesis; it is a hypothesized entity, but based on very strong biochemical evidence, as we will see in a moment. Most importantly, LUCA is not the first life forms.

There were most probably other life forms that originated. I mean we are talking about protocells; different kinds of protocells would have originated, and different kinds of protocells might have. Had different properties, they might have had, you know, different kinds of, you know, combinations of proteins and nucleic acids. However, it is from LUCA that all the life that exists today has arisen, or so we believe. Why do we believe that? Because if you look at the genetic code, it is almost universal with very minor exceptions across all life forms on this planet.

So we believe that this is because the genetic code comes from LUCA. Secondly, if you look at the amino acids, you know that amino acids can come in two different kinds of stereoisomers. The so-called L forms and the so-called D forms. Now it turns out that almost without exception, all life forms on Earth only use L amino acids. Nobody uses D amino acids, or very, very few do.

However, when it comes to sugars, we all use the D sugars, barring very few exceptions; nobody uses L sugars. Similarly, we are in a core set of biochemical pathways that are common across all life forms. From the lowliest of bacteria to the mightiest of elephants. Why is this happening exactly? Again, as we pointed out when we were looking at the evidence for evolution, that The simplest way to think about it is to think that this is because of a LUCA plus a universal common ancestor. And similarly, if you look at the machinery of the cell—the ribosome, the way the ATP is synthesized— Many of these components are universally conserved across all life forms. So, what were the properties of LUCA? Now, before you ask the question, the first thing that you should ask is how do you even figure out this thing.

So the simplest way to figure it out is by comparing the common genes and properties of bacteria and archaea. Now, why are we saying "bacteria" and "archaea"? Why are we excluding eukaryotes? That is because we have very good evidence, as we are going to discuss it. That eukaryotes arose from a combination of bacteria and archaea. So, the two initial domains are Bacteria and Archaea. Now, if you try to look at genes that are common across all organisms that we have sequenced to date, There are about 30 to 35 such genes, and those are mostly related to ribosomes.

But that does not give us much distinguishing power. So, what people have done is take the known bacterial and archaeal sequences under various kinds of assumptions, They have tried to figure out what the common genes and the common properties are between these two groups. Now, of course, it depends on what assumptions you are making. So, this is a very nice paper, this particular 2018 paper, in which they have made various assumptions and shown. What are the consequences of doing that, you know, taking that assumption and not taking that assumption? So, anyway, long story short, after doing all this stuff, what people have generally agreed on, You know, the common properties of LUCA are as follows.

It was single-celled, it had a lipid-bilayer membrane, and the cytoplasm was water-based. It used DNA as its primary genetic material, and it could replicate the DNA and transcribe it into RNA. It already contained genes; it already contained the universal genetic code. It possessed ribosomes to translate RNA into proteins and had a core set of enzymes for DNA repair. Genetic recombination occurs, and it multiplies by duplicating its contents and undergoing cell division.

So, these four sets that I am talking about are almost universal across all living organisms. Which is why we are very sure that you know they are most probably good candidates for being LUCA properties. The next set I am going to give you is mostly based on, you know, coming from this particular paper. Based on comparisons between bacteria and archaea under various levels of assumption. But from what we understand, it looks like LUCA was a chemoautotroph.

It produced its own nutrients using inorganic chemical reactions. And looking at the genes that seem to be common across the bacteria and archaea, it looks like they reduced carbon dioxide. Oxidized hydrogen and used acetyl thioester as key intermediates in its metabolic pathways. So, if you are a biochemist, this should tell you that there is. Which kind of biochemical pathways are used and how do they differ from, for example, what happens in eukaryotes today? And mostly it looks like it was anaerobic; it was a thermophilic form.

Therefore, it most probably lived in high-temperature environments. Could it be anaerobic hydrothermal vents? Maybe a very likely candidate. Do we know for sure? No, we cannot know for sure, but it looks like that is where you would find a LUCA. So, the main point that I want you to take home is here. Is that LUCA was not a simple, you know, protocell with a few proteins and a few nucleotides thrown inside it. LUCA was already a highly sophisticated metabolically organism that, it looks like, was already adapted to an extreme environment.

