Cell and Molecular Biology

Prof. Vishal Trivedi

Department of Biosciences and Bioengineering

Indian Institute of Technology, Guwahati

Week 01

Origin of Life and Evolution

Lecture - 03

Basics of Evolution

Hello, everyone. This is Dr. Vishal Trivedi from the Department of Biosciences and Bioengineering, IIT Guwahati. In the previous lecture, we discussed in detail the life and how life originated on Earth. So in that context, we have discussed the many theories that explain the origin of life on Earth. We have discussed the theory of special creation.

We discussed the theory of spontaneous generation, which actually believes that non-living matter gives rise to different types of organisms. But that theory was incomplete because it had not been based on the experimental evidence, and there were critical experiments that were performed by Redi, Spallanzani, and Louis Pasteur to disprove that this was actually happening in the current environment. And then later on, there were many other theories, like the theory of Catastrophism, the theory of Cosmozoics, the theory of the eternity of life, and ultimately we have also discussed the modern theory or the chemical theory of the origin of life. And chemical theory was the first theory that was based on experimental evidence, where Stanley Miller and Urey conducted a very meticulous and systematic experiment to prove that if you take inorganic substances and run them under primitive Earth conditions, which were reducing in nature, then you could develop biomolecules.

And that was the first evidence that life could have originated in the primitive environment because of the chemical interactions or from the inorganic molecules, and then they actually proposed the events of the experiments and how the different events could have happened on primitive Earth, and that's how they said that. Ultimately, the inorganic substances are going to react with each other to give you simple molecules, which they have actually demonstrated in their classical experiments. And then they said that these simple molecules are going to react with each other to give you the complex molecules. These complex molecules will then aggregate and give you the coacervates. And in coacervates, they will actually develop the tendency of living organisms.

If you recall, we discussed what a living organism is, which could be able to run its metabolism, produce energy, and repair itself. All of these properties were present in the coacervates. But ultimately, the coacervates started acquiring the biomolecules from the primordial oceans, and then they actually acquired the nucleic acids, proteins, and lipids, and ultimately the coacervates developed into the first cell. There is a complete breakage, or there is a gap that explains how the coacervates develop into the first cell, which could run its metabolism, draw nutrients, and so on. And one of the questions they were able to solve was why these things are not happening in the current environment and why the theory of spontaneous generation could not be successful.

Because the current environment is deoxidizing in nature and it becomes oxidizing as soon as these inorganic substances try to react spontaneously with each other to form simple molecules, they get oxidized, and because of that, they are unable to form complex molecules. So these are the things that we have discussed, and we have ultimately discussed that the simple cell is being formed. But as we know, that simple cell gradually developed into multicellular organisms, and then the multicellular organisms developed into higher classes. So the question in today's class that we are going to discuss is how and what the mechanism is for these simple primitive cells evolving into multicellular organisms or higher organisms. What have we discussed? We have discussed that life originated as a primitive cell with the ability to replicate, absorb nutrients, and repair damage.

Although we have very big gaps in how the coacervates develop into primitive cells, we still probably do not have a conclusive answer to that. These single cells are the starting material for forming the multicellular system and eventually developing the organisms with tissue and organ systems. So the changes, the progressive advancement of these organisms, is a process to acquire the traits so that they can adapt to the new environment, which is known as evolution. And Aristotle, who is considered to be the father of biology, regarded evolution as a ladder of chains, or the Scala Naturae, involving the hierarchical linking of a series of forms. So what you have seen here is actually the ladder of chain where the organic matter is placed at the bottom.

So what you see here is the inorganic matter that is being placed at the bottom; then the inorganic matter is being developed into the lower plants, which are going to be developed into the higher plants. And then these higher plants are being developed into the lower invertebrates like jellyfish and sponges, and then these jellyfish are being developed into the Insecta and Arachnida; then these insects are being developed into the snails. Then snails are being developed into crabs, and then crabs are being developed into squids or octopuses, and then octopuses are being developed into fish, and then fish are being developed into even more advanced fish. And then the fishes are being developed into the reptiles, and the reptiles are developed into the birds, and then they will be developed into the mammals, and ultimately he has kept the humans on top. This is simply not based on the experiment.

These are all simply based on observation as well as his own personal opinion that this could be the ladder of change in which the organisms are evolving. The question arises, what is the evidence that evolution is really happening? Because until we have experimental evidence, we cannot believe this particular type of scheme. We cannot say that lower plants are being developed first and that animals, plants, or humans are being developed later on. So then people came up with the idea of chemical evolution. The term evolution refers to the changes from one form to another.

