Introduction to Complex Biological Systems
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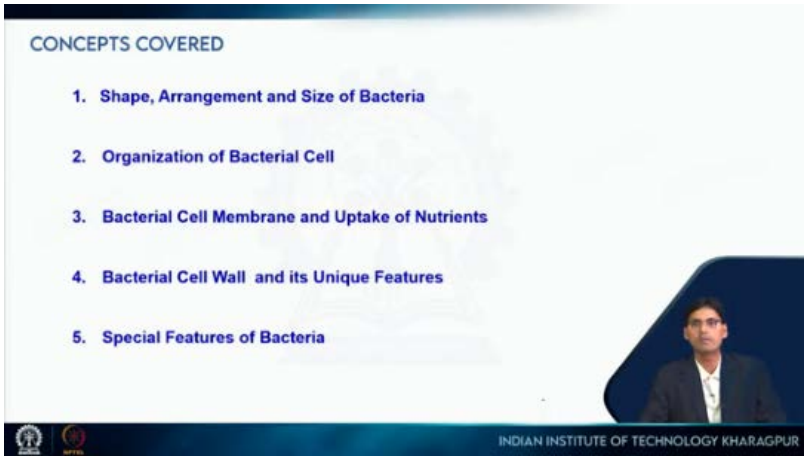
Lecture 42
Cell organization and unique features of bacteria

Welcome back to the online NPTEL course on Introduction to Complex Biological Systems. Currently, we are discussing infectious diseases, particularly viruses and bacteria, and this is Module 9. Today, in this lecture, I will mostly discuss different aspects of bacteria. Here, I will particularly focus on different types of shapes, arrangements, and sizes of bacteria, followed by the organization of bacterial cells, bacterial cell membranes, and cell walls, as both are very important for them. Also, some special features of bacteria. Now, since this course is named introduction to complex biological systems, I would like to clarify here that although bacteria are just unicellular, they are prokaryotes, but you will still see a lot of complexities present in bacteria. These complexities are sometimes evolving, which is a bit of a problem for us because, if you consider pathogenic bacteria, for example, their evolution makes it difficult for us to tackle them.

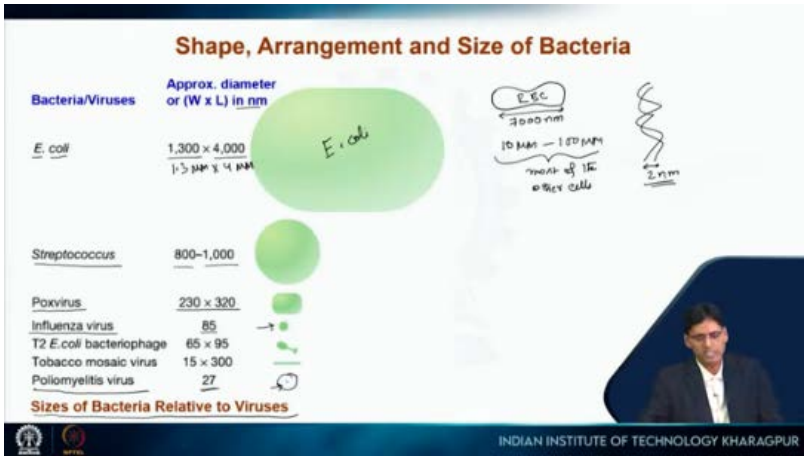
For example, many bacteria are becoming antibiotic-resistant over time; this is just one example, but there are many others like this. That is why the field of microbiology is constantly evolving. To address this issue, we need to know a little about the structure-function relationship of macromolecules present in bacteria, and I am going to discuss a few of them. Here, if you focus on the shape, arrangement, and size of bacteria, this is just to compare where we are now, like compared to mammalian cells or eukaryotic cells, etc. So here, in this diagram, I am trying to explain the size of bacteria relative to viruses. As you know, viruses are just particles and viruses are much smaller compared to bacteria. A very common laboratory strain, for example, E. coli, has its dimensions mentioned here 1300 by 4000 nanometers.



So, this is roughly the dimension of E. coli. This is E. coli. So I would say 1.3 micrometers here and 4 micrometers and here, whatever dimension we have mentioned, it is either its diameter or width by length. In some cases, if the bacterium is not long enough and is more or less spherical, then we mention it in terms of diameter. As you can see, Streptococcus is an almost spherical bacterium, so here the diameter is 800 to 1000 nanometers. Now, if we compare bacteria with some viruses, for example, the pox virus, it is probably bigger in size compared to other viruses; as you can see here. On the other hand, the influenza virus is much smaller. It is more or less spherical in nature, as you can see. This is the influenza virus, and it is 85 nanometers in diameter. One of the smallest viruses is the poliovirus; as you can see, it is almost invisible here, like a small dot, and it is only 27 nanometers in diameter and similarly, some other viruses are also mentioned here. This is just to get a sense of how their size compares between viruses and bacteria. Here, I would like to mention, for example, if you consider one RBC. So, this is a red blood cell I am drawing this way because there is no nucleus, and its shape is a little bit different.

