Environmental Chemistry and Microbiology

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Module - 8
Lecture - 38
Cell Biology - I

Welcome everyone to module 8 and lecture 38. We are going to start a new topic today called Cell Biology. Cell Biology has been split into 4 parts will be covering this particular topic.

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So, these are some of the topics that we are going to cover today. The first one is the importance of being small. And the textbook describes it as the cellular advantage. So, you might say that, why are bacteria and all of these organisms that are so small, they occupy such a prominent place; if we think about the biodiversity of organisms, bacteria have an especially important role; and they are perhaps the most biodiverse organisms that we know.

So, what is the advantage to them? Why are they able to survive both in terms of time and space? So we will take a look at that. And then we come to prokaryotic cells; what are the different shapes and sizes that we see in the environment; and the nature of cell membranes. Because that determines how they take in nutrients and how they excrete waste into the environment.

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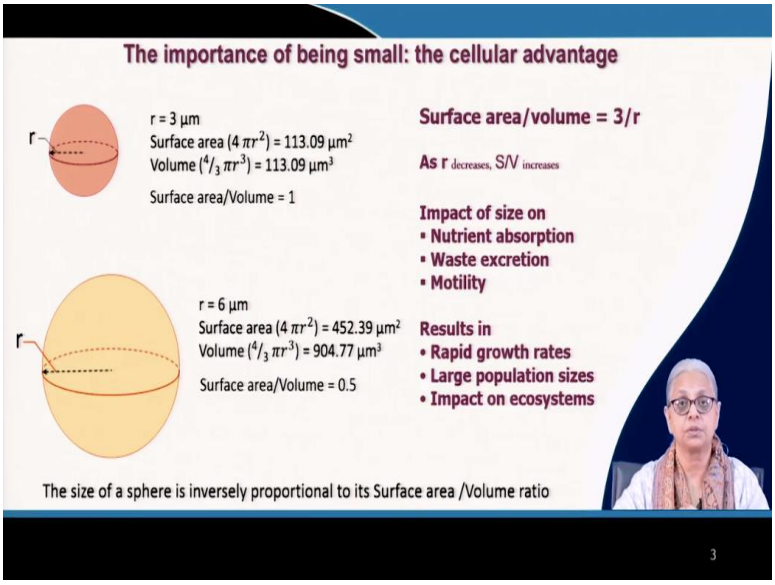

So, let us start with the cellular advantage, which is also the importance of being small for these bacteria. So, what I have here is a sort of illustration of a coccoid cell. So, as you know, the coccoid; we will come to more details about that later. But for starting, just to get an idea of this, the nature of being small and how does it work. So, we are taking a sphere. We are assuming that our bacterial cell is a simple sphere.

Now, we can make any assumption. You can say the radius is 1 micron; we can say it is 3 microns and 6 microns. So, we have a comparison here, of 2 different organisms. The radius in the first case is 3 microns. And in the second case, it is 6 microns. So, you have the surface area and the volume. In the first case, they are equal. And you can do the derivation.

So, $\frac{4\pi r^2}{\frac{4}{3}\pi r^3}=\frac{3}{r}$

And you can put it in terms of diameter as well. Now, the surface area divided by volume, in the first case is 1. And in the second case, the ratio is 0.5. So, what does that mean? If the organism is becoming bigger or is bigger, then the surface area by volume ratio is less? So, is there an advantage in being small? The answer is yes. Because, this ratio, the surface area to volume ratio is smaller.

As the radii go down, the surface area to volume ratio is increasing. So, the smaller the cell, the greater the surface area. And it is the surface area that brings in nutrients and excretes waste. So, remember, they do not feed like us. We feed by ingestion. We have only 1 inlet, and that is our mouth. So, whatever, whether it is water, whether it is food, it goes in through only 1 inlet. And the bacteria, on the other hand, do not feed by ingestion.

What we do is ingestion. And what the bacteria are doing is what is called absorption. And absorption is a surface phenomenon. So, the entire surface area is available for the bacteria to

feed and get nutrients. So, this surface area by volume ratio is crucial. And that is what determines the ability of the bacteria to get what it needs from the environment. So, here you have; as the radii go down, the surface area by volume ratio, which is also called the specific surface area in engineering; that will increase.