So, this means that we have a gap in our knowledge. What is the gap? When we were talking about, you know, the opinion-Halden hypothesis and the various steps of it during this discussion, We went up to the formation of protocells, and then we came from the other side and talked about LUCA. We do not really know how we went from the protocell to LUCA. So, that connection, what are the things? That led a simple bag of liposomes containing some macromolecules to something as sophisticated as this? We really have no clue. But we definitely know that it is very, very, very unlikely that the initial protocells were as complex as LUCA was. So, as I said, we do not really have any answers, but you can bet your life that scientists are working really, really hard to figure this out.

Now, at this point, I would like to quickly recommend a video to you. So, we covered, you know, abiogenesis in quite a bit of detail, but this particular video by Arvin Ash, This mostly talks about the concepts that we discussed here and takes a more lipid-first kind of view. But it also mentions a few papers that we did not really cover during our discussion and has very nice animations. So, it is highly recommended, and the components of this are part of the course. Now we need to talk about the concept of major evolutionary transitions. What are these? So, major evolutionary transitions are fundamental shifts in how living things are organized, and they typically happen when Simpler independent units join together to create a new, more complex unit that has many interdependent parts.

So, remember when we wrote in our first discussion, we were thinking about What are the various properties of life? We said that you know one of the things that we see is that. You know, most living forms, even the simplest bacteria, are pretty complex, and there are lots of components. These components seem to be interacting with each other, and you know you have a hierarchy. So, you have single-celled organisms, then you have simple multicellular organisms.

Then you have more complex multicellular organisms, and so on and so forth. And as you go up the hierarchy of complexity, you know the levels of complexity. How many interdependent units are there that keep on increasing? So, major evolutionary transitions refer to those situations in which you go from a relatively simple level to a more complicated level. And these transitions, as I am pointing out, often lead to increased complexity. And the fundamental change that happens is how information is inherited and transmitted over time. In other words, how selection ends up operating, not the basic mechanism, but What is the unit of selection that typically ends up changing during these major evolutionary transitions? And more often than not, there is some kind of cooperation across multiple entities.

So, for example, different kinds of cells cooperate to form a tissue, and different kinds of tissues cooperate to form organs. So, these are what I mean by cooperation among multiple entities. For example, you know honeybees cooperate with each other to forage for food. Those are the kinds of cooperation that we are talking about that often end up becoming a crucial factor. If this is not making too much sense, just wait for a minute; I will give you the major transitions that have happened.

So, whatever we discussed up to this point, you know about how you go from simple. You know, lots of polymers go into a proper bag containing these polymers, you know.

This part, this sequestration of the majority of transmissible information in the genes. and then the formation of a cell membrane to create a cellular life form, This is typically cited as the first of the six major transitions in evolution. The second major transition that occurred was the formation of eukaryotes. Now, why am I singling out eukaryotes here? Because remember, all the multicellular organisms that we have are eukaryotes, including us, obviously, right? So, it turns out that the formation of eukaryotes, also known as eukaryogenesis, is obviously a very, very interesting and special event.

