Nanostructure and Nanomaterials: Characterization and Properties

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Lecture - 29
Multi-Scale Hierarchy

In this lecture we learn about multi scale hierarchy. As this say there are two terms, multi scale and hierarchy. So, let us see what do they really mean. Multi scale, like if I take a ruler or a scale and then I measure the length and breadth of a paper, normal sheet of a paper. So, I can measure it using a particular ruler. But, say if I want to go too much finer scale such as say, I want to go a micro structure around to measure something more at a micron landscale, so I cannot take the same ruler or the same scale bar to go and measure a micron microstructure. So, I need to have a scale which is at a bit of a different level. So, that is a reason that that brings out to the aspect of multi scale.

And similarly, we have different scales going from atomistic or going to even higher microns molecular scale, nanoscale micron scale, and then maybe something like at millimetre scale then it can even go to constellations and stars with millions and millions of light years. And coming to the second part of it the hierarchy part, like if there is a king, he will have certain ministers beneath him working for him. Then again, all the ministers will have some servent serve to them. So, they can be second category of hierarchy. And then again all the servants will have kind of sub servants under them, so this tells a hierarchy build within the structure.

So, we have multi scale, scale means differentiating going from one landscale to a different landscale. And then hierarchy, it means what is the level like ruler like a king working and the person will have many-many servants under them. Each servant will be now the all the servants will have many-many sub servants under them. So, we will see that each minister will have certain servants, and each king will have many-many ministers. So, overall this basically is telling a hierarchy within a particular system. And how it is useful? Coming back to landscale.

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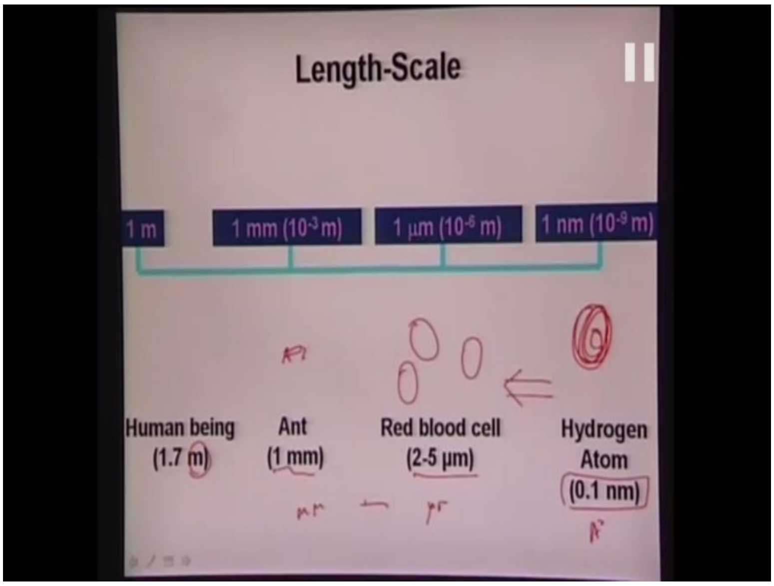

Like we can see that we can go start, we can start going from an hydrogen atom, so it will have certain atom with some electronic structure around it. And we see that, the length scale it corresponds to around 1 inch angstrom. Going to a much higher landscale of around microns, we will see that all the red blood cells which are existent in our body. It can have certain red blood cell which amount, which has a diameter of around 2 to 5 microns. And an ang, an ang basically will be millimetre and length, so going from angstrom level, to micrometre level, to millimetre level.

And as we know that, the human being is approximately so many metres tall. So, we will now come back to the landscale of a metre. So, we will have human, which will have a kind of landscale of around metre, so this tells the overall landscale. And hierarchy comes from the next line.