So, the diameter of an RBC is about 7000 nanometers. So now you can compare this with E. coli, and I should mention here that RBCs are, I would say, kind of smaller cells compared to other cells present in our bodies. Most of the other cells present in our body have dimensions between 10 micrometers to 100 micrometers; in this range, most of the other cells are present in our body, and this is an RBC, a red blood cell. and now, since we discussed DNA also in the first module, so now, if I draw our DNA here, what is the width of DNA? It is just 2 nanometers. Now, I believe that you have a kind of overall idea about

the dimensions of viruses, bacteria, eukaryotic cells, and for scaling purposes, you can consider the width of DNA, which is just 2 nanometers.



Now, these small bacteria, they organize in different ways; different types of organizations are also available. That is one thing, and although they are small, they still have different types of shapes. So, we are going to discuss on this slide about different types of shapes and organization of bacteria now. Here, this is cocci, or in singular form it is called coccus. So there are many bacteria that belong to this group, coccus. Their shape is roughly spherical. I would say it is roughly spherical in shape. If I give you one example, that is staphylococcus. This is a very commonly known bacteria, and then streptococcus. So, these are the coccus bacteria. So, in their name, in the genus, you can see at the end that it is coccus there.

So, they are roughly spherical bacteria. But they can stay just like in a single spherical object like this or sometimes they can form different types of higher order structure. For example, some coccus can be paired in this way, like two coccus staying together during division somehow. So, this is an example of bacteria I can say here diplococcus. So, this is two coccus, they are staying together as diplococcus; not just two, there are some other bacteria that can be in some kind of chain, as you can see here, this is in chain.

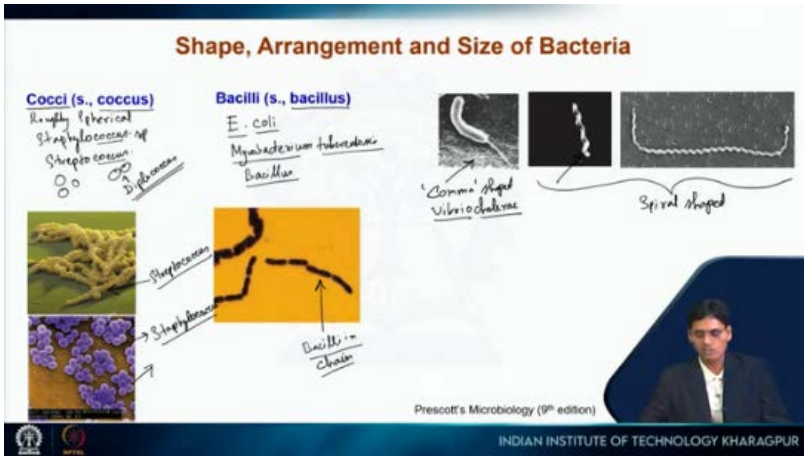
So, although they are coccus, they are in chains and this is a streptococcus. They are in chains and similar. So, this chain forms because when they are dividing, they are dividing in only one plane and they are not getting separated. So, as a result of that, although they are single cells, they are forming some kind of chain-like structure. Similarly, some other

bacteria, for example staphylococcus, divide in multiple planes and they are not getting separated. So, as a result of that, they are just like grapes. So, together like multiple cells. So, this is called a grapes-like structure, and staphylococcus aureus can form this kind of arrangement.

Now If we move to another form of bacteria, for example, bacilli or, in singular, bacillus, one very common example is Escherichia coli, and another common example is Mycobacterium tuberculosis and there are many species of bacillus. So, in their name itself the bacilli is there. So, all of them are kind of slender, like a rod-like structure, and this is called bacillus, and here you can see this is a bacilli in chains.

So, again during division they are not getting separated, so they are staying in a chain. So, these two, the coccus and the bacillus, are the most common forms of bacteria in terms of their shape. But there are some deviations from this standard format, like coccus and bacillus; as you can see, this one looks comma- shaped. Now this is one example: Vibrio cholerae is a bacterium, and this looks like this comma-shaped bacteria, and apart from that, as you can see here, their shape is somewhat spiral-shaped.

Bacteria and this spiral cell bacterium have some kind of advantage for them because, as you can see, this is almost like a screw. So, as a result of that it helps their motility. So, for example, they can go faster with mucus and penetrate the host also because of their screw-like shape, this spiral shape that is advantageous for them. So, this is like a little bit of discussion about the shape, arrangement, and size of bacteria. Now I will discuss particularly, I will focus on bacterial cell organization.



