Environmental Chemistry and Microbiology

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Module - 8
Lecture - 36
Cell Chemistry - I

Welcome everyone to the next module, module 8. This is lecture 36 and we are going to go through the first part of Cell Chemistry. So, what we are going to do in this lecture and the subsequent one is, we will cover some of the basics of cell chemistry. So, this is divided into 2 parts.

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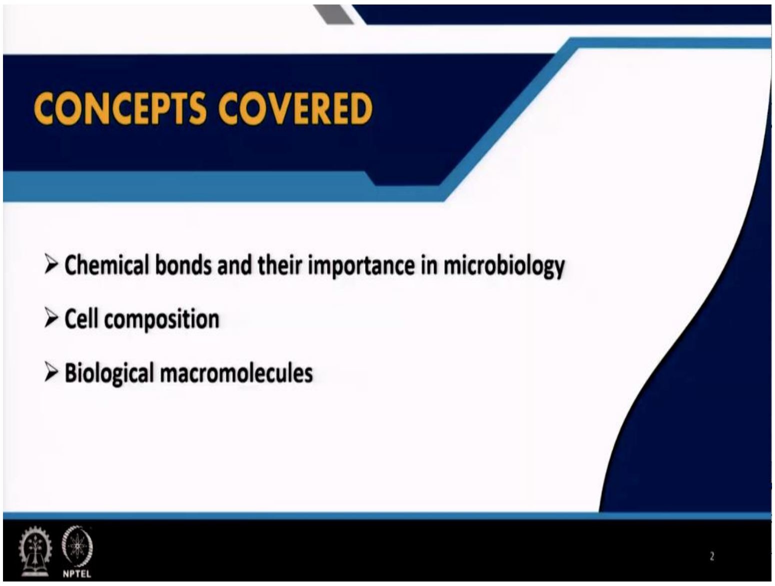

And some of the topics that we are going to cover are, chemical bonds that exist inside the cells. So, what are the cells made of? What are the chemical bonds? What is their importance in microbiology? What is the cell composition? And what are the major biological macromolecules? So, these are some of the things we are going to cover in this particular topic.

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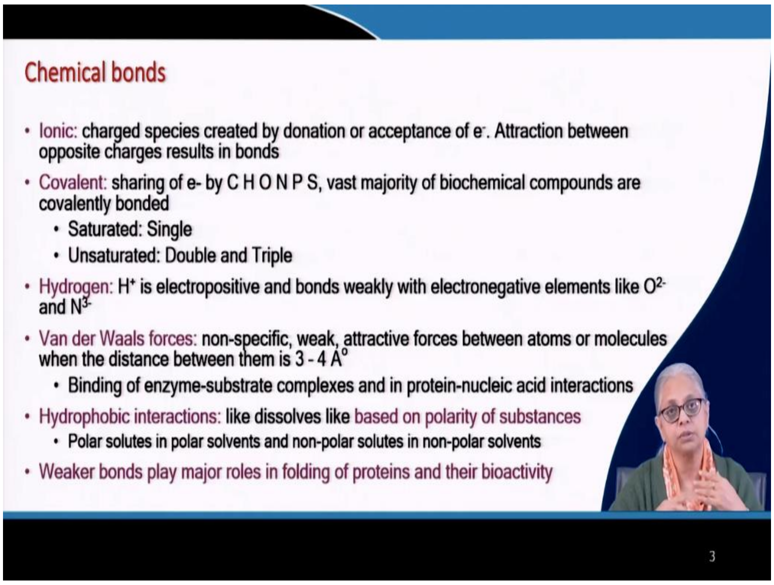

Let us just go through something that you have studied before. It always helps to go through it, at least a few dozen times, because these are fundamentals. It never hurts repeating them. So, you are all familiar with ionic bonds and covalent bonds. So, ionic bonds are formed when you have charged species. There may be ions, there may be compounds and they are formed. These ions or compounds will either accept or donate electrons. And in the process of donating or accepting electrons, they may become positively charged or negatively charged. And when you have opposite charges, attraction between these opposite charges will result in ionic bonds. Then we have covalent bonds. And covalent bonds are basically sharing of electrons.

And let us come to one of the most important concepts in biochemistry or in microbiology. And that is the major nutrients; I call them the big 6. So, carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulphur; these are the big 6 and these 6 elements comprise the bulk of the mass of any living organism perhaps, but more so for microorganisms. So, the sharing of electrons by any of these elements is basically going to result in covalent bonds.

And the vast majority of biochemical compounds are basically covalently bonded. And within covalent bonds, you have your saturated covalent bonds, which means there is sharing of (a single pair) electrons. And you have unsaturated covalent bonds, where you have double and triple bonds.