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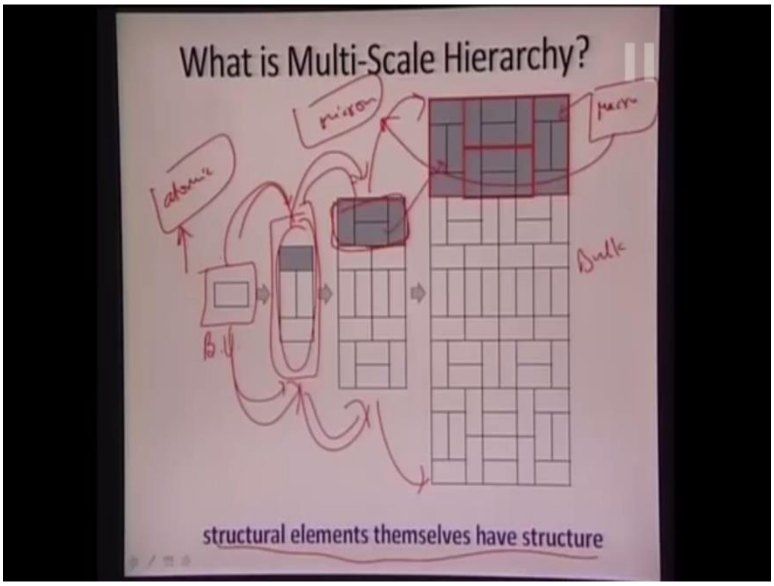

So, let us see what is multi scale hierarchy? So, in this particular case, we have a fundamental building block and that particular block will start repeating itself at certain landscales. And then that particular block will serve as a building block for a next hierarchy contracture. What is the advantage with nano landscale building block that we can make any complex ship out of it?

That if you have the fundamental building block itself will order a few molecules or few atoms, we can go atom by atom and then we can construct something very complex which is not achievable otherwise. If the overall block itself is a very, is at existing at a very higher landscale such as order of meters. We cannot construct something which is smaller than a metre. So, overall block has to be much more, much more bigger and much more simpler. As compared to that, if we have a building block which is nanometre in landscale.

So, that tells the advantage of nanostructures and how can you utilise that nanostructure? In terms of enhancing its mechanical properties or enhancing certain specific volume or maybe say a something like surface area or any functionality that part will see later on. But this tells that it gives us a chance to be able to play that that particular level, at the nano level and then form a hierarchical structure. So, this tells that how the structure are repeating.

So, this is our basic unit, and then it goes on to form much higher landscale elements, and then again it goes to forming as bigger blocks, and again to a very kind of a bulk structure. So, what is so specific about this thing is that, each block is again a repetition of what was there earlie. So, we had all these blocks which are now forming a unit in the bigger entity. And now, structure elements themselves will have some structure. So, that is one more advantage to it that, we can, we can have certain structure which is existent either at macro level, or at micron level, or it can be at the atomic level.

So, we can play with those couple of entities, that we can have structure with some hierarchy that a bulk structure will have certain micron level hierarchy, it will have certain structure repeating itself in at the micron scale. And then again that micron structure can have something which is repeating at a atomic or a nano scale. So, that is how the hierarchy is defined in structural materials. So, coming back to the way of hierarchy. We can define certain system like, which is existing, which is also manmade we are kind of certain networks.

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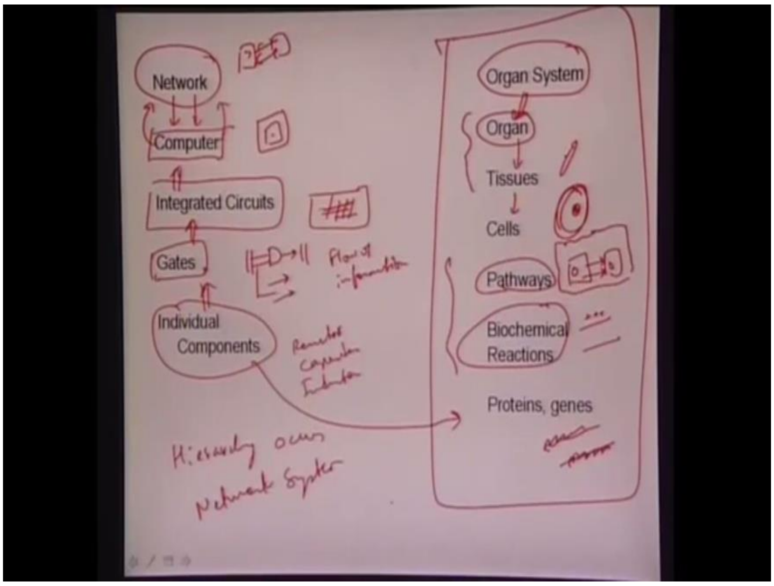