And that form is always for advancement. So the change in living organisms over time is known as organic or biological evolution. The process of evolution can be understood from the fact that unicellular organisms appeared first. Unicellular organisms appeared first, simple multicellular organisms came later, and they were later developed into complex multicellular organisms such as seed plants and vertebrate animals. The fish were the initial early vertebrates, and they gradually changed to form the amphibians and so on.

These amphibians produced reptiles, which evolved further to give birth to mammals. This hierarchical linking of different species is considered the ladder of the chain by Aristotle. In the same series, mammals have evolved into humans, evolving from ape-like primates by acquiring changes over the course of time. So the chemical evolution or the normal evolution is actually the gradual change in animal forms or organism forms so that they can acquire new traits. You might have seen that evolution is either very slow, where monkeys evolve into humans, or it could be very, very fast.

You might have seen the adaptations in bacteria and how they develop a single drug. Suppose you take a bacterium. For example, Mycobacterium tuberculosis, right? And if you treat it with a drug, Mycobacterium tuberculosis actually dies, right? But in due course, the mycobacterium tuberculosis actually makes changes in its cellular body, and that's how it develops multidrug-resistant MTB or drug-resistant MTB, right? So, because of that, it actually forms drug-resistant TB, and this is called evolution because now it is not going to be killed by this particular drug, and this is exactly what is happening. Once you are actually putting a challenge to a particular organism, it will try to come up with ways to overcome that problem, and that is the main basis of evolution. That it has to overcome, it has to acquire the additional traits.

For example, in the primordial oceans, the primitive cells are formed, which are the unicellular cells, right? And then unicellular cells were having the deficiency because unicellular cells cannot actually get support from neighboring cells since they are actually unicellular organisms. So what he thought is that let's have a multicellular organism, right? If you go to the multicellular system, the advantage is that, first of all, you can actually have a division of labor. You can say, "Oh, you will do this, I will do this," and all that. And on the other hand, even if one cell is under threat or is actually going to die, the organism will still be able to survive because it is going to overcome that particular type of problem. Similarly, once the multicellular system develops, it could actually evolve into an organ or an organ system.

And we know that as you progress through this system, you are actually acquiring more and more complexity, and more complexity always comes with additional features. And that's why the people have observed that the organism first appeared as a single unicellular organism like the protozoa, amoeba. Then it goes into the multicellular stage where it has actually developed the sponges and coelenterates, and all those kinds of hydra. For example, all this information came because we have classified the organisms and understood why it is happening. Then these multicellular organisms develop into a system where they can actually have different types of organs; for example, the Platyhelminthes eventually developed into a more advanced system, where you don't have one single organ but an organ system.

For example, humans have different types of organ systems, such as the liver, kidneys, pancreas, and stomach. So, every organ system is doing its job, but it is also trying to talk to its neighbor, trying to communicate with its other organ systems. For example, if you talk about digestion, digestion is actually not happening because of the simple alimentary canal. Digestion is also happening because it is getting support from other organs like the pancreas and the liver, as well as from some other systems. So, the organ system is the most advanced system that is present in organisms, and it helps that particular organism face different types of challenges.

So that is what it has been considered by Aristotle, and that's how he has prepared a ladder of chain. So what you see here is a ladder of chain that has actually been designed based on who can do what. It hasn't been the same way in which the organisms are evolving. This is based on Aristotle's understanding that this particular organism is, you know, having these kinds of deficiencies, whereas these deficiencies are not present in the other organism, so he has kept that particular organism at a lower level and has kept the other organism above that. For example, he has kept the human in the top right because it believes that humans have all the tools and know all sorts of systems so that he can actually overcome all sorts of problems.

Right? So that's why he has kept the humans in the top right. Whereas he has kept the lower plants and all those kinds of things at the bottom because they cannot do many of the things that higher plants or organisms can do, this is all about chemical evolution and the fact that evolution is happening. Once you talk about the science and when you say that evolution is happening, you are always looking for the experimental evidence to prove that there is actually a system through which the lower invertebrates develop into the higher vertebrates and then higher vertebrates develop into the different types of animals like mammals, birds, snakes, and all that. What is the evidence? What is the chemical evidence that evolution is really happening? So now the question is what the scientific evidence is that organisms have evolved from previously existing organisms, which means whether there is evolution or not, right? That is what we have to answer. So if you study the physiology, anatomy, and development of different organisms, you will gain clues about the several similarities between the related organisms along with the selected differences.

So the correlation of the differences within the related organisms has allowed us to identify the properties used to study the evolutionary stages of an organism. These evolutionary evidences are as follows. So if you study physiology, if you study anatomy, if you study how different organisms have different types of developmental stages and how they are actually similar to other organisms while still having their own peculiar features. That all, if you correlate it, will actually give you a detailed understanding of the relationship between different organisms, and that's how you can study or understand the evolutionary stages of an organism. These evolutionary pieces of evidence could be classified into three points.