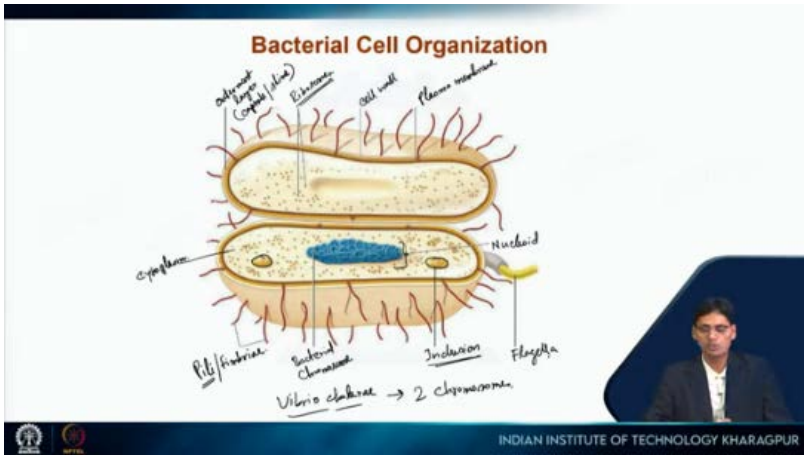
There are few things which are very similar to eukaryotic cells, but there are few things which are completely different and unique to bacterial cells. So, here, as you can see, this is just a kind of section through bacteria so that we can explain what is present inside the bacteria; that's why we are showing it in this way. and, here as you can see at the center here. So, whatever you can see here, this is a nucleoid. So, since you know that bacteria do not have an organized nucleus, only the bacterial DNA, the chromosome, is present inside the cell, and this is called a nucleoid, and this one, I can say, is the bacterial chromosome.

Here I should mention that almost all bacteria have a circular chromosome and just one in number. Some exceptions are there, for example, vibrio cholerae, so they have two chromosomes. This is just some exception. Vibrio cholerae has two chromosomes and now, if you see inside the cell, we have cytoplasm, and now look into this in the cytoplasm; some kind of granular structures are there, a little bit bigger in the cell. This is some kind of inclusion. So, they are some kind of storage body. So, mostly they store different types of carbon and phosphate components. So, these these are called inclusion and now, apart from that, inside bacteria there are a lot of ribosomes which are absolutely required, as you know that ribosomes are the major thing for translation, so in order to carry out translation, they must have ribosomes inside them, and then, like, there are multiple layers on the surface. The innermost layer is called the plasma membrane here. I will discuss it in more detail soon. The plasma membrane, and just outside the plasma membrane, bacteria have a cell wall. Animal cells do not have a cell wall. Plant cells have a cell wall, but bacteria have a cell wall, and this cell wall is kind of unique. I am going to discuss it in more detail soon. So, this is the cell wall, which is mostly composed of peptidoglycan and now, many bacteria, but not all bacteria have, outside the cell wall, some kind of capsule or slime layer.

So, this is the outermost layer. It can be a capsule or some slime layer present just outside the bacteria, but again, not all bacteria have this kind of layer. So, these are some of the important structures present in bacteria, but, as you know, they do not have membrane-bound cell organelles like the endoplasmic reticulum, mitochondria, and so forth, as you already know. Apart from that, on the surface, some bacteria have this kind of hair-like structure, which is called pili and fimbriae. They are very similar structures, hair-like structures present on the surface of bacteria.

Again, not all bacteria have pili or fimbriae, and this helps with adhesion; I would say sometimes it is important for bacterial mating. So, they can transfer some genetic content from one bacterium to another through these pili. And now, this one is flagella. It's much bigger and more robust compared to pili or fimbriae.

This is flagella and flagella is involved in bacterial movement. So, flagella rotate and move, which is why many bacteria can move from one place to another. So, these are some kind of overall organization of bacteria. Now, I will discuss some of the important features of bacteria step by step.

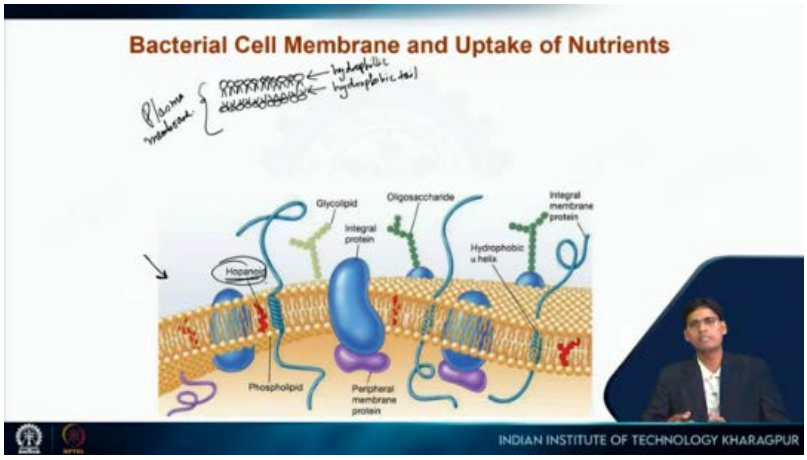


So, bacterial cell membrane and uptake of nutrients, why is it important? As I already mentioned, on the surface, you have the membrane first, which separates the cytoplasm inside from the outside environment and just after the plasma membrane, we have the cell wall and sometimes an outer envelope. But the thing is the plasma membrane acts as a selectively permeable barrier, why? Because the cell wall and outer membrane of some bacteria are much more porous in nature, many things can pass through this, but the plasma membrane acts as a selectively permeable barrier. So, the plasma membrane is a lipid bilayer. This is very similar to the eukaryotic plasma membrane, with some minor differences, which I will mention. So, as you can see, here is the lipid bilayer, and this is the plasma membrane and here this is hydrophilic phosphate group and this is hydrophobic tail, hydrophobic tail. So, in this plasma membrane, many things cannot cross here. Only selectively can certain things cross through this membrane. And also, in the membrane itself, there are many protein carriers and channels-those things are present to facilitate that