So, as r decreases, S/V or the specific surface area increases. And that is why the smaller the size of the cell, the greater the advantage in absorbing nutrients. And that is what the bacterial advantage or the cellular advantage is all about. So, as I said, the impact of size on nutrient absorption, waste excretion, and motility. Now, smaller is better for the simple reason that it is a small volume as well as surface area.

They can move in their environment more conveniently because they are small. I think the best example would be to try driving a small car versus a big car in a congested city. You know that a small car has an advantage. It can park in places where a big car cannot park, right. So, that is a little bit about the motility of bacteria as well. So, then we have nutrient absorption and waste excretion. So, we have already understood that part.

What is the impact of this advantage? The first impact is: If the organism is small, it needs fewer nutrients. That is one thing. It has a greater surface area to volume ratio and it means it can absorb a lot. And that will result in rapid growth rates. So, if the nutrients in the environment are available, the growth rate is very rapid. And this will result in large population sizes.

So, if you think about wastewater, municipal wastewater; has millions to billions of cells per milliliter. So, imagine the number of cells that can exist on the nutrients available in the wastewater. So, the population sizes are very large. And they have a very strong impact on the ecosystems. But because anytime you have bacteria or any other small organisms, their impact on ecosystems is enormous. So, they are a very significant part and a fraction of the total biomass in any ecosystem. And you know from ecology that, they can be primary producers; and many of them are decomposers. So, they are the beginning and end of every food chain. So, you know how enormous the impact of these prokaryotes especially is on the environment, as well as any ecosystem.

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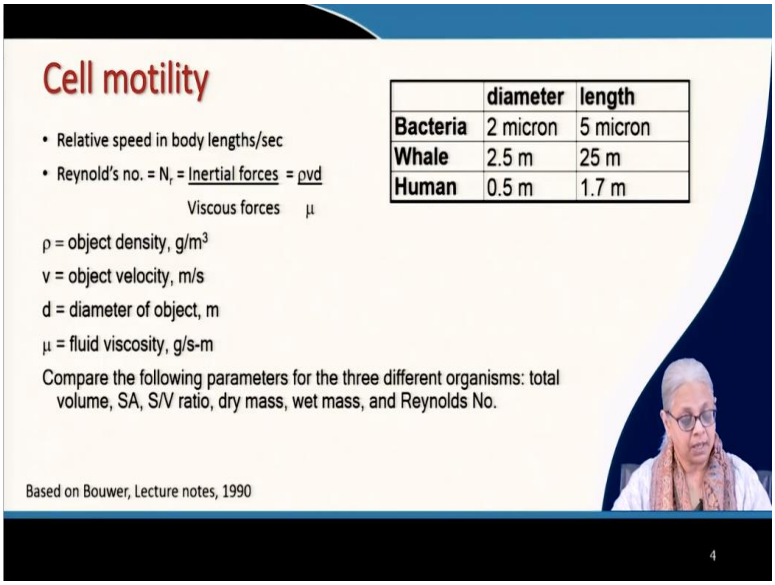

	diameter	length
Bacteria	2 micron	5 micron
Whale	2.5 m	25 m
Human	0.5 m	1.7 m

Let us take a little closer look at the motility of cells. How do they move? We will take a look at the method of movement, and that is the flagella. We are not going to go there right now. We are going to take an engineering perspective on the way cells move in their environment. So, what we have here are a few important data. It is very easy to find this data. You can look at it in any textbook or; in my case, I took this data from the internet.

So, we can assume that the bacteria have a diameter of, let us say 2 microns, and a length of 5 microns. We have whales, which are the other end of the size spectrum. So, if you think about the largest animal on the planet, especially animals that live in aquatic systems, the largest animal is the blue whale. And it has a diameter of about 2.5 meters and a length of about 25 meters. How do human beings compare with these 2 organisms?

First of all, we do not live in water. We can only swim. We do have the ability to swim, but we cannot survive in water. So, that is one major difference. The diameter is right in between. So, we have a 0.5 meters diameter, assuming that we are elongated cylinders. You know, we do this in engineering all the time. So, we are following the same ideas. And the length is about, let us say, 1.7 meters.

For doing these calculations, we are going to assume that each one of these organisms is a cylinder with the diameter and the length that is shown over here. So, I can measure my ability to cover distance while I am swimming. So, if I am swimming, I know how much distance I can cover in a few seconds or minutes and so on, right. We can convert that to body lengths because that will put it on a relative scale. So, I can measure it in meters per second or I can measure it in body lengths per second, to put it on a relative scale. So, when you have bacteria, you have microns. When you have whales, you have a few meters. So, we see that humans

have a length of more than 1 meter. So, that is just to give us a sense of relative speed. So, that is 1 parameter that is calculated over here.