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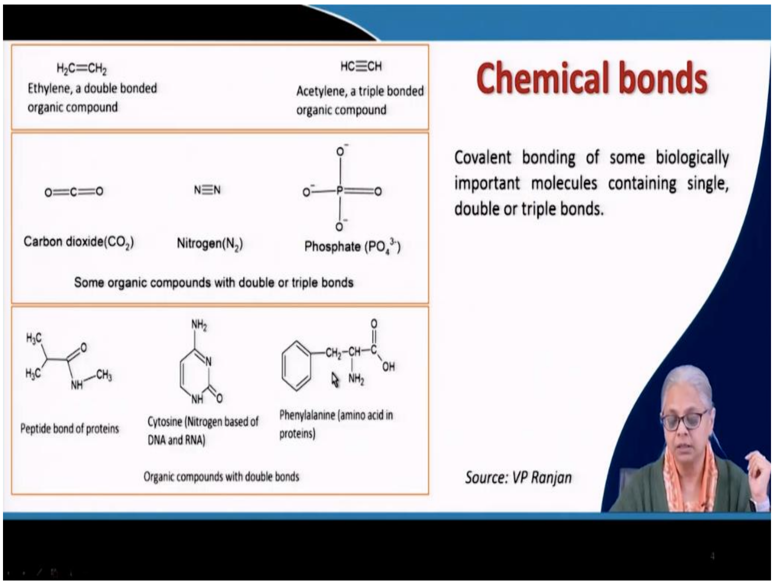

So, let me just go through a few of these examples. So, you have ethylene here, where you have a double bond between the 2 carbon atoms. And you have acetylene, which is a triple bonded organic compound. So, you have a triple bond between the 2 carbons. In carbon dioxide, you have carbon associated with 2 oxygen atoms, and both these C-O bonds are double-bonded.

Nitrogen: The 2 nitrogen atoms are triple bonded and in phosphate, you have phosphorus double-bonded to 1 oxygen and single-bonded to the remaining 3 oxygen atoms. In proteins, we have carboxyl groups. Proteins or amino acids are identified by the fact that they have 1 carboxyl group and 1 amine group. And you can see one of them is a double bond and the rest are all single bonds.

In the nitrogenous bases, we have a ring structure. And then we have phenylalanine which is an amino acid, which is an aromatic compound or a benzene ring with a large functional group attached to it.

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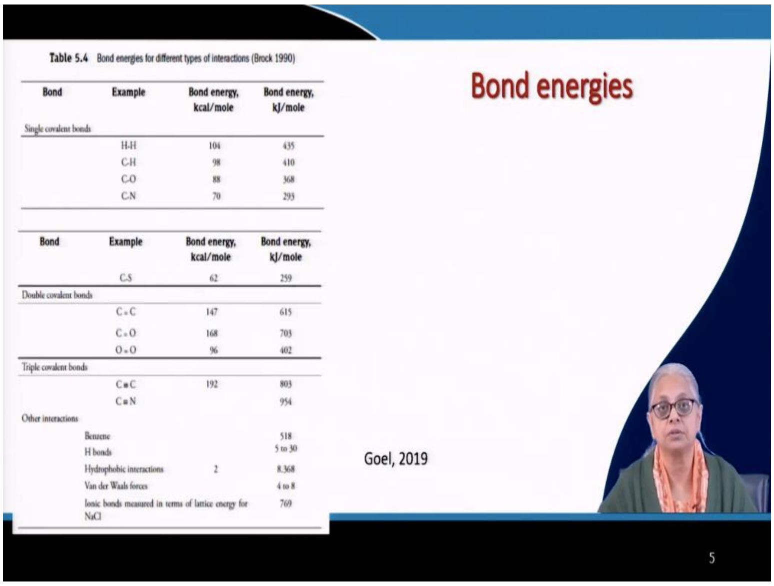

Table 5.4 Bond energies for different types of interactions (Brock 1990)

Bond	Example	Bond energy, kcal/mole	Bond energy, kJ/mole
Single covalent bonds			
	H-H	104	435
	C-H	98	410
	C-O	88	368
	C-N	70	293
	C-S	62	259
Double covalent bonds			
	C=C	147	615
	C=O	168	703
	O=O	96	402
Triple covalent bonds			
	C≡C	192	803
	C≡N		954
Other interactions			
	Benzene		518
	H bonds		5 to 30
	Hydrophobic interactions	2	8.368
	Van der Waals forces		4 to 8
	Ionic bonds measured in terms of lattice energy for NaCl		769

Just to give you an idea about the bond energies. And this is very important from a biochemistry perspective. So, remember that it is the making and breaking of bonds that is going to be utilized by the organism for either its catabolic reactions or its anabolic reactions. So, when I say catabolic reactions, it means breaking down the compound to create monomers and new biomass. So, there is a release of energy when compounds are broken down and when new compounds have to be formed, those are anabolic reactions and that is where the energy is inputted into these new compounds that are formed. And that again takes a large amount of bond energy to be formed. So, these bond energies are extremely important for us to understand how much energy is required by the microorganism in either making certain compounds or in breaking them down, what does it get in terms of energy.

So, this is a very crucial point. So, you can see the single covalent bonds. You can see the bond energies for the different elements. So, 2 hydrogen atoms, carbon and hydrogen, carbon and oxygen, carbon and nitrogen. You can see the bond energies, both in terms of kilocalories per mole versus kilojoules per mole. In terms of double covalent bonds and triple covalent bonds, similarly for 2 different elements; whether it is carbon and sulphur, carbon and carbon, carbon and oxygen, 2 oxygen atoms, all of them have different bond energies.

And this is what it takes to either get energy or to make these compounds; and you need energy inputs. We also have bond energies associated with aromatic rings like benzene. We will come to the other 4 types of bonds. And these bonds, despite their weakness; look at the magnitude of difference and not just 1 order of magnitude, but 2 orders of magnitude difference. So, hundreds of times less bond energy is there in hydrogen bonds, hydrophobic interactions and Van der Waals forces.