So, we have one very huge stations made up of many, many, many computers and they basically do the data exchange. So, we have certain networks with some computers, so each computer forms a basic unit of a network. So, now we go from a network to a computer, and then coming deciphering the computer itself, we will see that each computer will have certain chips introduce in it. Because computer is the one which is doing certain calculation, and then it is performing certain functionality of a network.

A network is the one which is giving us the overall picture, or the overall processing of a particular process which is being assigned to it. So, computer forms the basic units of the network. Now, computer, in computer we will have many-many integrated circuits or integrated chips which basically do the function they form certain IC chips, which will have many-many circuits device onto them. And then again, the way integrate circuit work is through certain gates. So, we have diode and all that which will have, which will assign a certain direction to the information.

So, the gates are the one which will have a input, and have an output, and depending on the, on the, on the design of the gates will get a path of the for the flow of information. So, that is what is defined by the gates that in which direction the information is to go, and how much it has to go. But again, all those gates will have certain very fundamental or individual components, such as registers, maybe capacitors, inductors. So, these are the very functional units, the basic fundamental units which are dominating it the individual component level.

So, we can see that, we need to have registers, capacitors, inductors, and all that to really go and form a gate. And now, these gates they decide the flow of flow of information and those, that thing is decided by a certain integrated circuits. And many integrated circuits they go and form a computer, and many-many computers they go and they become a functional part of a network. So, this is how the overall hierarchy occurs. How the hierarchy occurs basically in the network systems?

So, and this thing the hierarchy and this particular landscale it is not only existing only at networking system, not only on the manmade structures, but it is also existed in a biological structure. So, how does it occur is, like we have a human, human will have certain organs and kind of organ systems which work in harmony to give the overall functionality to a human. An organ systems, such as the overall system which is working, it will have many-many organs to it.

Like for digestion, we need to have our mouth, the food has to go there, the person will chew the food, it has now to go through stomach get a gat a digested out there, it has to flow through intestine, and it has to follow a excretion thereon. So, there are many organs which really go and form a organ system such as for digestion as we just realised. So, there are many organs which are dominant and taking a certain part of this particular function such as, chewing or any ingesting it, getting it process, and all those things in stomach, and then again getting it digested in the intestine and so on, so each organ.

Now, each organ will have many-many tissues. So, each tissue will itself, there are many-many cells which really go and form a tissue. And cells are nothing but more complex features with a nuclear cytoplasm and so on. So, if you, and again they sells the service path ways for the information. So, one cell has to interact with another cell in terms of passing certain information that, the food has now to be digested, the food is now at this particular condition, and what is overall condition of, for the further action.

And again, the pathways are created again by a performing some biochemical reactions that they generate some sort of a potential over its surface. And through those potentials or those chemical reactions, the information passed from one cell to the another cell. And again if you, if you see that how this particular information is generated that is through again by protein chains or the genes, which have, which are again the basic units of all those cells and tissues. And those basically go about providing the information. And we can see there are some more similarity between the structure which was, which is existing biologically or naturally.

But, all the individual components they correspond more like proteins and genes gets the correspond more to like which was like pathways or they are governed by a certain biochemical reactions. And certain integrity circuits, more like organs and tissues. And the overall computer like, maybe like a organ, and then whole network like a organ system. So, that is how we can see the similarity between the multi scale hierarchy, which is existing either like an as engineer or what is existing naturally. So, this is what is all about the multi scale hierarchy.