The next parameter that we are calculating is based on Reynolds number. So, those of you who are from civil engineering or any of the other engineering branches may be knowing about Reynolds's number. So, Reynolds number is abbreviated as R_e or N_r, depending on what source you are looking at. It is a unitless number and it is the ratio of inertial forces divided by viscous forces.

So, the inertial forces are shown by $\frac{\rho v d}{\mu}$. ρ is the density of the object; v is the velocity of the object, and d is the diameter of the object, and μ is the fluid viscosity in grams per second per meter. I can calculate. So, based on these dimensions, as well as assuming the viscosities.

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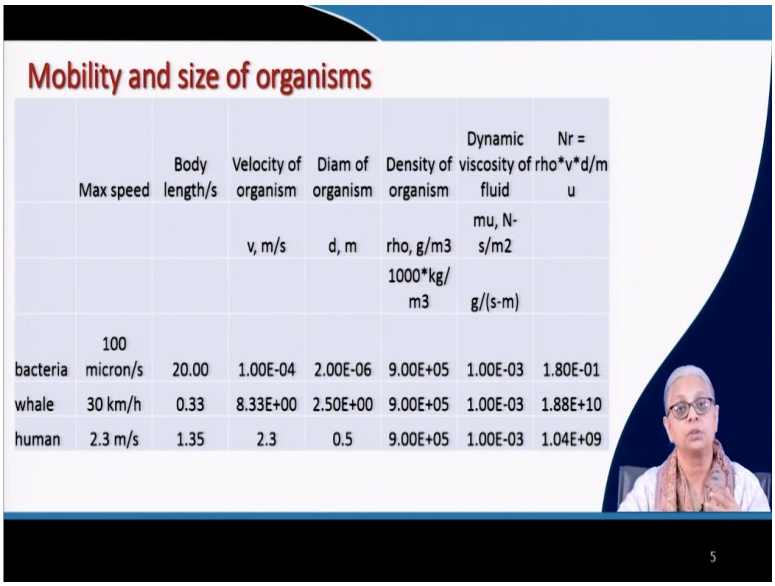

So, I have assumed a viscosity of 10^{-3} newton-second/m^2 has been converted. And we have a maximum speed. So, let us say the maximum speed of bacteria is 100 micron/second; for a whale, it is 30 kilometers/hour; and for a human being, it is 2.3 meters/second. I can convert that to body lengths because I know the length of the organism.

So, if I want to compare how fast do these organisms move; you can see that the bacteria are moving 20 body lengths per second. So, just imagine that it is faster on a relative scale, it is much faster than a whale or a human being. And we normally think about whales as being able to move very fast in the water. So, you can get a sense of comparison here. You can convert it into velocities. If you just put it in terms of meters per second, it is not much. They are very tiny organisms and they are not even visible to the eyes. So, it is not much in terms of meters per second. But on a relative scale; because you cannot compare a micron-sized organism with

a 2.5 meter long or 2.5 meter diameter whale. So, you have to give it a sense of relativity, which the body length per second gives you.

I have already mentioned the diameter. The density of all organisms, in this case, for simplistic reasons, has been assumed to be the same. Look at the Reynolds numbers. What does the Reynolds number tell us? The Reynolds number tells us the ratio of inertial forces to viscous forces. So, if the bacteria has less than 1 as the Reynolds number; and the other 2 organisms, humans and whales have far greater than 1 as their Reynolds number. What that means is that the movement of bacteria is dominated by viscous forces. So, the analogy that people often use is of human beings swimming in a tank of sugar syrup. So, imagine that you are dumped into a tank of sugar syrup, and you have to swim in it. That is when viscosity will dominate. So, for the bacteria, swimming in water is similar to that.

So, we have high viscosity; and we have high inertial forces for whales and human beings. Now, what difference does that make? Why am I going into this? So, this was all about the cellular advantage. This is not an advantage. This is the cellular disadvantage. So, if you know swimming, you know that; when you go swimming, what do you often do? You take a kick off the wall, right?