Now, these are extremely weak bonds but their importance in microbiology and biochemistry is enormous, because the stability of the higher-level structures is dependent on these weakest interactions. And we will be seeing a lot of that in the subsequent slides. So, I am not saying that the covalent and ionic bonds are not important. They are very important. But the importance of the weak bonds cannot be underestimated, because almost all bioactivity is associated with the presence of these weak bonds.

So, that is where we are right now, hydrogen bonds. How is a hydrogen bond formed? So, hydrogen is electropositive and it will bond weakly with electronegative elements like oxygen and nitrogen. And some of you may have studied this.

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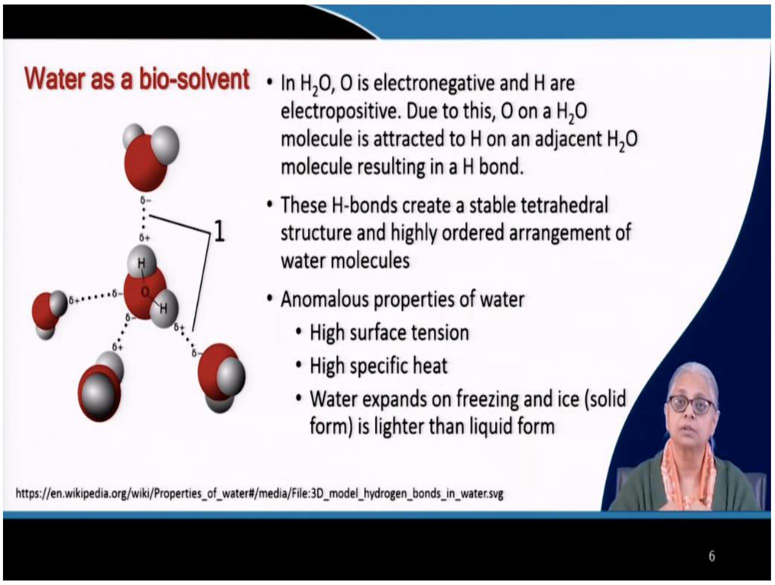

You know that water is a bio-solvent; you know that it is H_2O. So, you have oxygen and you have the two small hydrogen atoms attached to the oxygen. Now, because oxygen is much bigger, it attracts the electrons towards itself. It becomes more electronegative, while the hydrogen atoms are more electropositive. So, there is a polarity within a water molecule.

So, there is one side of the water molecule that is electronegative; and the other side where the 2 hydrogens are, is more electropositive. Now, because of this polarity, you will get an orderly arrangement of all water molecules with each other. They form a very ordered and stable structure. So, this stable tetrahedral structure and highly ordered arrangement, makes water the unique bio-solvent that it is.

Without water, there is no life and life began in water. And why is water such an important media, both within and without, for the cells? So, it has these unique properties mainly because of the hydrogen bonding between adjacent water molecules. So, the anomalous properties of water that we know; we know it has high surface tension; we know that it has high specific heat; we know that it expands when frozen and ice is lighter than liquid, than the liquid form, the solid form is lighter than the liquid form. No other solvent has the same properties. And this is what allows life to survive even under sub-zero condition. So, when the ambient temperature is sub-zero, it is that layer of ice that forms literally an insulating blanket that allows life forms to exist below the ice. So, all these things are what makes life possible. And it is very important. It is all based on this hydrogen bonding. So, that is all about hydrogen bonds.

Let us now come to Van der Waals forces. These Van der Waals forces are non-specific. These are weak attractive forces that exist either between atoms or between molecules. And this is most apparent when the distance between them is 3 to 4 angstroms. These forces are operative in, you have enzyme substrate complexes. So, the binding of the enzyme to the substrate complex is because of Van der Waals forces (correction: and other interactions). They are important in protein nucleic acid interactions. So, these are some of the things that are very important when we think about Van der Waals forces.

Then we come to hydrophobic interactions. This is the third one of our weak interactive, weak interaction energies or forces or whatever you want to call them. So, we know that like dissolves like. And that is based on the polarity of substances. So, a polar solute will dissolve in a polar solvent. And a non-polar solute will dissolve in a non-polar solvent. Now, what is important in terms of examples? For example, the formation of the plasma membrane. So, you have the plasma membrane which is made out of amphipathic molecules or the phospholipids. These phospholipids have a hydrophobic tail and a hydrophilic head. Now, what happens is that when you have a large number of these phospholipids in solution, in water, they will automatically arrange themselves in a bilayer. So, this bilayer will have heads all facing water; and the tails will all face each other. So, there is a hydrophobic layer that is sandwiched between hydrophilic heads. In practice, this makes the plasma membrane practically impermeable to anything including water.

So, it precludes water. It is like having an oil layer in between 2 water layers. So, this is a very important reason for looking at hydrophobic interactions. And I will be later on talking about the folding of proteins. The tertiary and quaternary structures of proteins also have an important role for hydrophobic interactions. So, these are some of the things that matter. Let me also say one more thing; weaker bonds, like these; so, hydrogen bonds, Van der Waals forces, hydrophobic interactions, these are extremely weak, as I have shown in this table.