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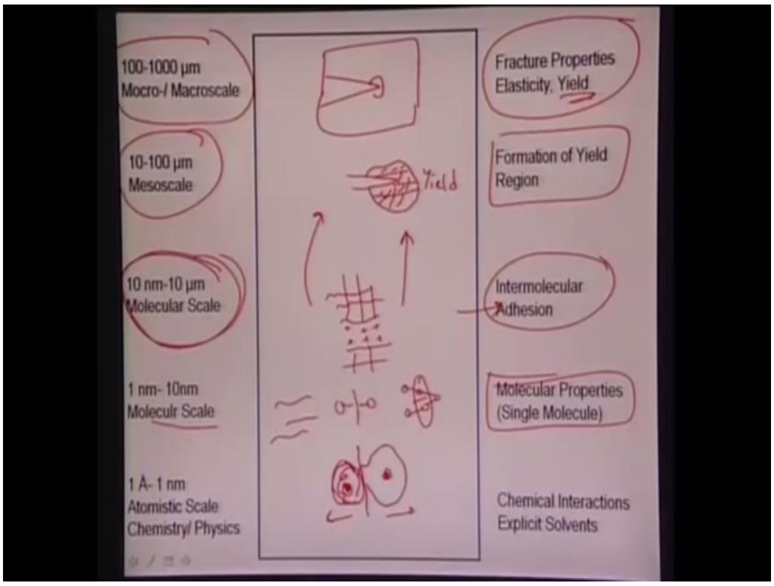

So, how the functionality changes at each particular stage? And again coming to more engineering problem. If we see that, what can happen starting from a macro scale to a micro scale? So, we have more of a macro scale. And we see that we have a particular body which is getting fractured, so we have a crack, and then we can see some crack is already propagated.

So, this particular part is eeled by fracture properties, or the bulk properties are being added by a macro scale. And then again more at just the tip of this particular crack, we can see that they can be formation of some eeled region just at the crack tip will see certain elongation of bonds, and all that. How the particular, how the particular region is getting eeled it. So, that part of plasticity we will see near the crack tip. And then going more to it, more at the molecular scale, which is a comparison of 10 nanometre to 10 microns, it is called molecular scale.

We will see how molecules are basically interacting to lead to the debonding of particular species at that molecular level. So, we will see that, the bonds which were existing out here, the how they are broken, and that is basically leading to a overall debonding between the material and eventually cracking of a particular material. And then again, we see more or less molecular properties are again dominated by individual molecules. So, we see that individual molecules, how they are interacting with one another and then leading to a overall cracking between them.

So, just at that crack tip, we will see we had atoms, atoms, atoms. And then we see there are some debonding which is occurring between these two particular atoms. So, that is what is being decided by individual or single molecules. Then again, more at the atomistic level, we can see how the chemical interactions or atomistic scale how the things are occurring. So, it will go as, take us more to the atomistic level of maybe of an individual atom, and how the electronic structure is being defined to it, and how does it is basically overlapping with the electronic structure of another atom, and then how do they basically separate at that particular scale?

So, we can see that, at atomistic level we have only single atom, and we are defining its electronic structure at that particular scale. And how it is interacting with the another molecule, another atom, at the similar scale how it is basically overlapping the electronic structure, and then it is deciding the mechanical property at that particular level. Then, going on to the molecular state, we see that there are certain chains, certain chains of atoms and how they are interacting with one another. It can, it is more at the molecular level, that we have many-many atoms which are aligned with one another, and how they are interacting with the nearby chain to overall cause a cracking.

And then coming to a more of higher level molecular scale like 10 nanometre to 10 micrometre, we see there are something called inter molecular adhesion. So, we have many molecules, how they are adoring to the nearby lying molecules. And those basically go on to form a kind of eeled region. Eeled region means, it is more at a mezzo scale. So, initially we had a bonding at a atomistic scale then went down to molecules, molecules again they had some between the chains interaction. And then we have something called intermolecular adhesion, or within a less than 10 microns.