So, when you start swimming, you take an initial kick that allows you to cover a huge amount of distance before you start paddling and moving your arms and so on, right? So, that is because inertia dominates. So, you get momentum. You get that initial momentum from the kick of the wall. And that allows us to coast or cruise while we are swimming.

And what does the whale do? It just flips its tail a few times and it gets an enormous amount of momentum simply by doing that. So, they can cover enormous distances in the water, simply because of these inertial forces. Now, the poor bacteria do not have an advantage in this case. For them, because viscosity dominates, because of their small size, it is the viscosity that rules. And that is evident over here. Now, this, as I said, is the opposite of the cellular advantage. They can get their nutrients, but the movement is difficult. And movement, when they do have to do it, is generally in response to the requirement for nutrients. So, they do have to move in response to their requirement for food. That is one thing. And the second thing is, they have to utilize a huge amount of energy to get to their food.

And that is the conclusion from this entire exercise is to show you how difficult it is for these bacteria to get their food. They expend a lot of energy before they can derive energy.

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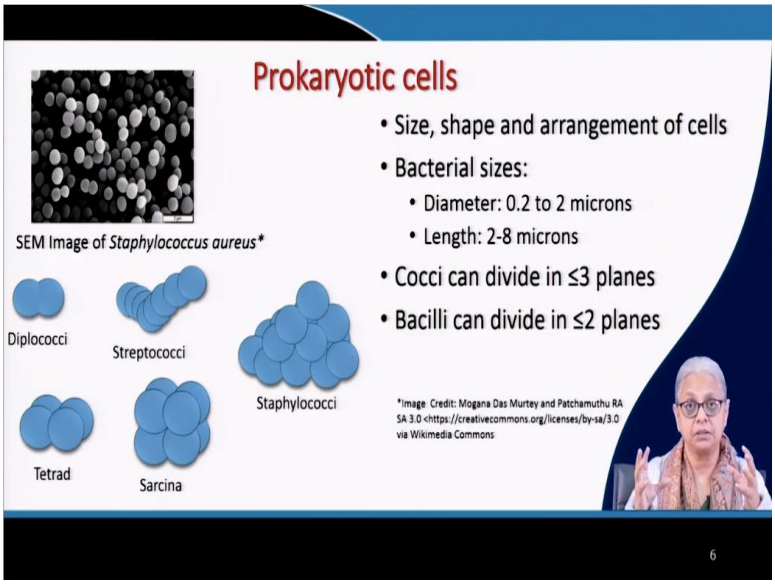

Let us come to their shapes and sizes. So, here we have a huge bunch of prokaryotic cells. As I already mentioned quite a few times that bacteria are the most biodiverse organisms that are known. And part of it is because they are so small. So, that is also part of the cellular advantage. And I should also mention over here, that they are also the most primitive organisms on the planet. So, when we talk about the beginning of life, most of us agree, I think, without any debate, that all life is likely to have begun with prokaryotic cells. They are the simplest life forms that continue to exist, right from the day that life began on the planet.

So, let us start with the size, shape, and arrangement of cells. We all know, I think most of you have studied in high school that; if you have a single cell, which is capable of living on its own; and then when it reproduces, it reproduces by binary fission. So, that single parent cell becomes 2 daughter cells. And those 2 daughter cells are now the parent cells, and they become 4 daughter cells and so on. And that is how the bacteria continue to reproduce. So, if you have cocci, similar to this particular species, Staphylococcus aureus; and let us imagine that we have a single coccoid cell. If it reproduces in one plane, just like a line. So, a line is your one-dimensional reproduction. And this particular coccoid has split into 2. So, it is a diplococcus. If it continues to split, but it continues to form a chain, and then it is called streptococci. So, streptococci is a long chain of coccoid cells. They are all independent. If you split one of the cells away from the chain, it will live independently. It will continue to reproduce and go through the same phenomenon all over again.

Then we have; supposing it starts reproducing in 2 directions. So, let us say we have a single cell and it is reproducing in, let us say x and y directions. So, up to diplococci and streptococci,

let us say it is in one direction. So, x-direction. In the tetrad, you have a single cell. It is reproducing in both directions. So, first, it becomes 2; and then it becomes 4. So, this becomes a tetrad. And that is 2 dimensional.