And you can see that they are 2 orders of magnitude weaker than either covalent or ionic bonds, but they are the basis of the bioactivity of proteins and so many other biochemical reactions.

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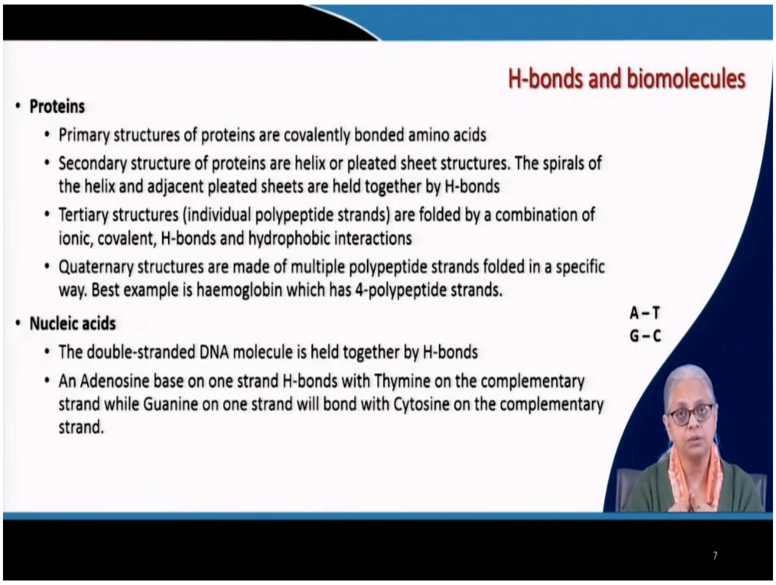

Let us take a look at hydrogen bonds and how they play a part in the bioactivity of different macromolecules. So, we are going to look at proteins and nucleic acids. I will be showing you some graphics about both of them in the second half of this topic. But for now, let us just keep in mind that the primary structure of proteins is just a sequence of amino acids. They are all in a particular specific sequence and that sequence is going to determine the nature of the protein. So, these are strong bonds, covalent bonds between adjacent amino acids. That primary structure is important, but by itself, it has no biological activity. The biological activity of proteins and enzymes comes from the higher-level structures.

So, you have the secondary, tertiary and quaternary structures. So, it is the folding of this primary strand that will determine these higher-level structures and we will see graphics that will make it clearer. There are 2 types of folding that proteins undergo.

So, the primary or what we call the primary structure, we call it a polypeptide strand. Polypeptide for the number of amino acids that are part of the polypeptide strand. Now, these polypeptide strands can either form a helix. So, if you can think of a spring, a metallic spring, it is a helix structure. So, the same kind of thing is formed by proteins. That is one type of structure. The second type of structure is a pleated sheet. So, when you fan-fold paper, that is a pleated sheet. So, these proteins, these polypeptide strands form either helices or they form pleated sheet structures. The spirals of the helix; so, if you can imagine your metallic spring, the spirals, each circle of that helix is bonded to the adjacent circle by hydrogen bonds. That is how the spacing and the folding is maintained. And similarly, you have multiple polypeptide strands. And each of them is, you can imagine that they are fan-folded and each of these sheets is stuck together to the adjacent sheet by hydrogen bonds.

So, if you look into any of the textbooks, you will find good graphics explaining all of these. It is very important for understanding how these proteins are folded. That is the secondary level (structure). The tertiary level (structure) now has a mix of all types of bonds. It has ionic bonds; it has covalent bonds, like disulphide bridges; those are covalent bonds. It has hydrogen bonds; it has hydrophobic interactions.

Now, remember that many of the amino acids have non-polar functional groups. So, these non-polar functional groups are hydrophobic. Because of their hydrophobic nature, you will have amphoteric properties in these molecules and that will also result in certain spatial arrangements. So, we will go into that in the next part of this topic. And then finally, we have quaternary structures.

Quaternary structures are formed when you have more than one polypeptide strand in a particular protein. So, the best example is hemoglobin. Hemoglobin is something that you have all heard about and it has 4 polypeptide strands. Each one of these 4 polypeptide strands is folded in a particular way. And they are arranged spatially in a particular fashion. Now, there is also a heme group that is associated with each one of these polypeptide strands; and that is the active site.

But, if there is any disturbance to the way the protein is folded, then the bioactivity is going to be compromised. So, the entire bioactivity of a protein is associated with any one of these levels of structures: secondary, tertiary and quaternary structures. And in all of them, you will find that the weak interactions: hydrogen bonds, Van der Waals forces, all of them are important.

Then we come to nucleic acids. So, nucleic acids, you have either DNA or RNA. And we will take a look at both of them in the second half. The DNA is a double-stranded molecule. I will show you the structure, like I said, in the second half, where complimentary nitrogenous bases, adenine will bond to thymine on the adjacent strand. So, you have 2 strands. Adenine on one will bond with thymine on the other. Guanine on one will bond with cytosine on the other and these bonds are hydrogen bonds. So, they are very weak bonds, which allows the double-stranded structure to come together or fall apart easily. And that is crucial to these bioprocesses. Because, unless the making and breaking of these DNA strands is easy, it becomes too energy-expensive. So, this is how all the processes of reproduction, replication of the DNA strands, the RNA, protein synthesis; all of this is based on weak hydrogen bonds.