They can be either related to morphology or structural evidence. It could be because of the embryological evidence or it could be because of the paleontological evidence, which means you are actually going to study the fossils. So fossils are also very good evidence that will actually prove who came at what time. Within the morphological and structural evidence, you can have the anatomy; you can have the evidence that actually indicates how the body is organized. Then you can observe the similarity within the physiology.

So you can have homologous organs or analogous organs, and you can also study how the physiology is being modified by gradual modifications. You can also study the connecting links. Connecting links are the organisms that are actually connected between the two different organisms. They have features that are common to both organisms. So let's discuss each of these pieces of evidence and try to understand how the scientists have come up with the idea that evolution is really happening and that there is a series or scheme through which these organisms are evolving.

Once a scheme is proposed by Aristotle, in which he has linked all the organisms and the ladder of species, he has proposed it, but that was not based on the experimental evidence. So let's first discuss the morphological and structural evidence. So, as far as the morphological and structural evidence is concerned, if you do the comparative study of the morphology, which means that the anatomy of organisms indicates that a few of the features are similar. These are as follows. So if you try to see the morphological and structural evidence, what you can see is that you can identify the similarities between these features, or you can understand the differences.

So if you go with the similarities and the differences, you can be able to understand how this mechanism could be evolved. The first is that you can go with the body organizations. The body organization of different organisms is evolving over time with the different levels of organization. The unicellular organisms with single cells are the most primitive body organization, followed by cells that arrange to give rise to tissues. The tissues gather to form the organs, and the organs cooperate to form the organ system, for example.

So, this is what we are talking about. Initially, we had unicellular organisms. These unicellular organisms then differentiated and realized that we are actually in danger because as soon as we experience any kind of scarcity, for example, if there is a food shortage, a unicellular organism will die because there is no alternative source. But once it develops into multicellular organisms or can be developed into tissue-level organisms, what will happen? Here you have the single cell, so you have one cell, right? Suppose you have developed into tissue-level organization and you have a hundred cells, right? And again, there will be a food shortage. So what will happen? Out of these hundred cells, what will happen if, suppose, ten cells are going to die, okay? These 10 cells are actually going to die, and they will have the organic matter. This organic matter is actually going to be utilized by the remaining 90 cells.

Number one. Number two, since it goes into a stage where it has the hundred cells and if there is a threat coming, like, for example, if there is a prey that is actually trying to kill them, you have the hundred people who are fighting. So you can imagine that if you have a single person fighting the enemy, it is difficult. It is not possible to win. But if you have a hundred people fighting the same enemy, there could be a possibility that you may be able to win. You can fight with full strength, right? So you can be protected, number one.

Number three, that is the protection, isn't it? Even if running the physiology as well, if you have a hundred cells, these hundred cells would actually be able to do things more efficiently because you would be able to exchange materials. For example, if you have a single cell and you cannot even take care of the byproducts of the metabolism, the byproducts are actually going to ultimately kill the unicellular cells, right? Whereas if you have the hundred cells, the byproducts could be scavenged by the other cells, and because when you have the 100 cells, some cells are actually going to be new while some cells are going to be old. So, these new cells are going to be more efficient in terms of performing the functions, whereas the old cells are actually going to be less efficient. So, these old cells will still survive because they have the support of the new cells. Similarly, once the tissue develops into the organ, it will actually come up with more and more sophistication because the organ will be more organized.

So it is going to have different types of tissues, and therefore there will be a further level of division of labor. And once the organ develops into the organ system, you are actually going to have support from the different organs, so that is actually going to make things more and more systematic and sophisticated. For example, in humans, we have different types; for example, in a single cell, the single cell performs all the functions, whether it is respiration, food intake, or taking care of byproducts. Whether it is the water imbalance and so on, in the case of humans who have developed the organ system, you have the heart, or the circulatory system, which is actually going to take care of the circulation of the material or distribution. Then you have the lungs, which are going to do the respiration; similarly, you can have the liver, you can have the kidneys, and all those kinds of things.

So all these organ systems have their own dedicated functions. But that does not mean that these organs are not going to talk to each other; the heart is always going to listen to the brain, and the liver is also going to coordinate. So, there will be coordination among the different organs, and that's why there will be an organ system. Therefore, the organ system is the highest level of organization that exists.