So, that is why I have said cocci can divide into 3 planes, all 3 planes; x, y, and z planes. If it divides into all 3 planes, we call it sarcina. And if it continues to divide over a long period of time, but the cells do not break away; so, if the cells do not break away, they create what is called staphylococci. So, this becomes, after a small amount of time, a few generations, this becomes staphylococci because you would get an amorphous mass of cells. It is a cluster of cells and they have divided in all 3 directions. So, you get this amorphous mass. Bacilli are slightly different. They are rod-shaped bacteria.

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So, here we have bacilli species. You can see, they are all elongated, rod-shaped bacteria. So, this is a single bacillus. If it divides in one direction, you get diplobacilli. If it continues to divide in the same direction, forming this long chain or filament, you get streptobacilli, the same nomenclature. And coccobacilli are slightly different. They are not so elongated. So, they are more like a spherical shape but slightly oblong, almost like an egg shape. So, these are coccobacillus organisms.

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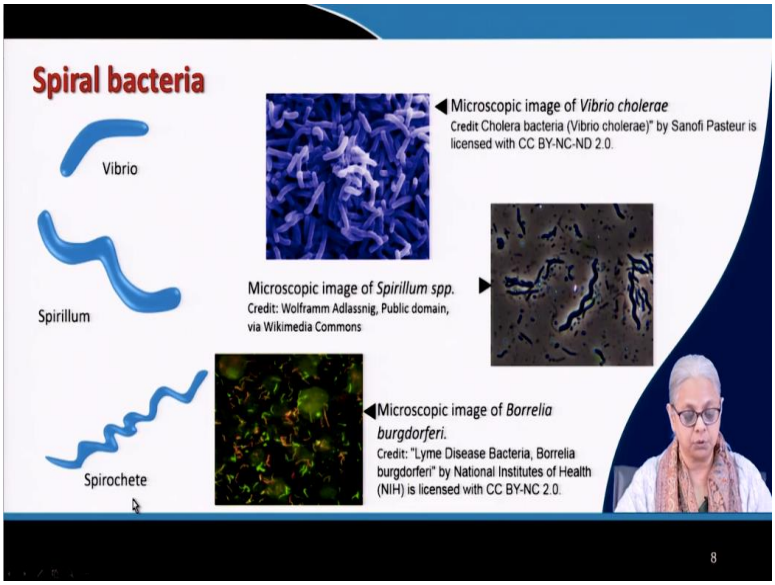

Then we have some more interesting forms. So, the next one is Vibrio. Vibrio, which is very famous for being Vibrio cholerae. It causes cholera. It is comma-shaped. We used to call it a comma-shaped organism. So, this is an example of Vibrio. So, here we have Vibrio cholerae in SEM. And then we have Spirillum. Now, the entire body of the bacteria is slightly helix-shaped. So, you can see Spirillum and Spirochete. So, you can see the nature of these 2 species. So, you have Spirillum here. You can see the wavy type of body that it has. And Spirochete is slightly helical. And here is another image of another helical organism Borrelia species.

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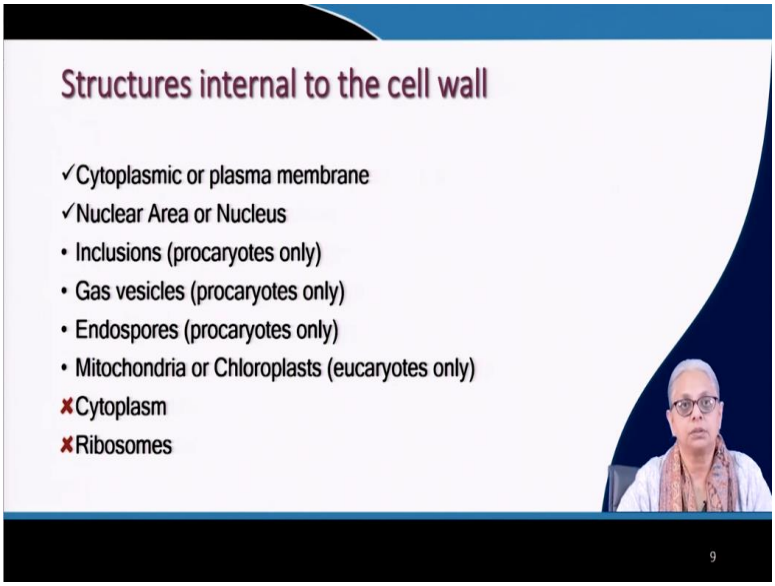

So, having seen the sizes and shapes of the different types of prokaryotic cells, we now come to another issue; and that is the structures that are internal to the cell. So, we will take a look at

the cell wall later. But we are going to start with the cytoplasmic membrane or the plasma membrane.