process. So, I am going to discuss this selective permeability across the membrane. Because this is very important. Why? Because, particularly, bacteria are single-celled, and whenever they are present in some solution or some natural environment, like, the surrounding is constantly changing.

So, as a result of that, bacteria should efficiently control their environment inside the cell-like concentration of salt and concentration of nutrients. They should carefully take care of those things. So, that is why this is very important to understand. So here, as you can see, this is a much more complex organization we are showing, present in the plasma membrane. There are many things, like glycolipids, oligosaccharides, and integral membrane proteins, there are many things present on the membrane itself and as you can see, in this red color is mentioned here, hopanoid.

So, this is just, I would like to mention here, in eukaryotic cells, as you know, we have sterols. For example, in our plasma membrane, we have cholesterol, and in the case of bacteria, they do not have cholesterol; instead, they have a hopanoid kind of thing. This is very similar in structure to sterols and gives more flexibility to the membrane. So, now, if I go to the next slide, here is the bacterial cell membrane and the uptake of nutrients. So, there are two major types of uptake.



So, I would say one is diffusion and the other one is, I would say, active transport mechanism, diffusion, and active transport. As you understand, diffusion is not requiring energy in terms of ATP required. Active transport, we have to spend some metabolic energy in order to carry out this kind of transportation. So, diffusion particularly here can

be passive diffusion and facilitated diffusion. So, passive diffusion is only applicable for very selected material.

For example, I would say carbon dioxide and oxygen gases are dissolved in solution, and they can go through passive diffusion inside the cell or outside the cell. So, this is passive diffusion. But, the facilitated diffusion is a little bit more complex than passive diffusion. Here, some kind of membrane protein is involved in this kind of diffusion, but both of them like passive diffusion and facilitated diffusion. Since we are not using any energy, this should be done on the basis of concentration gradient and in terms of concentration gradient, if some concentrated stuff is present outside, it should go inside, or something which is present more inside the cell will go outside. So, this depends on the concentration gradient. In particular, in case of facilitated diffusion, as you can see, some carrier protein is present here. So, this is a carrier protein, as you can see this is a carrier protein present on the membrane. So I would say this is in this membrane; this is the outside, and this is inside.

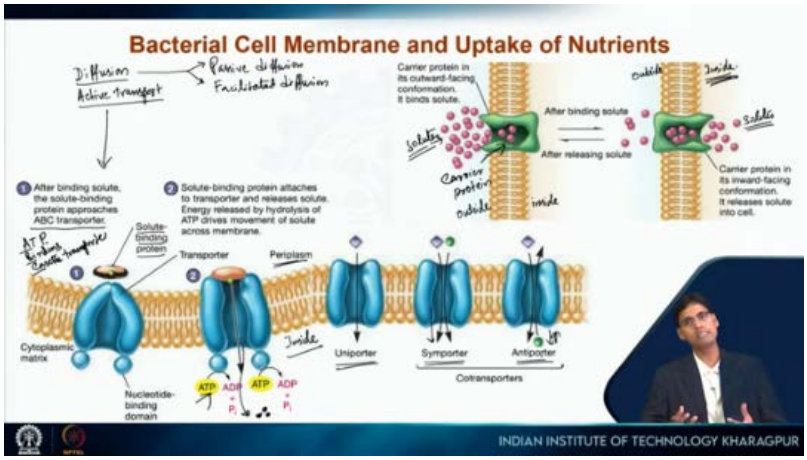
Similarly, here in this membrane, this is outside, and this is inside. This is the same membrane; the same thing is happening here. We are just showing the next step in facilitated diffusion. In the first step, as you can see, these carrier proteins are facing outward due to some conformational changes. This is due to a conformational change in the protein, which helps these solutes enter into the carrier protein. As you can see, these are the solutes; it can be some nutrients. So, now after binding the solute, the conformation changes, and then the carrier protein releases those solutes. Here inside the cell, as I already mentioned, this is the inside of the cell, and they are releasing the solute. So this is one such mechanism where no energy is required, but this facilitates diffusion. Normal diffusion occurs here, but some carrier proteins are facilitating this process.