There is nothing more that I can say about the importance of hydrogen bonds.

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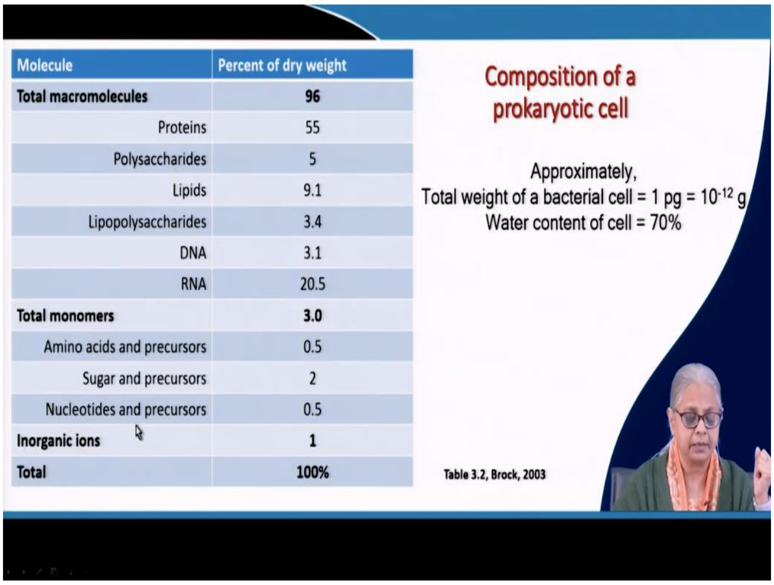

We will come back to this point again. Let us take a look at the composition of a prokaryotic cell. Now, prokaryotic cell; I think I may have mentioned at some point in the past that we are dealing with bacteria. Prokaryotes are bacteria; and these bacteria are studied better than any of the other microbial groups. So, the composition of the prokaryotic cell is what we are interested in over here and there are 2 things to keep in mind over here. One is the total weight. So, when I say total weight that includes the weight of the organic compounds including water. So, the total weight of a bacterial cell, as a simple approximation, we generally say it is 1 picogram. And 1 picogram is 10 to the power -12 grams. We also know that by and large, the water content of a cell; minimum is 70%. It can go up to 80 or 90%.

Then we come to the dry weight. Now, if all the moisture is removed from the cell and you look at what is the organic content of the cell in terms of macromolecules: 96% of the dry weight of the cell is these macromolecules; and the remaining is monomers and inorganic ions. So, the monomers are 3%; the inorganic ions are 1%; and the bulk of it is macromolecules or what are called biopolymers or biological polymers. So, out of this 96%, proteins are 55%; polysaccharides or carbohydrates are 5%; lipids and fatty acids are 9.1%; lipopolysaccharides, which are lipids and polysaccharides together, that is 3.4%. And the nucleic acids; DNA is 3.1%; RNA is 20.5%. The remaining are monomers. So, this is a broad understanding of the composition of a prokaryotic or bacterial cell. So, we have polymers. The monomers of proteins are amino acids. So, you will obviously have some amount of monomers floating around; and that is 0.5%. The monomers of carbohydrates or polysaccharides are sugars; that is about 2%. Nucleotides and their precursors are the monomers of DNA and RNA; and that is another 0.5%.

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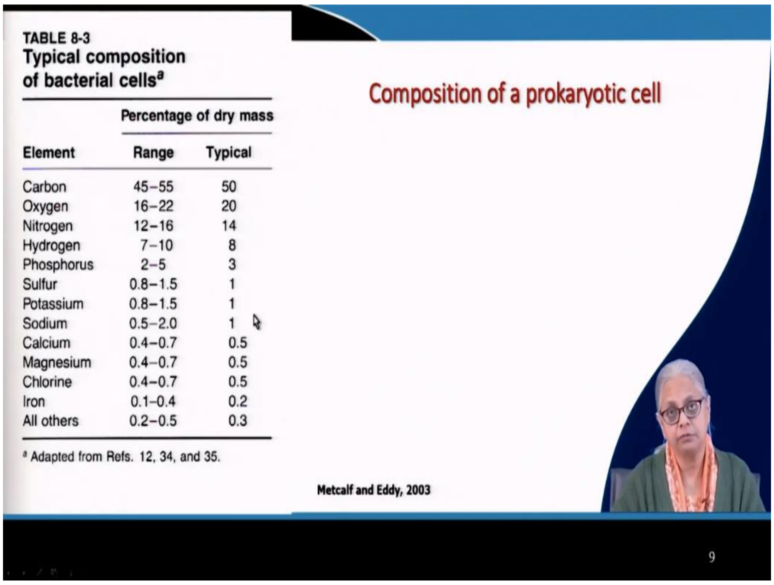

That is in terms of macromolecules. What about the elemental compositions? So, from an engineering perspective, it is often very important for us to know the elemental composition of a cell. And this is from another textbook that we use for wastewater engineering. So, this is the typical composition of bacterial cells. So, carbon is about 50% of the dry weight. Oxygen is about 20% of the dry weight. Nitrogen, 14%; hydrogen, 8%; phosphorus, 3%; sulphur, potassium, sodium, about 1%. These are what we call macronutrients. And then we have the micronutrients. Calcium, magnesium, chlorine, iron and so many other elements that are part of the periodic table, they are all below 1% and we call them micronutrients. The others equal and above 1%, they are all macronutrients.