So, what is happening individually at each molecule, how they are responding to it? Then, we have some sort of a plasticity within the grain, like if you had one grain, so there are many-many atoms associated with that, so what is happening within a particular grain. And then eventual elasticity, fracture properties are eelding which is more at a bulk scale. So, it is, it means how the slipping is occurring across many-many grains. So, we can see the overall dimension is around 100 t0 1000 microns. So, what is the overall eelding occurring across the grains?

Formation of eeled region within particular grains at 10 to 100 microns. And then intermolecular adhesions, which are which can extend up to 10 microns, and then molecular scale, and again atomistic scale. So, this is how a overall pictures looks like in terms of solving an engineering problem, say solving cracking how it is occurring at different, how the each level is responding to the particular cracking.

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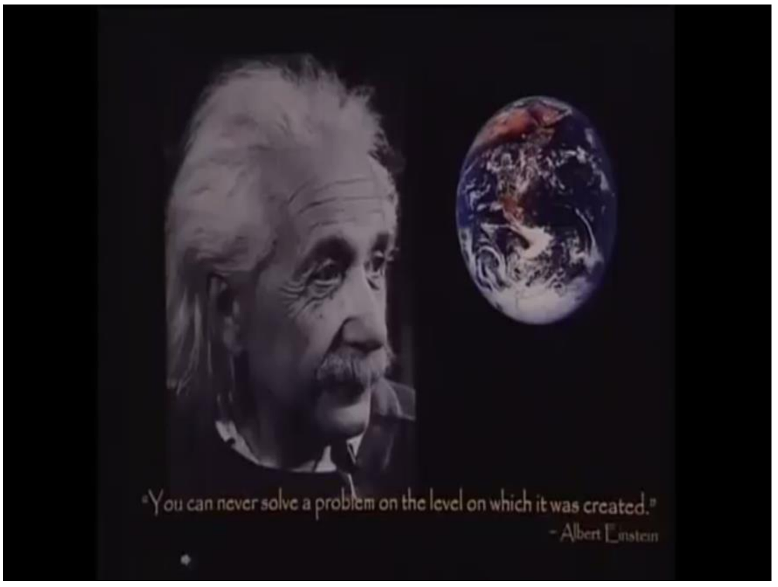

((Refer Time: 15:41)) it is being said by Albert Einstein that you can never solve a problem on the level on which it was created. So, basically if you want to solve the problem you have to break it down into smaller entities. So, that is what thing is all about multi scale hierarchy that we have a hierarchy and we have variety of scales. So, basically it break down the problem in terms of its hierarchy, we go from one step to a second step lower and then this we solve at a different landscale as well.

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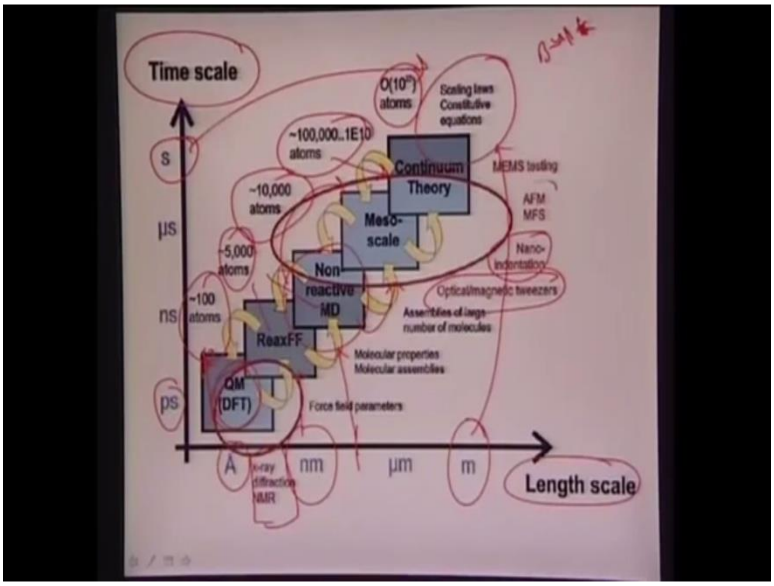