Now, let's see the example. An amoeba is unicellular, while a sponge is multicellular or at the tissue level of organization. However, these cells are not organized into tissues to exhibit the cellular level of organization. Whereas in the case of coelenterates like the hydra, cells are organized to form the tissue but later do not form the organ. This is a tissue-level organization. Similarly, in the Platyhelminthes and higher animals, the different types of tissue give rise to the organ systems of organization.

So, if you go with this kind of evidence where you have the body organization as a criterion, you understand that probably the living or unicellular organisms appeared first. Then they will be developed into tissue-level organization, then they will develop into the organ, and then they will develop into the organ system. So if I go with this, only this particular evidence, I will say that the amoeba is evolving into sponges and then sponges are evolving into coelenterates. And the coelenterates are going to develop into the platyhelminthes, and the platyhelminthes are actually going to develop into the higher vertebrates, and then subsequently into the vertebrates. The same is actually also true for the plant system, like the unicellular plants such as algae, which is actually going to develop into multicellular plants like fungi.

Then the fungi are going to develop into the Bryophyta, and then the Bryophyta is actually going to develop into the Pteridophyta, and the Pteridophyta is going to develop into the Gymnosperm. These are the lower plants, and then the Gymnosperm is going to develop into the Angiosperm. So if you go by the body organizations, you could get clues as well as the scheme through which the organisms are evolving from pre-existing organisms. Then we have the homologous organs.

That is another piece of evidence. The organs of different species of common descent that look different and perform different functions but have similar structures, similar topographic origins, and similar embryonic origins are called homologous organs. Homologous organs mean that the organisms' anatomies are going to be identical, but they are actually going to perform different functions. So they will perform different functions, but their anatomy is going to be different. We have a couple of examples.

The homology is based on divergent evolution. So it will actually be based on divergent evolution because of the adaptations; these single organisms evolved into these three organs. But he has not changed the anatomy; he has only changed the way these organs are going to be utilized. One of the classical examples is the forelimbs of vertebrate animals. So we have the forelimbs in the man, cheetah, whale, and bat. They are of different shapes and perform different functions.

For example, these are used for grasping objects. So these are the four examples: you have the hand in the case of man, then you have the cheetah, so you have the four limbs in the case of the cheetah, then you have the whale, and then you have the bat. And you know all these four vertebrate animals are different. For humans, they actually use their hands to hold objects, while the same forelimb is used for running in the case of a cheetah; in the case of a whale, that forelimb is converted into limbs for swimming, and the same is also used for flying in bats. In each case, the structure of the forearm has a similar plan to the upper arm, having the humerus followed by the radius and ulna, and the hand with the carpals in the wrist. So, if you see the anatomy, its anatomy remains the same, right? You have the humerus, and you have the radius and ulna.

So, you have the radius, ulna, and then you have the hands, right? So here also you have the humerus, the radius, the ulna, and then you have the hands. But the functions are different. In the case of humans, it is for holding objects, whereas in the case of cheetahs, it is for running. So it has been adopted accordingly. It has been adopted to provide that particular type of function, whereas in the case of the whale, it is for swimming.

And this bat actually has the membrane. So the last part is actually getting the membrane. Because of that, it got converted into a wing. That's why it is being used for flying. All vertebrates have a basic similarity in the structure of their forelimb due to their origin from a common ancestor with five digits. So that's why all these animals actually originated from a single ancestor, and that ancestor actually has a pentadactyly feature.

So pentadactylus means the organism that is actually going to have five fingers. Then we have another example. Another example is the thorn and the tendrils you have seen. Thorns are actually used for protection in plants because they protect the plant from herbivores, such as cows or buffalo. All these grass-eating plants have thorns so that when animals try to eat them, the thorns cause injury, and that's how they are protected.

Whereas the tendrils are actually being used for climbing, they will be found in the creepers and will be used for climbing. So the thorns in bougainvillea and the tendrils in the passion flowers are homologous organs in the plant because they actually have a similar kind of anatomy, except that here you have pointed knobs, whereas in the other case, they are converted into spiral, spring-like structures. They look different and help the plant in climbing, but both arise from the axillary position and are modified branches. So these are actually modified branches. One is used for climbing, and the other one is used for protection from herbivores or from cattle.

Then we have the analogous organs, an organ that performs the same function and looks similar but is quite different in its structure. So these analogous organs are actually exactly the opposite; they perform the same function. So they have the same function, but they are different in terms of structure, which means that if you remember in the case of the homologous organ, it was actually telling us about divergent evolution, whereas the analogous organs are going to tell us about convergent evolution, which means these two are actually examples of convergent evolution. So, if you see analogous organs, they actually indicate convergent evolution because the structure is more important than the function, which can be based on the adaptation to that particular environment. So the example is that there are several examples, such as insects and winged birds.