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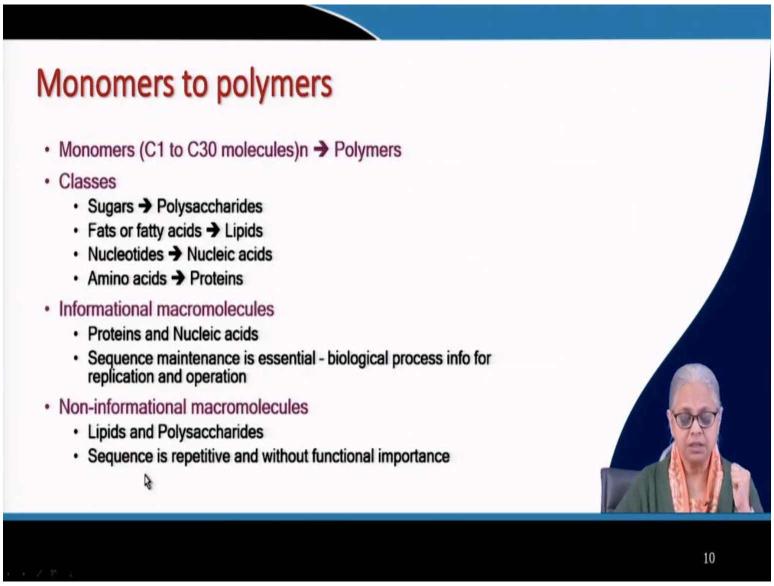

We have seen the biomolecules or the biomacromolecules or biopolymers, whatever you want to call them. Now, these biopolymers are made out of monomeric units. Depending on the nature of the polymer that we are looking at, these monomeric units may be few tens or hundreds of monomers attached together in either non-coding sequences or in particular sequences. Now, each of these monomers can be as small as a C1 compound to as much as C30. C30 means ‘containing 30 carbon atoms’. So, you can have very large monomers or you can have very small monomers. So, these monomers can be C1 compounds all the way to C30 like fatty acid compounds. And these monomers will be linked together, maybe tens of them or hundreds of them and so on. So, we will take a look at all of them.

Now, we have 4 major classes of biological macromolecules. Like I said, there are carbohydrates, proteins, lipids and nucleic acids. So, the monomeric form of the polysaccharides or carbohydrates is sugar; for the lipids, it is fats or fatty acids; for the nucleic acids, it is nucleotides; and for the proteins, it is amino acids. And we are going to take a look at these details in the next part.

Remember one more thing, that out of these 4 classes of biological macromolecules, we have informational macromolecules and non-informational macromolecules, which means that the sequence of the monomeric units is important. That has useful information. So, these informational macromolecules are proteins and nucleic acids. We know that DNA is the genetic code. This genetic code will then be given (correction - used) to the RNA.

And the RNA; there are 3 types of RNA, which I will talk about later. These 3 types of RNA are required for protein synthesis. The protein sequence of amino acids or rather the sequence of amino acids in proteins is again very essential for their biological activity. So, sequence maintenance is crucial to biochemical reactions. Without this sequence maintenance, the bioprocesses will be jeopardized and the organism can die. So, sequence maintenance is crucial for the life processes. All biological process information of replication, operation and so on is based on these sequences.

Then we come to non-informational macromolecules. So, lipids and polysaccharides. Just as we know from our own diet, we know that sugar and fat, they do not provide any information. What are they doing? They are providing mass and energy. Same thing for the microorganisms. Sugar and fat are useful only for providing organic carbon and energy for the organism to survive. So, the sequence is repetitive; it has no functional importance; it is a source of mass and energy for the organism.

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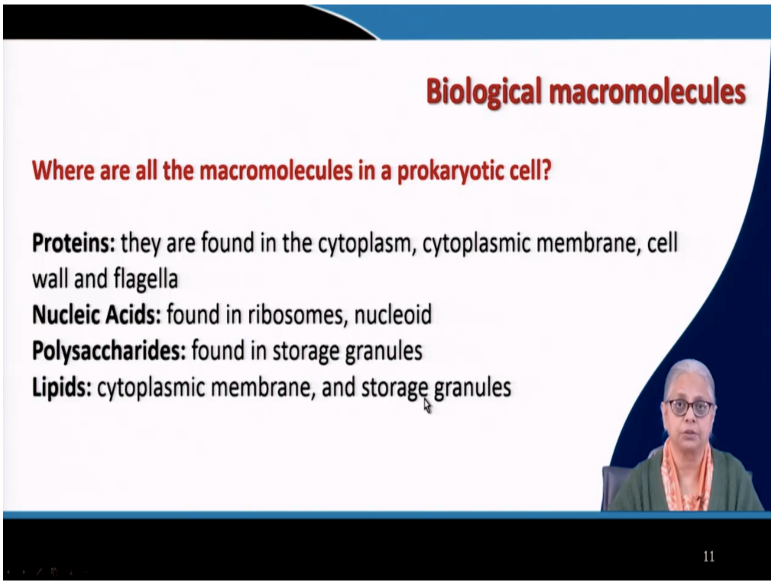

Where are these macromolecules located? What is the location? So, the proteins are generally found in the cytoplasm, the cytoplasmic membrane, the cell wall and the flagella. So, we have seen a little bit about the cell structure. We are going to focus more on the cell structure, in the next topic on cell biology. And when we look at microscopy and cell biology, we will be able to understand how important these are.