But although this is observed in many bacteria, I would say this is not that common because, in natural conditions, if you consider bacteria naturally present in some water or other places, there are not that many nutrients available, not so much of a nutrition-rich environment. So, as a result, it is not always easy to take nutrients from outside to inside via this facilitated diffusion method. So, if the nutrient amount is low outside, then it needs to spend some energy to uptake those nutrients from outside to inside in that way. So, here

I am going to discuss that part, also that is active transport. So, where we need to spend some energy here.

So, this transportation phenomenon is very similar in the eukaryotic system also. So, here as you can see, like in this plasma membrane, this is called particularly the ABC transporter. So, ABC transporter means ATP-binding cassette transporter. So, ABC, ATP-binding cassette transporter. So, as you can see, on the plasma membrane, we have some specialized protein molecules present here.

So now I would say this is the inside, that is the cytoplasmic side, and this is the periplasm outside. But it is periplasm because just after that we have the cell wall also, which is why this is periplasm. So, as you can see here, some solute-binding proteins are available here. Solute-binding protein is a kind of protein that will bind to the solute, and after binding to the solute, this solute-binding protein will bind to this protein, the ABC transporter, and it will send the solute inside the cell. So, as a result, the solute will now be inside the cell. So but, in order to carry this out, we need to spend ATP, as I already mentioned. This is a kind of active transport mechanism. Now, this active transport can be uniport, or co-transport. Uniport here means one kind of substance going in one direction. For example, whatever I mentioned in the case of the ABC transporter, as you can see here, one kind of solute is going only inward. This is a uniporter—one thing is coming. Co-transporter here means that two substances, one can be an ion, and the other can be something else, are moving. If both of them are moving in the same direction, it is called a symporter; if they are going in opposite directions, this is called an antiporter. So, I just discussed this transport phenomenon because this is very important to understand in terms of across the membrane, as I already mentioned, the basic mechanism is very similar to eukaryotic cells. Now, I just discussed the plasma membrane. Now, I am going to discuss the bacterial cell wall and its unique features. This is very important.



Because of this cell wall, because of the unique features of the cell wall, there are many antibiotics we use that prevent bacterial growth. So, as you can see here, this is some kind of electron micrograph here. So, this is some bacterial cell, and here this is more like a reconstituted image. So, this is a reconstituted image so that it will be easy for us to understand.

Now, as you can see this is cytoplasm. and this is P here, P stands for plasma membrane. So this is PM, PM means plasma membrane.

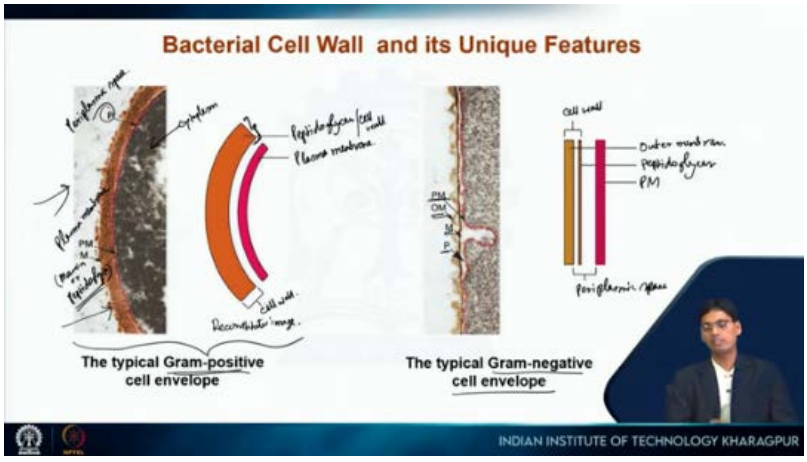
So, then in this case this is murine, P stands for here periplasmic space and this is plasma membrane. So, I am just erasing this periplasmic space, the space between the cell wall and the plasma membrane. So, this is periplasmic space and this is M. Here M stands for murine or peptidoglycan, same thing murine or peptidoglycan. This is the major component of the bacterial cell wall. So, this is a reconstituted image; you can see this is the peptidoglycan or cell wall, and this is the plasma membrane and together as you can see this is the cell wall. Similarly, if you see another group of bacteria, this is found in one group of bacteria. In another group of bacteria, all things are similarly labeled here. This is the plasma membrane, this is periplasmic space which is a little bit bigger, more space available here. This is the murine or peptidoglycan and this is the outer membrane.

So, this outer membrane is not present in this group of bacteria. So, now as you can see here, particularly if I level here now, this is plasma membrane, this is peptidoglycan, and this is outer membrane which is absent here on the left side, whatever I am showing that is absent, outer membrane is not there, and together this outer membrane and peptidoglycan

here we are saying this is cell wall and here periplasmic space. So, now these two different types of cell wall, you can see their organization, but now when scientists use some kind of specialized technique. So, these bacteria are called gram positive because Christian Gram invented this technique of bacterial staining.

He found that these bacteria are taking a dark purple color, and these bacteria are called gram positive bacteria. On the other hand, this group of bacteria are gram negative bacteria. This is happening because of their differential properties in their cell wall. Particularly, I would say because of the very thick peptidoglycan layer, as you can see, this is the very thick peptidoglycan layer and, because of that these bacteria behave as gram positive bacteria.