So, this is how it comes out to be. We have a time scale out on the y axis and landscale on the x axis. And we see that more at, more at the angstrom level, we see as the dominant effects are nothing but the density functional theory of quantum mechanics which is much more dominant at atomistic level. And the time required for its modelling its to the order of picoseconds. Then, we have some force field parameters which can incorporate up to say 100s of atoms and it can go up to a nanometre scale.

And then going on eventually onto more numbers of atoms say up to approximately 5000 number of atoms and it can go up to say order of couple of less than a micron. But, it tells about the non reactive molecular dynamics out here. And then again we can go to something called mezzo scale. Mezzo scale is like kind of a interlayer between macro and micro, so that is how it is defined by the mezzo scale. So, what is the problem with atomistic modelling is that, if we are incorporating only very few number of atoms, and few number of atoms they don’t really represent what is happening at the bulk scale.

And if you go to the bulk scale, the computational abilities are not as good enough to mimic and to really capture all the millions and millions of atoms 10 to the power 23 order of 10 to power 23 atoms which is nothing but an Avogadro number for one mole. And to incorporate many moles of atoms and predict what will happen eventually in bulk. So, that is not really feasible and it has very time consuming, very costly as well.

So, there we utilise more of a scaling lodge or concentrative equation which are nothing but the bulk equations. So, we can test them in those particular manner and it comes to the order of seconds and it is length scale, landscale comes out to the order of few meters which is nothing but the bulk material. So, which is nothing but the representative of the actual thing what will, how the material is being really represented as.

So, now the continuum theory or the mezzo scale kind of bridges between those two, and we can see that now here we are considering around 10 to the power 23 atoms. And I can go to continuum theory with a 10 to the power 10 atoms or more, or again and in mezzo scale we are thinking about, we are considering only about 10000 atoms, and more in the non reactive MD or real force field parameters we are taking upto 5000 atoms. And quantum mechanics we consider around 100 atoms. So, this is how the overall thing really go on to.

And again if you see one more thing the kind of characterisation techniques which are much more dominant in those particular location, like for to the, for deciphering something in the order of angstrom to nanometre we have x-rays or array mark, and then if we want to go to more of micron level or more we have optical or magnetic twisters or perform nano indentation and so on. And then we have AFM, MFS and so on. So, these are the overall things how we can really distinguish and classify and characterise all the nano materials or going to the bulk properties.

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And bio mimicking, bio mimicking is one of the very fascinating fields which have recently emerged. Because nature is the perfect engineer, and unlike we engineers the nature will tend to optimise everything around it. If we want to make something very tough, we will go only about its toughness not about its ((Refer Time: 19:35)) not about its ductility, not about it say vetting properties, not about its shocking properties shock absorbing properties. But, we will go only about one property of probably increasing its hardness or maybe say strength.

So, nature is the perfect engineer and that is the reason we want to learn from always because nature can handle compression, tension, sheer, at the same time it can distribute energy in terms of absorbing the impact. It can stick the things together, very nicely we see that how the gecko can really stick itself onto the wall. It can provide strong foundation in terms of providing a good skeleton or a good ((Refer Time: 20:12)). It can regulate temperature, humidity, and light such as in termite mounts. It can also create beautiful colours as in peacock feathers or even a butterfly wings.

So, we can see how nature can really go about perfecting everything what it has created. But, as engineers we want to mimic it for the sole reason that we want to optimise many, many, many properties which can be structural, which can be related to colour, related to chemistry, or related to anything. So, that is the thing we need to learn from nature and for that it is something called engineering branch is called bio mimicking.