The nucleic acids are found in the ribosomes and in the nuclear region or the nucleoid. And the polysaccharides are found in storage granules. And the lipids are distributed in the cytoplasmic membrane, as well as in the storage granules.

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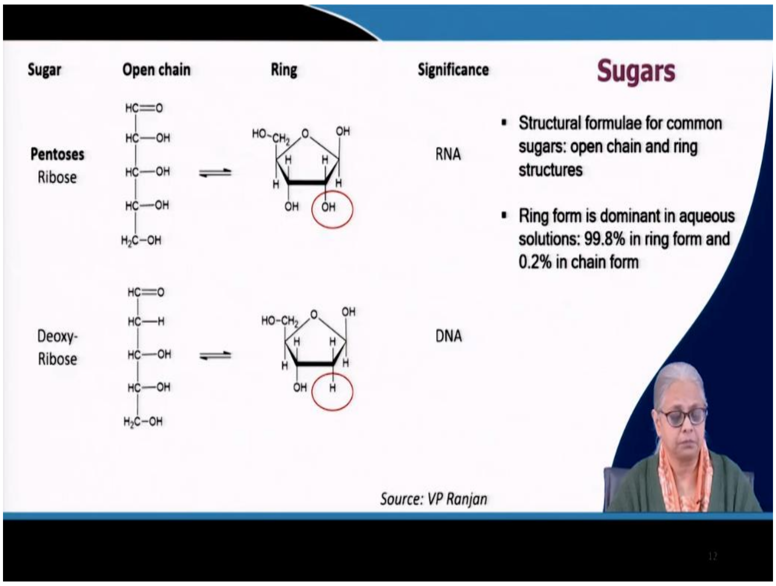

So, like I said, let us take a look at some details. We will take a look at each of the monomeric units and how they form polymers and what is the nature of those polymers. So, let us take a look at the first set of monomers; and that is sugar. So, it is easy to start with sugar. There are 2 sugars that are shown over here. The first one is a pentose and the second one is (a hexose) glucose.

So, let us take a look at where the pentoses are. The pentoses are part of RNA and DNA. So, ribose is a pentose. It has 5 carbon atoms. And you can see them written in open chain form and ring form. Now, those of you who have studied a little bit of organic chemistry, you probably know that the ring form dominates in aqueous solution. So, it is never formed; it is never available in the open chain form. You have very minute amounts that are present in open chain form. The bulk of the compound is always present in ring form. That is the stable arrangement of the sugars. So, the ring form is dominant. 99.8% of the sugars are present in ring form. And like I said, the pentose is, whether it is ribose; when it loses its oxygen, it is called deoxyribose. And this deoxyribose is the sugar that is present in DNA.

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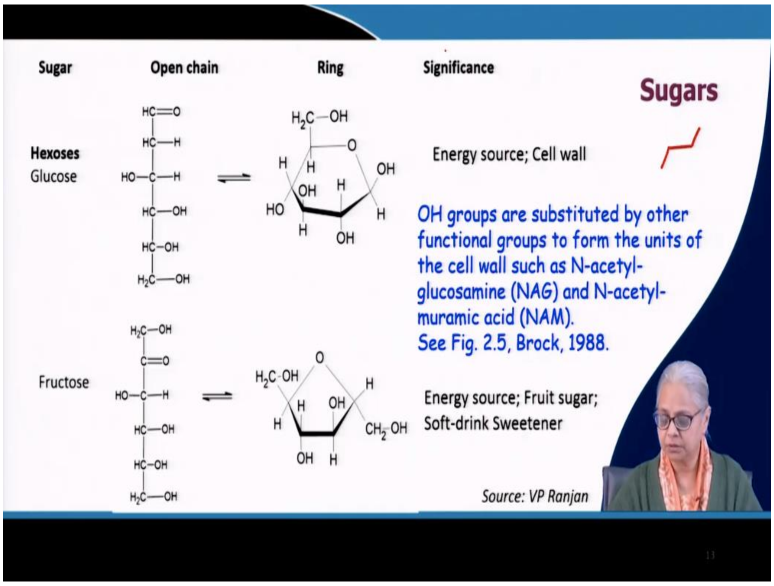

Then we come to glucose. Glucose is a hexose. It means, it has 6 carbon atoms. And these 6 are shown over here in open chain form and in ring form you can see the spatial arrangement. You probably know that glucose is, it kind of forms a chair structure. So, it forms a chair structure. This is the structure of a glucose molecule. And it is not only an energy source, but it is also a major component of the cell wall. And I will show you something more about that in the next slide. So, these OH groups at the C2 position are substituted by other functional groups.