Why? Because the theory states that, well, it is no longer a theory, we more or less, you know, have extremely good evidence. To indicate that this is what happened is because it happened through a process known as endosymbiosis. So, what really happened? So, if you remember, I told you that you had LUCA, and from LUCA, you had two major domains: the bacteria and the archaea. Now, it turns out that at some point, some anaerobic archaea engulfed, you know, engulfed a bacterium, sorry, An anaerobic archaeon. It ended up engulfing a bacterium, an aerobic bacterium of the type proteobacteria, about 2.2 billion years ago. And this merger became very important. This merger is what led to the formation of eukaryotes. And these aerobic bacteria that were engulfed and incorporated were the ones that formed the mitochondria. And it turns out that this was about 2.2 billion years ago. And then, at some point about 1.6 billion years ago, there was one more such event that happened. And in this particular case, an aerobic eukaryote that already had the mitochondria, There was one more incorporation of a bacterium, but this time it was a cyanobacterium. And this cyanobacterium now ended up forming chloroplasts. And this lineage is what led to the formation of green plants. Now, the formation of green plants is very, very important because, remember, they are the ones that are fixing carbon dioxide and giving rise to oxygen, which is very important for the oxidizing atmosphere that we have around us today. So, these two endosymbiotic events are what lead to the formation of the eukaryotes as we know them today. So, just to show you the major transitions. So, here is the first transition that we talked about you know, Separate genes and cell membranes came together to form genomes within the cells. So, we had compartmentalized the genomes. and this is what allowed the formation of large complex genomes and everything else associated with them. At some point, separate unicellular organisms. They ended up forming symbiotic relationships with the incorporation of mitochondria and plastids.

So, that is how eukaryotic cells were formed. And once eukaryotic cells were formed, there was a transfer of genes. between the mitochondria, plastids, and nucleus, and vice versa. So, that is how the genomes inside the organism became hybrids from multiple sources. So, the remaining major transitions are that, at some point, asexual unicellular organisms became sexual unicellular organisms. So, sex evolved, and this is where meiosis ended up coming, and we have already discussed how sexual reproduction and in what ways it could have sped up evolution.

Then, at some point, unicellular organisms became multicellular. The point is when you know you could have differentiation at the level of cells and differentiation at the level of tissue. And then there was the germ-soma separation that ended up happening. We have discussed the importance of all these things. Then, at some point, the multicellular organisms led to the formation of eusocial societies you know, the bees, the wasps, and the ants that we discussed. Of course, this did not happen across the board; you know, it only happened in a few lineages, but wherever it happened, you know. The reproductive and non-reproductive functions were separated into two different organisms, which is a huge thing. Otherwise, in all cases, burying these eusocial organisms requires the same organism to function and perform both roles. Both reproduction and everything else related to body maintenance.

It is only in multicellular organisms that you know these two functions get separated into two different bodies. So, which is why many people have even argued that the entire colony of an ant or the entire hive of the honeybee is an organism. That is a different philosophical argument. And finally, different species came together to form mutualistic associations; for example, lichens. And that is when you had physically evolved in the evolution of physically conjoined partners, you know, various kinds of endosymbionts.

And that is supposed to be another major transition. So, this entire idea of the major transitions comes from a famous book by Maynard Smith and Eörs Szathmáry. The major transition in evolution. And you know, generally, this is supposed to be one of the major landmark books in evolutionary thought. Okay, so until this point, one thing that we did not cover was what really happened after the eukaryotes came in and of course, you know a lot about evolutionary biology; macroevolutionary biology is there. You know, which group led to which group, and so on and so forth. Unfortunately, we do not have time to cover that bit, but I will make two recommendations. Two videos; they are not a part of this course; they are more for your own information. so that you have a better understanding of the entire topic.

So, the first is this 36-minute video called A Timeline of Life on Earth: 4 billion years of history by a channel called SciShow. Very fast-paced, very informative; in fact, there is lots of information, and overall, it is pretty enjoyable—nicely done. They use simple photographs; they do not have animations, nor do they have very fancy photography, but nice stuff. The second one is "The Evolution of Life" with David Attenborough.

It is 48 minutes or so long; it is slow, but it is majestic. The photography is mind-blowingly superb, as you can expect from a BBC documentary. And of course, you have Sir David Attenborough in it. So, between these two, You should get a lot of information about the other macroevolutionary changes that occurred in the various crops. So, now that we have looked at the evolution of the other life forms, We will turn towards the one species that interests us the most, which is, of course, us, right? So, we are now going to look at how exactly human beings evolved, whether they are still evolving, and so on. But that is what is going to happen in our next discussion. See you then. Bye.