So you have seen the wings of the butterfly, right? So this is the butterfly, and you might have seen the wings in the case of a bird, right? Both are actually analogous origins because they are both used for one function, which is flying, right? They are both used for the same function, flying, but their anatomy is different. You see the anatomy of the bird wings, and you see the anatomy of the flies, right? They are very different, aren't they? So the wings of birds and insects are analogous organs. In both organisms, these organs are used to fly in the air, but they differ in terms of their structures. The insect wing is an extension of the integument, whereas the bird wing is formed of limb bones covered with flesh, skin, and feathers.

So they are different in terms of their origins. This is coming from the integuments, whereas this is actually an extension of the forelimb. So where you have the feathers and all those kinds of things, and that's how it actually gets the ability to fly. So it is actually able to change the air, and that's how it is actually able to uplift the birds. Then we have the other example where you have the fin and the flippers; the pectoral fin of the fish and the flippers of dolphins are flattened organs used for swimming. So here in this case, we have one function, which is swimming, right? So for swimming, these two fish are actually using their fins, and they have fins and flippers.

So they are actually doing the same function, but their anatomy is different. However, their structure is different. The flippers are the modified pentadactyl forelimb, whereas fins are pentadactyl. So these two are actually formed from different origins and different structures, but their function is the same. So, the other evidence within the category of morphological and structural evidence is the gradual modifications.

In several cases, the organs or tissues exhibit gradual modifications during the course of organic evolution. For example, the heart is the classical example because it was initially two-chambered. Then it got converted into three chambers and then into four chambers. Within the two chambers, you have the auricle and ventricle. Within the three chambers, you also have the auricle and ventricle, and so on, right? So you see here, if you have the two-chambered heart, it will have one auricle and one ventricle, which are actually present in the fishes.

If you have three chambers, it is actually two auricles and one ventricle, which is actually present in amphibians. And then there is a pseudo four-chambered heart, which has two auricles and partly divided ventricles found in reptiles or snakes; and then you have the completely well-developed four-chambered heart in the case of higher reptiles like crocodiles, birds, and mammals. So between this, you also have the four, which is partially, you know, quoted, right? So this is what you said, right? This is actually going to be an intermediate stage, isn't it? And this is the two chambers, so this has only two: the auricle and the ventricle, right? And before this, there would be one chambered heart which was formed, right, which was the primitive heart probably formed and that got, split into two chambered and that's so, if you see like a cockroach or lower invertebrates, they don't have the heart but they have a pumping system and that is not having a chamber. So there is no one-chambered heart present in any animal, but the system that is present in lower invertebrates is like they have a pumping system, although that does not involve a chambered heart.

So you can imagine a two-chambered heart. A two-chambered heart has an auricle and a ventricle. Now, what is the disadvantage? The disadvantage is that it is actually not going to avoid the mixing of the blood. You know that the auricle has pure blood, whereas the ventricle has impure blood. So if you don't have the chambers, you are actually going to mix this blood later on because the auricle is actually going to receive the pure blood from the lungs, and then it is actually going to pump that blood into the body. So once you go from the two-chambered to three-chambered or three-chambered to four-chambered and so on, that is actually going to increase the efficiency of the work.

You can be able to very precisely control which chamber is going to accept the deoxygenated blood, which chamber is going to give you the oxygenated blood and so on. And that's how you can avoid mixing the blood and how you can perform the functions properly. So if you see the gradual modifications, this is just one example where we have taken the example of the heart. It actually says that initially the fish are being developed.

So fish, then, are actually given rise to amphibians. Then amphibians are developed into lower snakes or lower reptiles. Then the lower reptiles developed into the higher reptiles, such as crocodiles and other similar creatures, and then the higher reptiles evolved into mammals or birds. So if you see, all this evidence clearly says that the ladder of species proposed by Aristotle was not completely correct. It was based on some assumptions, but here you see that if you look at the ladder of species, this is not a sequence in which it has been placed. It is being placed in a different sequence where the birds are placed lower than the reptiles.

Then we have another advantage; the other example is the connecting links. So, what is the connecting link? For example, you have two or three organisms, right? So you have organism one, organism two, and the connecting links. Now this connecting link is actually going to diverge into these two species. So it is actually going to have a mixture of properties that are present. So if this is supposed to be A, this is B, it is actually going to be AB. So this, first of all, this organism is evolving, right? And then, depending on the conditions, depending on the environment, and depending on the other kinds of adaptations, this particular thing has given up the B character.