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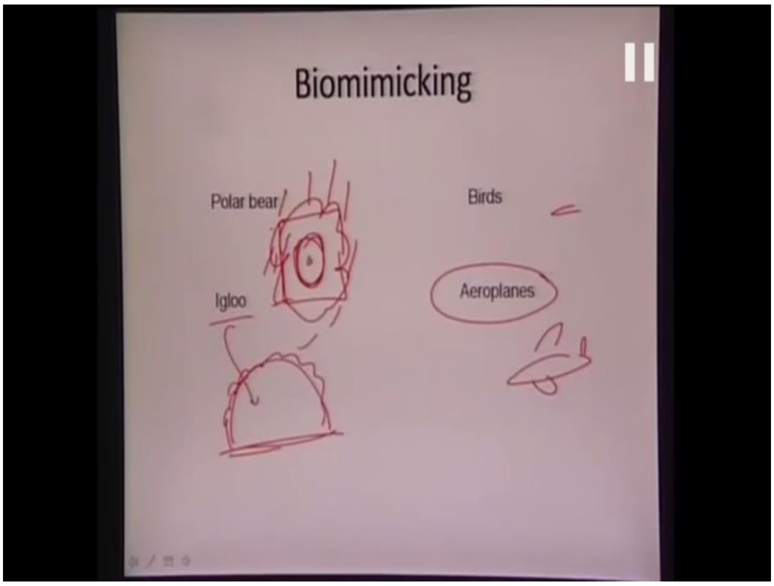

And we have always being learning from nature in the past. Like we have polar bear, it tend to go and form some holes in the polar regions. So, basically we get something at certain regions, a kind of a covering with ice and it keeps the bear pretty warm in even in winters. Similarly, we have in the polar regions human have started making igloos, which can keep the Eskimos warmer even during winters.

So, that is the overall insulation effect of the, of the snow or the ice and that keeps them pretty warm, pretty warm even during very high winters or during very chilly winds. Similarly, for the birds we have learnt how to make aeroplane. So, that is what how we have learnt to make aeroplanes from the flight of birds. So, we have always been mimicking the nature in any way such as, starting from aeroplanes or even going to the ships, we have, we have learnt to how to make it float using waves and all such things. So, we always have been mimicking nature, as an engineer we want to always go for perfecting it. And then many-many examples of how we can tap the, how we can really tap what is happening in nature and bring it back to the, bring it back for the community.

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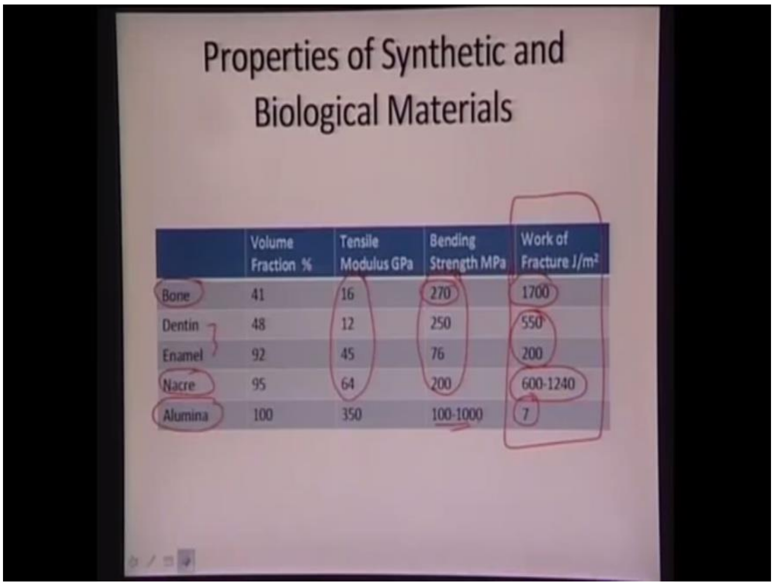

	Volume Fraction %	Tensile Modulus GPa	Bending Strength MPa	Work of Fracture J/m²
Bone	41	16	270	1700
Dentin	48	12	250	550
Enamel	92	45	76	200
Nacre	95	64	200	600-1240
Alumina	100	350	100-1000	7

And there certain properties of biological materials, which tend to be very very stronger, very very tougher, like the bone. It has bending certain around 270, but it is work of fracture around 1700 joules per metre square. And as we compare to alumina to which is a ceramic material, it has sorry, it has work of fracture of around 7 joules per metre square.