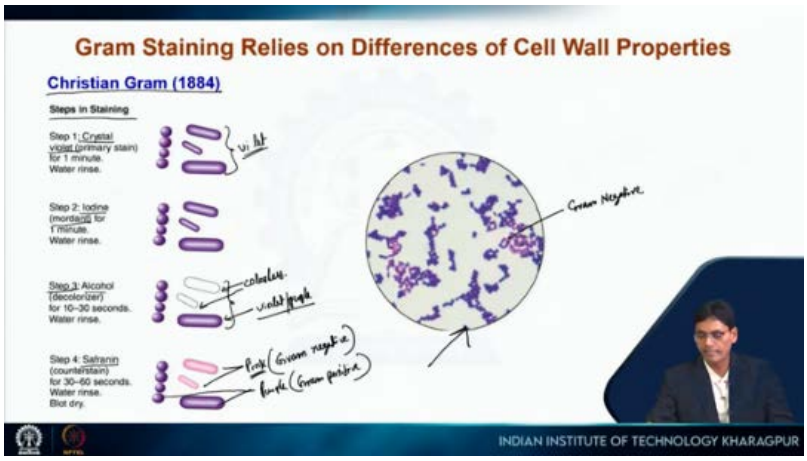
On the other hand, if you see the peptidoglycan layer is very thin in case of gram negative bacteria. So, then what is the technique here? Very briefly, I will go through it; particularly, this gram staining relies on differences in cell wall properties. So, as you can see these are the steps in staining. So, as you can see, there are different types of bacteria; if you can first make some kind of smear, then the first step is crystal violet staining.



So, after crystal violet staining, you can see that all bacteria are violet in color, dark violet in color and then we add some iodine; this is called mordant, so it will fix the color, and the color retention will be better. Then, in step three, we wash those bacteria by alcohol for decolorization, so as you can see now here, some bacteria here are now colorless, but these bacteria are still violet or purple in color. So, after this step, we add some counter stain that is safranin, which is some kind of pink color, and as you can see, those colorless bacteria

are now pink in color; this is in pink. So, this bacteria, whatever pink color bacteria we are getting after this staining method, this is now we say gram negative bacteria and this is gram positive. So, purple here is gram positive bacteria. So, as I mentioned, Christian Gram invented this technique, and accordingly we named gram-negative and gram-positive bacteria, and this is a very important step even in a clinical setting. So, in this way initial characterization of bacteria can be done.

Through this technique, very quickly we can divide bacteria into two groups, like either gram positive or gram negative. In the case of gram positive, they have a thick peptidoglycan layer, and that is somehow preventing this decolorization step. So, as a result of that, gram-negative bacteria are getting decolorized. So, they do not have the crystal violet color anymore, and as a result, when we add the counterstain, in this case safranin, they get a pink color. So, here is some kind of real picture as you can see this pink color bacterium is gram-negative bacteria and here deep purple color is gram-positive bacteria. So, now, I just mentioned the cell wall, but I would like to mention a little bit more about the chemistry of the cell wall, which is very important for therapeutics and also for antibiotics. So, peptidoglycan is unique because it is not present in a plant cell wall, and animals do not have a cell wall.



So, as a result of that, if we can target the peptidoglycan synthesis, we can stop peptidoglycan synthesis; then we can prevent bacterial growth also. So that is why it is very important, and peptidoglycan is a polymer of sugar and amino acid. Sugar here is n-acetyl muramic acid and n-acetyl glucosamine, so this is N-acetyl glucosamine and here

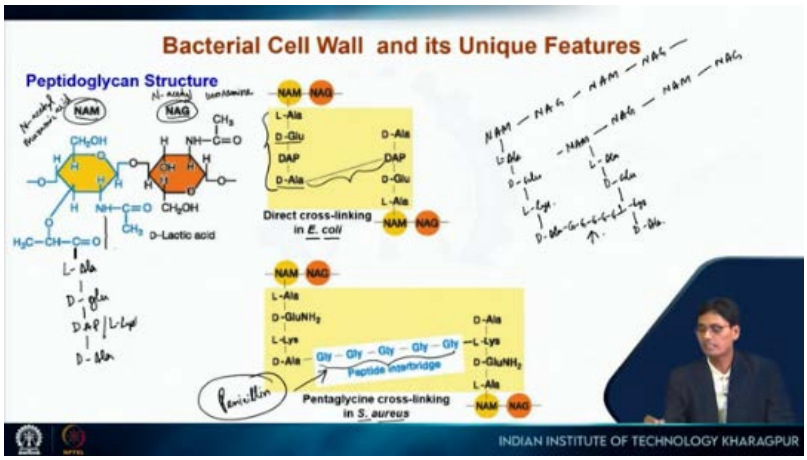
this is N-acetyl muramic acid. So, in short we are writing NAM and NAG. So, these are the sugar repeating units present in this spectroglycan chain and now this NAM or the N-acetyl muramic acid is attached to amino acid here.