So if it gives up the B character, it will develop into organism A. If there is a giving up of the A, it is actually going to develop into the organism B. And that's how the connecting link is actually going to tell you that these A organisms and the B organisms are related to each other. They are actually going to have their common ancestors. You might have seen that kind of common ancestry also exists even within the different races among humans. The living organisms exhibit characteristics of the two different groups of organisms and are known as the connecting links.

There are a few selected examples of connecting links, and a few examples are as follows. A new example is Euglena. Euglena has the dual character of both a plant and an animal. So Euglena is actually going to be a connecting link between plants and animals, and it is considered that probably Euglena-like molecules are evolving, which actually have chloroplasts on one side, and they also have the system so that they can catch prey. It can perform photosynthesis through specialized chloroplasts, and it can perform contractile vacuoles, mouth functions, and binary fission, and it can actually eat just like an animal, and that's why this is considered to be a connecting link between plants and animals.

Then we have an example two, which is a peripatus. It is an example of a connecting link between the arthropods and the annelids. It has a worm-like body, which is characterized by unjoined lengths similar to those of annelids, whereas it has claws, jaws, tracheae, and a dorsal tubular heart like an arthropod. So this is what I was talking about: the dorsal tubular heart, which is present in the cockroach and is actually pumping the blood, but it is a single-chambered organ with tissue, and it does not have well-defined muscles and other structures to pump; instead, it is actually distributing blood and is considered to be a heart-like structure. So this is what, right? Peripatus is an example of a connecting link between the Arthropoda and Annelida.

Similarly, you have the egg-laying mammals. You know that the mammals are actually giving rise to the babies, right? But in this case, we have the egg-laying mammals. So egg-laying mammals are the connecting link between reptiles and mammals. For example, you have the duck-billed platypus. So this is a duck-billed platypus. It has a few mammalian characteristics such as hair and mammary glands, and it has a diaphragm, whereas it lays eggs with yolk, which is similar to reptiles.

So, if you recall when we were talking about the classification of living organisms and the features of the mammalian system, we said that there are seven characteristics that should be present in mammals. Like one of the characters, the hair, the mammary glands, and the well-developed respiratory system. So these are the three characters that are present in the duck-billed platypus, but they were also going to lay eggs with yolk and eggshells, which is similar to reptiles. Then we have several more examples of the connecting links. For example, we have the Neopalina, which is a connecting link between the annelids and the mollusks.

Then we have the Balanoglossus, which is a connecting link between the non-chordates and the chordates. So I'm not going to discuss the multiple features. The only idea was to just give you the understanding that the connecting links are actually very, very crucial evolutionary evidence that the two organisms have actually evolved from that particular organism. Then you have Chimaera, which is a link between the cartilaginous and the bony fishes. Then we have Coelacanth, which is actually a link between the bony fishes and the amphibians, and then you have Sphenodon, which is a connecting link between the amphibians and the reptiles.

So connecting links clearly highlight the fact that the different organisms have evolved together from a common ancestor, and that is very strong evidence that evolution is happening from the earlier primitive forms of these organisms. Then we have the embryological evidence. The comparative study of the embryology of different organisms shows the striking similarity between them. To explain this phenomenon, the biogenetic law was proposed by Ernst Haeckel. And what does this law say? This law states that an organism in its individual development follows the different developmental stages through which its ancestors have passed in the course of their evolution.

What it means is that if the man is the best organism, according to the ladder of species as per Aristotle, and if it is supposed to have the fishes, the snake, and the amphibians, for example, if all these actually represent the sequence it has followed. So when the baby is born, it will first be an amphibian, then it will be a fish, and then it will show features like a bird, and finally, it will eventually develop into a human. So what Ernst Haeckel is saying is that the organism's individual development follows the different developmental stages through which its ancestors have passed. So man has passed through multiple stages by which it has actually reached this final stage.

But when the baby is going to be born, that is exactly what happened. When the fetus is born, it is actually swimming in the womb, right in that water, and then it will behave like a fish, and eventually it will develop into an amphibian, then a fish, and then eventually it will develop into a man. So, this is what the example is showing here; it will be showing examples of fish, salamanders, tortoises, chickens, rabbits, and a man. So, what you see here is that initially it is actually going to have the fetus, which is going to look like the amphibians, and then it will develop into a fish-like form, and eventually it is going to form the baby in the case of man. So, in other words, this law also says that ontogeny repeats phylogeny, which means if you want to go with the development, it is actually going to follow phylogeny.