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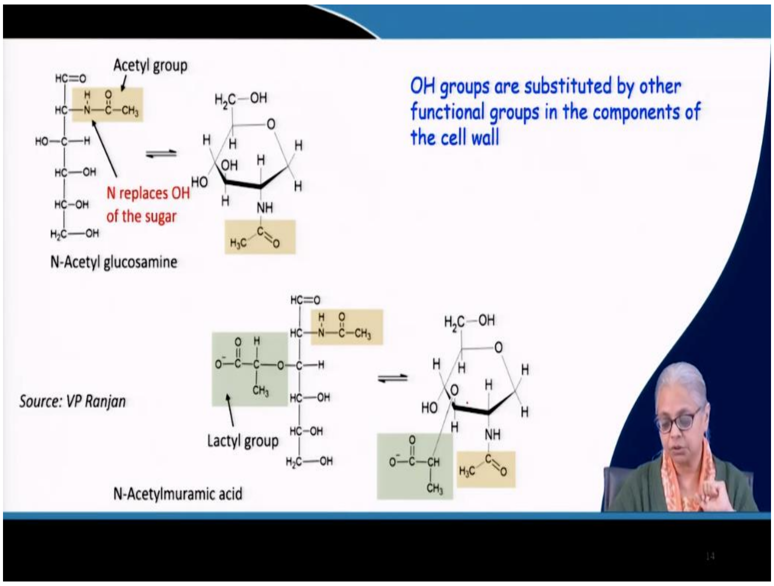

So, the cell wall is made out of what we call derivatives of glucose. So, you have N-Acetylglucosamine and you have N-Acetylmuramic acid. And these are, this is the ring form. And at the C2 position, the OH group has been replaced by this (N-containing functional) particular group N. N replaces OH of the sugar; and you have this attachment. So, you have the acetyl glucosamine functional group attached to nitrogen. So, this is one of the building blocks of the cell wall.

There is another building block of the cell wall; and that is N-Acetylmuramic acid. So, in some textbooks, you will find this shortened to NAG and NAM. In other textbooks, you will find G and M. So, either way, these are the building blocks of the cell wall of the bacterial cell. And it does have several significant properties which we will come to in later topics. So, again you have another functional group at the C3 position. And this is going to give it different properties. And like I said, it is all part of the cell wall. Now, when we think about hexoses, we have glucose, sucrose, fructose, lactose; all these are different types of sugars. Now, out of the hexoses we have glucose and fructose.

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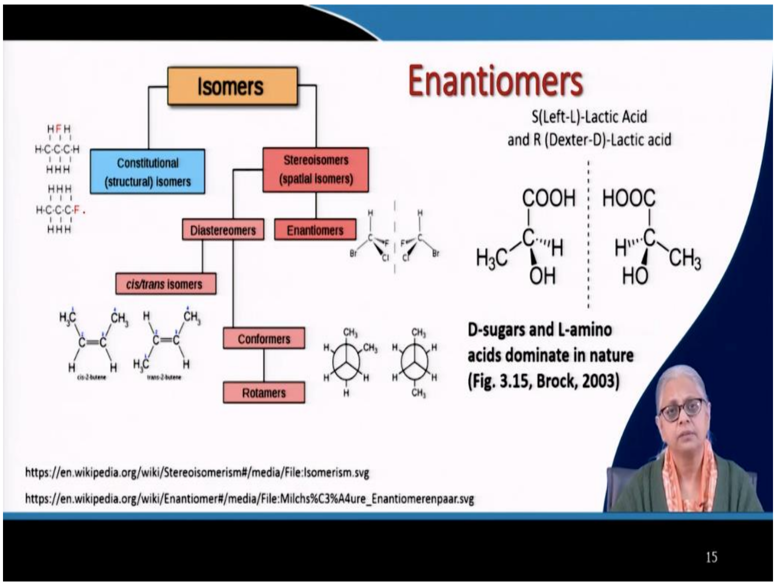

And lactose and sucrose are disaccharides. So, those are already, 2 monomers attached together. So, there are all kinds of sugars that are present in nature, as well as within the cells.

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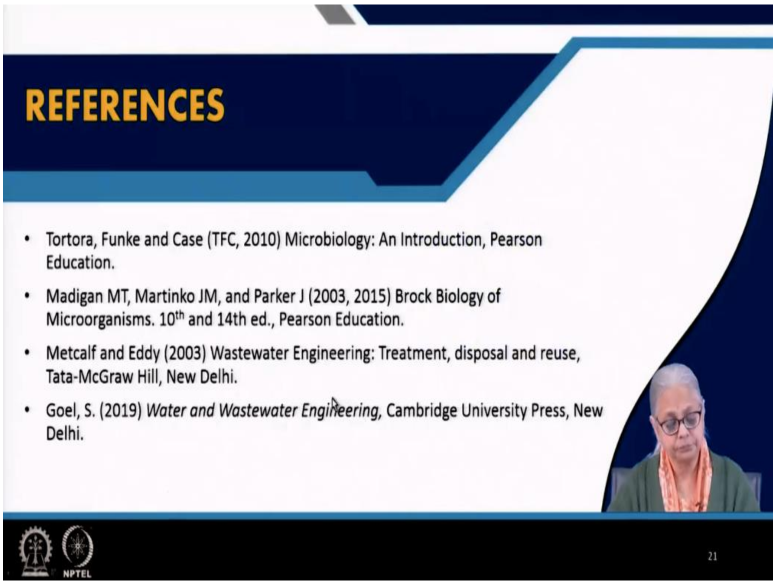

Thank you. And I will stop the first part here; and we will continue with the second part.