So, alanine followed by glutamic acid followed by diaminopimelic acid or sometimes it can be L-lysine also depending on different types of bacteria. So, now here another amino acid is D alanine as you can see in this figure. So, this is in E coli. So what happened is we had a chain of sugar polymers and the repeating subunit like NAM, NAG, NAM, NAG. So, it is repeated that way and then some small peptide chain mostly made up of four amino acids. So, they are hanging from the N-acetyl muramic acid, as you can see here this way, and these amino acids are a little bit different, as you can see. When we discuss proteins, most of those amino acids are L-form amino acids, the natural amino acids which are present in proteins, but here many of the amino acids are D-form, like D-glutamic acid and D-alanine, and that is advantageous for bacteria because they are some kind of resistance to different peptides and many other things, as a result of that, I would say this is bacteria's advantage for bacteria. Now, this cross-linking is very important between this short peptide and another short peptide, as you can see some cross-linking here. This is direct cross-linking in the case of E. coli. But in the case of some other bacteria like Staphylococcus aureus, as you can see here, pentaglycine, 5-glycine, they are actually helping in this cross-linked process.

So as you can see, particularly the antibiotic penicillin, or its derivative, they stop this cross-linking process, and therefore peptidoglycan cannot be synthesized, and that is why it acts as antibiotics. So, whatever I discuss about this peptidoglycan structure, you will get a bit more three-dimensional understanding if I draw it in this way. So, I would say NAM, NAG, NAM So, it is going like this.

Similarly, NAM, NAG. So, this way these are the sugar polymers. Now, from NAM we have this L-alanine and then D- glutamic acid and then L-lysine and D-alanine similarly from here also this N-acetyl muramic acid also you have the similarly this peptide L-alanine, D-glutamic acid, L-lysine and D- alanine now what happened this D-alanine is attached to this L-lysine by pentaglycine, in the case of Staphylococcus, this is the cross-linking. Similarly, again, a peptide will be hanging from this NAM and from here also

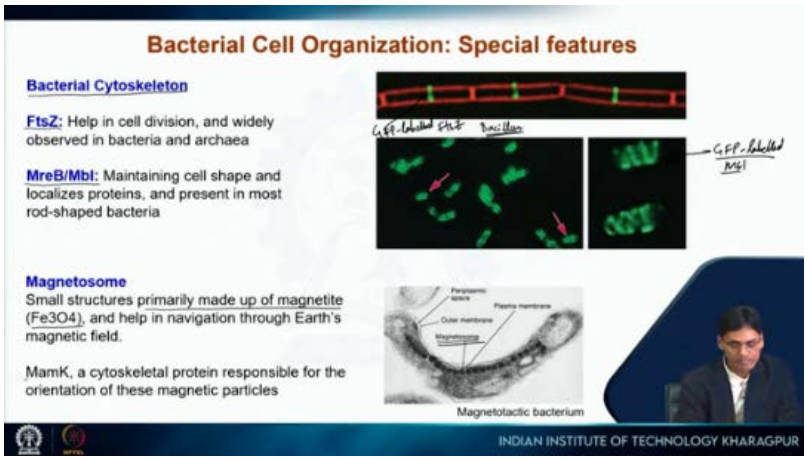
hanging like this, and again, this cross-linking. So, this way, it will make up a kind of strong mesh-like thing, and this layer is present in much greater quantity in the case of gram-positive bacteria compared to gram-negative bacteria. That is all. Now, some special features I am going to discuss about bacteria. So, as we know, the cytoskeleton is present in eukaryotic cells, for example, microtubules, actin, and intermediate filaments.



But current research also revealed that in bacteria, they also have some kind of cytoskeletal material, as you can see here, FtsZ. So, this is very similar to a homolog of tubulin. So, this is similar to eukaryotic tubulin. So, it helps in cell division and is widely observed in many bacteria and archaea. So, for example, we are showing here in Bacillus.

So, Bacillus are rod-shaped bacteria; it is in Bacillus And another cytoskeleton you can see here, MreB or Mbl, is again some kind of protein maintaining the cell shape and localizing proteins inside the cell. This is also present, and this is an actin homolog. So, this is present in bacteria. So, this is very interesting, as you can see here, this is GFP-labeled. FTSZ, and this is GFP-labeled Mbl protein present in Bacillus. Another interesting feature in bacteria is that some have small structures primarily made up of magnetite, as you can see here. They help in navigation through Earth's magnetic field. For example, many animals, particularly some birds, dolphins, and fish like tuna, have a magnetic setup built into their heads that aligns their magnetic poles and enables them to migrate from one place to another. Similarly, some bacteria also have this kind of magnetism. This helps them align and move through Earth's magnetic field.

It's very interesting. So, this is bacteria. They are simple, just unicellular organisms, but they still have this kind of complexity. MamK is another cytoskeletal protein responsible for the orientation of magnetic particles inside bacteria. Here, we show a magnetotactic bacterium. Now, a few things here, some special bacterial features, for example, capsule and slime layer.