The phylogeny refers to the different organisms through which you have evolved. Let's take the development of a frog as an example. In its developmental stage, it forms a fish-like tadpole larva with a tail, then fins and gills for breathing in water. This indicates that the frog evolved from fish-like ancestors. So, that is a classical example where the tadpole or the frog is actually forming a species; like, you know that the frog is initially giving rise to the eggs, then those eggs are being fertilized, and these fertilized eggs are then, if they are swimming in the water like a fish, eventually developing all other kinds of appendages and other things, and then they will develop into the frog.

Then we have the paleontological evidence. So what is paleontology? Paleontology is the study of past life based on the fossil record. Paleontology studied the number and nature of fossils in the early rocks and the distribution of fossils in the successive data. Now the question is what fossils are, how they are formed, and to provide information about evolution. Fossils are the remains or impressions of ancestral organisms preserved by natural means in some medium.

For example, this is a fossil of insects in amber. The media found with fossils are like sedimentary rocks; it could be amber, it could be asphalt, it could be volcanic ash, ice, peat bogs, sand, and mud. What is the mechanism of fossil formation? So, during the formation of sedimentary rock, the dead animals from the sea or large lakes and the land are carried out to the sea or large lakes by the river, sinking down and getting buried in the rock. So, when a rock is forming, for example, this is a rock and it is accumulating soil. It could be possible that one dead animal is going to fall and then it is actually going to be covered again with that particular soil particle, and because of that, since there will be no entry of oxygen, this particular organism is going to be preserved.

The supply of oxygen is limited in this condition and prevents the decay or reduces the decay rate to a minimum. So, because it will not allow the decaying to occur at a faster rate compared to what we could see in the open, it is actually going to give you an impression. So, when you take it out, it is actually going to give you an impression of that particular animal, and if you take out the soil, it will actually give you the molds. As a result, the animal remains preserved in the rock and has formed the fossils. The hard remains of the dead were preserved layer by layer in the sedimentary rocks.

The fossils present in the deeper layer are older, and the upper layer has more recent ones. There are several different kinds of fossils. These fossils are distributed in amber, asphalt, ice, volcanic ash, peat bogs, storm dust, and sand dunes. So this is the table where I have shown all the different types of fossils, their formation, and examples. For example, there are fossils where the entire organism is preserved. The examples are the woolly mammoth in Siberia, insect exoskeletons, mummies of mammals and birds found in California, and the giant elk of Ireland.

So these are the different skeletons. The other example is the skeletal material. So in this case, you cannot develop the entire organisms, but you can have some parts like the bones, teeth, shells, and all those kinds of things. then you have the molds and the cast so here you will not get even the skeleton or the entire organism but you will going to have the negative impression so in this the hard part trapped in the sediment and that hardened to rock skeleton dissolved leaving its impression as the mold So this is a gastropod from Portland, which is an example of a fossil, and these are other examples of the fossils that are present. So the question is, how can you determine the age of the fossil? The age of the fossil can be determined by the following methods. So in the past, people used relative dating methods.

In the early days, the mechanism of absolute dating was not present. And as a result, the relative dating techniques were used to determine the ages of rocks and fossils. In this technique, the position and erosion rate of rock in a particular environment are analyzed. The older rocks, situated deeper, had ancient fossils, while the superficial rocks contained fossils of more recent origin. So in this relative dating technique, if you have a rock and you find a fossil here, since this is actually in a deeper portion and this is a shallow portion, this is going to be an earlier fossil and this is going to be the later fossil. But this is all based on relativity, so that's why people were looking for an absolute dating method, and they have developed multiple absolute dating methods.

These methods use the spontaneous decay of unstable radioactive nuclei into stable radioactive nuclei at a constant and known rate. Absolute dating techniques use radioactive nuclei in three different methods. The first is the uranium-lead technique, which involves uranium decay. So if you see it very clearly in the uranium-lead technique, this technique was introduced by the Baltoid in 1907.

So, rock contains uranium, specifically uranium-238, in the form of the mineral zircon. Uranium decays spontaneously to lead as per the given scheme. So, you have the uranium-238; then it will go on to form the thorium-234, and then it is going to form the protactinium, and so on. And ultimately, what you're going to form is the lead. So depending on the amount of lead and the amount of uranium, you can identify how many life cycles and how many half-lives are being crossed.

For example, in one half-life, uranium will develop into thorium, but the difference is 4.5 times 10 to the power of 4 years. So if you count the number of half-lives, you will be able to determine the age of that particular fossil. So, it has a half-life of 4.5 billion years, which means it will take this many years to decay 50% of uranium.

So, the determination of the content of uranium and lead in a rock or fossil can be used to determine the age of the rock. For example, if I got 40% or if I got the 50% decay, suppose I got the total amount and suppose I got 10 mg of uranium and 10 mg of lead. That means that there is a 50% decay, and that means that the age of that particular fossil or the age of that particular rock is 4.5 billion years. You can easily calculate the same way, right? If you have, for example, 2 mg of uranium and 8 mg of lead, then you can also calculate, right? You can calculate. So there will be 80% decay, right? So that's how you can calculate the age of that particular rock using these kinds of equations.