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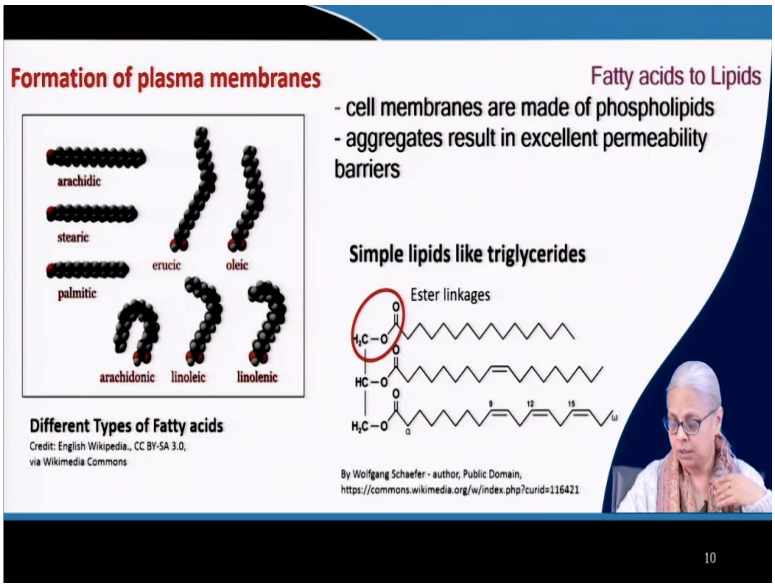

So, the first thing we are going to take a look at is, how is the plasma membrane formed? What are the building blocks of the plasma membrane? So, I think I mentioned this when I was talking about the monomers or fatty acids going to lipids. And we saw what simple lipids like triglycerides look like. And we looked at complex lipids like phospholipids and glycolipids, sulfolipids, all of that.

These phospholipids, sulfolipids, glycolipids; are the building blocks of the plasma membrane. So, this is the first thing, cell membranes are made out of phospholipids. And phospholipids are true for bacteria. Remember that bacteria, the domain bacteria applies to modern bacteria, the ones that you see in your normal environment. Archaebacteria have sulfolipids and glycolipids, which we will come to later.

They all have fatty acids. So, we have our glycerol molecule; and it has 3 fatty acids. You can see these long-chain fatty acids in this particular graphic. And these fatty acids are linked to the glycerol by ester linkages. So, these are some of the fatty acids that can be part of the plasma membranes. And they all vary in terms of the number of carbons in each of these fatty acids. They vary from C16 to C18 or even more.

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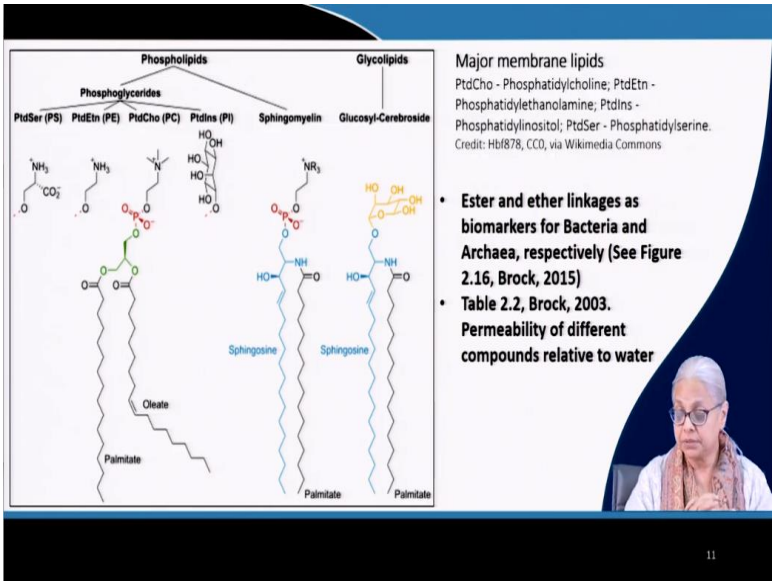

More examples of these phospholipids as well as glycolipids. So, here you have examples of phospholipids as well as glycolipids. I am not going to go into any detail. I do not expect anyone to memorize all these things. This is just to impress you with the fact that they all have this structure. So, you have this glycerol, which has these long-chain fatty acids attached to it, just like it is shown over here.