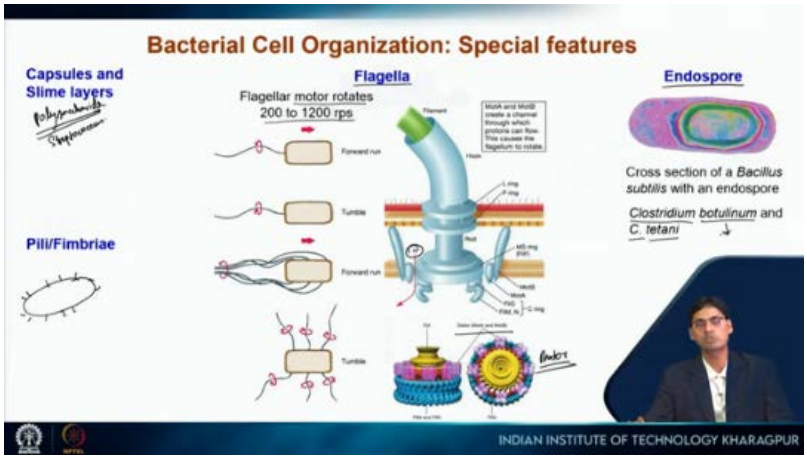
Capsules and slime layers are present in some bacteria. For example, during Griffith's experiment, I discussed Streptococcus pneumoniae. They have a polysaccharide layer. This is mostly made up of polysaccharide in streptococcas, the streptococcus pneumonia so it helps in evading the immune system. So, immune cells cannot quickly phagocytose those bacteria. So, this is again some kind of advantage for bacteria, and sometimes it also helps in attachment. Bacteria have pili or fimbriae, as I already mentioned. So, here they have small hair-like structures, and they again help in adhesion, sometimes in mating, like you know, this is called sex pilus or ape pilus. So, this is helping mating, and now flagella, which are much bigger and robust compared to pili or fimbriae, as you can see some bacteria they might have just one flagella or they might have multiple flagella, and they help in the movement of bacteria and also inside the flagella, so they have some kind of motor which rotates very very quickly, so this is kind of an astonishing number if you see here: 200 to 1200 revolution per second. So, this is again I am saying revolution per second.

So fast they can move, and based on their movement, based on their direction of the movement, different types of motion can be observed in bacteria and here. We do not need to go through the details of the structure, but here I am trying to show how a complex

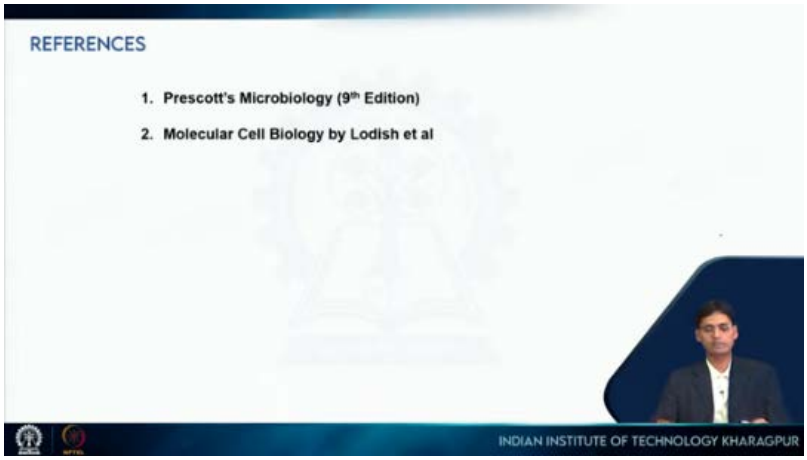
system can be integrated even in a small cell like bacteria. So, this is the organization of flagella as you can see, this is the motor present in the base of the flagella. It requires some energy to help this motor to rotate, and particularly, I would say this proton movement helps the movement of this motor also, and it helps bacterial movement. This is very important, and although flagellum is not present in all bacteria, many bacteria have flagella.

At the end, this is another one, the endospore. So, endospores are present in some bacteria. They are very medically important and challenging for medical professionals also because This endospore present inside bacteria is very much resistant to heat and certain types of radiation, including gamma radiation. So many chemical substances that we generally use. So most chemicals, you cannot really use this to kill everything, like disinfectant. You cannot use it to kill endospores, and they are very resistant and this is present in some bacteria like Clostridium botulinum, which causes botulism, and Clostridium tetani, which causes tetanus; here we have the botulinum toxin from Clostridium botulinum, which is very, very toxic and a potent toxin.

So it is very challenging to take care of this endospore problem. So, that is all. Something mentioned here: horizontal gene transfer mechanism in bacteria and its implications. It will take a little bit more time; I will discuss it in some other class.



So, that is all, and you can refer to any of these textbooks. Mostly, I cover information from this textbook, and some information is also present in this book as well.



Thank you very much.