Then we have the carbon dating method. The carbon method was also introduced by W.F. Libby in 1950. The radioactive carbon C^{14} is found naturally in rock, and C^{14} has a half-life of 5,600 years. C^{14} decay gives rise to nitrogen^{14}. Carbon dating methods can be used to determine the age of fossils up to 25,000 years old. So you can see that you have the uranium method, the carbon method, and the potassium method, and all these methods actually have a multiple range in which you can use.

Then we have the Potassium Argon method. Radioactive potassium is easily found in rocks of all kinds; it has a half-life of 13.9 years and it disintegrates to form Argon. So you can actually use all three of these methods to calculate; there will be no relative dating methods. So these absolute methods will actually tell you what the age is, whether it's 10, 20, or whatever, right? And that's how you can correlate the different fossils that are found even in different areas or regions within the world. Now, what is the utility of determining the age of the fossil? If you determine the age of the fossil, you can use that information to calculate when that particular organism appeared. And based on these, the people have come up with the geographical scale or geographical timescale, right? The geological time scale is actually going to tell you the appearances of different animals, so the use of the radioactive dating method has allowed for the determination of fossils found in the different sedimentary rock samples.

It has allowed for the calculation of the presence of different organisms preserved in the rock sample in the form of fossils. In addition, it helps scientists predict that the Earth is approximately 4.5 billion years old and that life appeared on Earth almost 400 million years ago. So this information actually came from the carbon dating or the absolute dating techniques. Since then, the Earth's history has been divided into five different time frames known as the eras.

Few of these eras are divided into periods, which in turn are split into the epochs. The different eras are as follows: the Archezoic era, which started from 4600 to 3500 million years ago. Remember that it is always done in the reverse order. You see the higher number and then you see the lower number. So this means we are talking about it from the reverse side.

So it is the first era and began with the formation of the Earth and the presence of the solar system. There are no fossil forms available from this era. This means this is the era when the Earth is actually being formed. Then we have the Proterozoic Era, which started from 3000 to 1000 million years ago. It is the second era and began with the origin of prokaryotes, primitive metazoans, and eukaryotes.

Reports are available about the scanty fossils from this era. Then we have the Paleozoic era, which started from 570 to 280 million years ago. See, there is actually a gap, and these gaps exist because there are no fossils found between this age and that age; we cannot have any idea what is happening. So it is the third era, known as the era of ancient life. It saw the appearance of invertebrates, fish, amphibians, and reports of spore-bearing plants.

Trees, ferns, and the origin of conifers are present. Initial reports are also available about the scant fossils in this particular era. Then we have the Mesozoic era, which is from 225 to 135 million years ago. This era saw the appearance of toothed birds, therian animals, reptiles, and the dominance of dinosaurs. In addition, placental mammals were also found. Reports of cycads and flowering plants are also available.

And then you have the Cenozoic era, or the modern era, which started 135 million years ago. This is the modern era, and it witnessed the dominance of present-day man, modern mammals, birds, fishes, and insects. So this is what we have discussed so far. What have we discussed? We have discussed the evolutions. We have discussed what the different evidences we have produced are that actually support the existence of evolution.

So we have discussed the morphological and structural evidences. We discussed how the body organization gives you the idea of how different organisms are evolving from the pre-existing environment. Initially, you have cellular level organizations, then you have tissue level organizations, and then you have organ or organ system organizations. We have also discussed the many advantages as well as the disadvantages of these systems. Then we have also talked about the homologous as well as the analogous organs, and we have said that the homologous organs are actually going to give you the idea about diverging evolution, whereas the analogous organs are going to give you the idea about converging evolution. So if you could study the homologous as well as the analogous organs, you would be able to make very clear and crystal-clear pictures of when they appeared.

And then we also talk about the gradual modification, how the different organisms have adapted to the changing environment, and because of that, they have changed their physiology and their organs. We have taken an example of the heart and discussed how the heart is being converted from two chambers to four chambers. And then we also discuss the connecting links, which are very crucial features or crucial evidence that prove that these two organisms come from that particular ancestor. And then we also discuss the embryological evidence as well as the paleontological evidence.

And at the end, we have also discussed the different eras. We have also discussed the geological time scale and the different types of eras that are present. So with this, I would like to conclude my lecture here. In the subsequent lecture, we are going to discuss how evolution is happening. So until then, goodbye. Thank you.