These are the long chains of the phospholipids and glycolipids. An important point, which I think I mentioned in the previous topic is the difference between bacteria and archaebacteria. So, remember, these are the 3 domains of all living organisms. 2 of them are occupied by prokaryotes; and it is only the third domain that is the eukaryotes.

Now, why are bacteria and archaea so different? And that is mainly because the plasma membrane has; it is different from all the other plasma membranes. So, to put it another way, bacteria and eukaryotes have similar plasma membranes, where these triglycerides are the same structure. So, they have the same ester linkages. Archaebacteria, on the other hand, which I have been saying for quite some time, go back to a long time in the evolutionary past of living organisms; they have ether linkages. So, that is used as a biomarker to separate archaebacteria from bacteria. And so, when I was talking initially, in the very first lecture, I said, bacteria serve as a tool for understanding life processes as well as evolution. So, when we talk about the evolution of life on the planet; and why are we the way we are, etcetera; all these things; are the tools that we use for probing life processes. And this is something that, as I said, tells us a great deal about how life began when it did, which was 3.5 billion years or even more, further back. 3.5 to 3.9. billion years ago is when prokaryotes probably were born on the planet, and eukaryotes are very new, comparatively speaking, they are about 2 to two and a half billion

years ago. And human beings are very new entries on the planet. They are very new, compared to all these organisms.

But the important point for going off on this tangent, because, even though it does not seem to have anything to do with environmental microbiology; it really does, for the simple reason; and I keep saying this again and again. Life began when there was no oxygen on the planet. So, our current understanding is that there was no oxygen; it was very high temperature and fairly low pH conditions under which life began. And these archaebacteria, probably organisms that date back to those times under which life began, because they are extremophiles; and they are capable of surviving in the harsh conditions under which life began. And the modern bacteria and ourselves and other higher organisms that are dependent on oxygen, are a different branch of this evolutionary process. So, that is why these are quite interesting. And remember that organisms modify their environment. And this is the best example of that. Oxygen on the planet has come mainly from algae. So, it is the phytoplankton that have contributed the greatest amount of oxygen to the planet. And it is because of this biotic, abiotic give and take, let us call it; the give and take between the biotic part of the environment and the abiotic part.

It is important to remember that today's environment has been formed by these organisms or their predecessors. And these predecessors themselves have created new environments. So, it does have a lot of importance from at least a scientific point of view.

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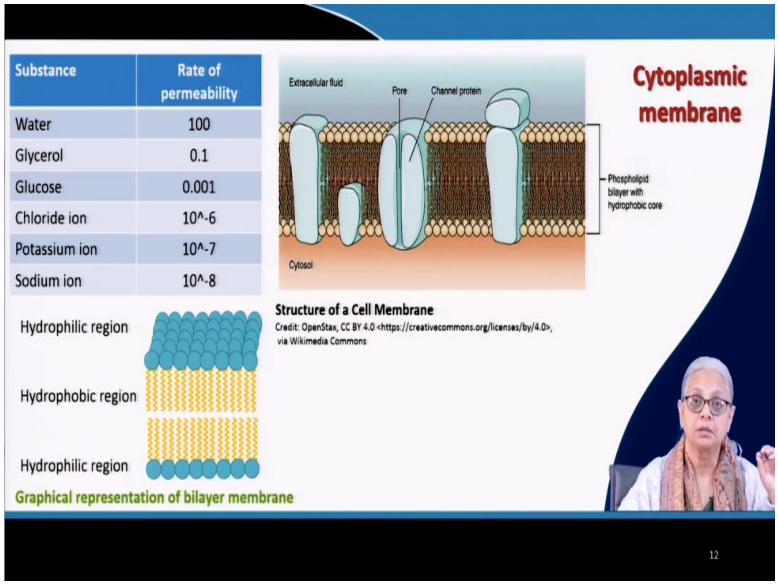

So, before I go to permeability, let me show you the structure of these plasma membranes. Now, that is also a very interesting structure. So, I already mentioned to you that these phospholipids, glycolipids, sulfolipids, all they are amphipathic molecules. Amphipathic means one side, this side which has oxygen is hydrophilic. And the other side has the fatty

chains; these fatty chains have no oxygen; they are only carbon and hydrogen; they are hydrophobic. So, we call this the head and these are the tails. So, every molecule has this 1 head, the glycerol; and 3 tails, 3 or 2 tails, minimum 2 or 3 tails. Now, because the head is hydrophilic and the tails are hydrophobic, you get this automatic, spontaneous, orderly arrangement of these molecules will happen in water.

It is like oil and water, literally like oil and water. What happens when you add a little bit of oil to water, under room temperature? It will form a layer of oil at the top because oil and water do not mix. So, oil is hydrophobic; so, they do not mix and you get this layer. Now, here we have similar compounds. We have something that likes to be in the water and we have something that does not like water, it dislikes water. So, all the tails will cluster together and the heads will move towards the water. We are in an aquatic environment. So, in an aquatic environment, all heads move towards the water, all tails are in between. So, you get this sandwich layer in the middle of the hydrophilic layer. So, you have hydrophilic → hydrophobic→hydrophilic. And this entire layer is not bonded together. This is a simple and perhaps the best example of hydrophobic interactions, which I again talked about in the previous chapter. So, when I was talking about weak interactions, like Van der Waals forces, hydrogen bonds, and so on; hydrophobic interactions are the crux of the matter for plasma membranes. So, you see this bilayer membrane. So, this bilayer membrane is formed; literally, an oil layer surrounded by water layers at the 2 sides.

Now imagine any compound trying to pass through this layer. Not possible. Because you have hydrophilic, you have hydrophobic. So, any hydrophilic compound, cannot pass through the hydrophobic layer. And any hydrophobic compound, cannot pass through the hydrophilic layer. So, from a practical standpoint, this plasma membrane, without any bonds, is a perfectly impermeable layer. And that is how the bacterial cell maintains its integrity. It is fragile; just imagine how fragile it is, because it does not have any bonds. None of the molecules are bonded together. But, because of the nature of the molecules, they have created an orderly arrangement. And this orderly arrangement is what prevents anything from going in or out, without a protein; or without a protein to help in the process.

So, the plasma membrane, truly speaking, is a semipermeable membrane, for this reason. So, if you have just the plasma bilayer or the phospholipid bilayer; if you have only that, then it is perfectly impermeable because nothing will get through. However, the cell needs to pick up

nutrients and it needs to throw out the waste. So, it is doing it somehow. How is it doing it, is because of this.

So, it has pores; it has channel proteins; you have transmembrane proteins; you have proteins that are on one side of the membrane; all these things are what allows nutrients to come in and waste to be excreted into the environment. So, that is the entirety of the structure of the plasma membrane. So, you can see how incredible it is, literally. And more proof of permeability. So, if I put the permeability of different compounds on a scale relative to water; and we assume that water can pass in and out; which again is not entirely true, even though some textbooks do have that. We know by now, and I think I mentioned that in the milestones; and somebody has been awarded the Nobel Prize for showing us that aquaporins or these proteins have been discovered.

And their role in the permeability of membranes is that it is these proteins are the ones that allow water even to come in and out. Even water is not going to pass freely. So, you look at all the other compounds. How well do they pass through the membrane, in comparison to water? So, water is given a 100, just to give a relative scale. Glycerol is 0.1, which means 1000 times less permeability compared to water. Glucose is even less than that. So, that is 10^{-5} times. For chloride, it is 10^{-8}. Because, here we have 10^{-6}, we divide it further by 100. And that gives us an idea that chloride ion is 10^{-8} times less permeable than water. And similarly, for the potassium ion, it would be 10^{-9}. And for sodium, it would be 10^{-10}.

So, that is how impermeable the membrane is to almost everything. So, it is relatively impermeable and it becomes permeable only because of these transmembrane proteins. And we will be taking a good look at some of the processes and the transmembrane proteins that determine the processes that happen in and at the membrane because this membrane is not for the protection of the cell. This is too fragile a structure to protect the cell.

It is the site of ATP synthesis for the bacterial cell. So, this is not protection. The cell wall is for protection. We will come to that in the next topic. But for now, it is sufficient for you to know that the cell membrane exists solely for mediating the transport of nutrients and waste products in and out of the cell. This is the barrier that determines what goes in and what goes out. And it is the proteins that span the membrane that determine this.