So, it is 1000s of times lesser than what is available in nature. Even dentin, enamel, the work of fracture is around 20 to 50 times as that of a alumina. And again coming back to nacre, which is nothing but a sea shell, it is again made of a ceramic material, so ideally it should have very low work of fracture, but it shows a work of fracture of more than 100 times as that of a alumina. But, seem to one more thing that tensile modulus is pretty low for all this materials, the bending strength is pretty low for all this materials.

But, for alumina the bending strength is very high, but still the work of fracture is very-very poor. This happens just because the way the nature has designed all this materials, the architecture of how the bones are basically made or how the dentin and enamel or the maker of this structure has been made. This is the way the architecture has been done, in terms of having a proper way in which the crystallites and the, and the complained material, how they have been merged together. So, that part we will see as we go along, but that is the beauty that the way they have been arranged they can increase their fracture toughness by more than 1000 times of their actual ingredient materials. So, that has a beauty of the multi scale hierarchy out here.

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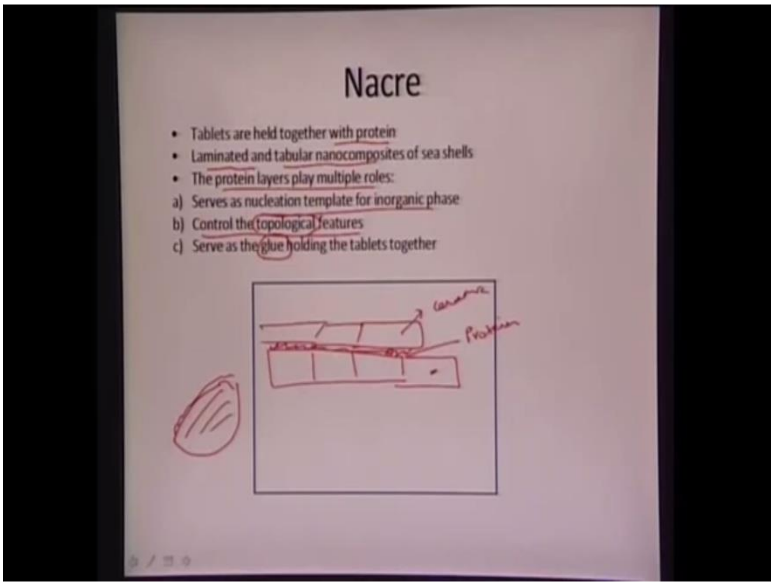

A maker, there are some tablets which are held together with a protein, maker is nothing but a sea shell. So, probably what you see in the near the beach that you have certain sea shell with certain linings over it, and then this is nothing but a sea shell. And then we can see that this particular material does not break even when you drop it.

So, in this case what is happening is, there are certain tablets and those are held with a protein layer. So, we have certain tablets, which are glued basically with certain protein material, and this is what basically absorbs the shock. So, you have ceramic, paring kind of thing, and again these are nothing but the laminated and tabular nanocomposites. So, they are kind of tabulated out here, and then they have a protein layer which is binding them together.

And the protein layer basically plays multiple roles, first of all it serves as a nucleation template for an inorganic phase or the, or kind of a carbonate phase, calcium carbonate phase. It also controls the topological features because this is what actually so deciding factor above the overall toughness for this particular material, and also serves as a glue. So, basically it is nucleated template, it is controlling the topological features, it is also serving as a glue. And that basically gives it much more toughening effect as compared to anything else.

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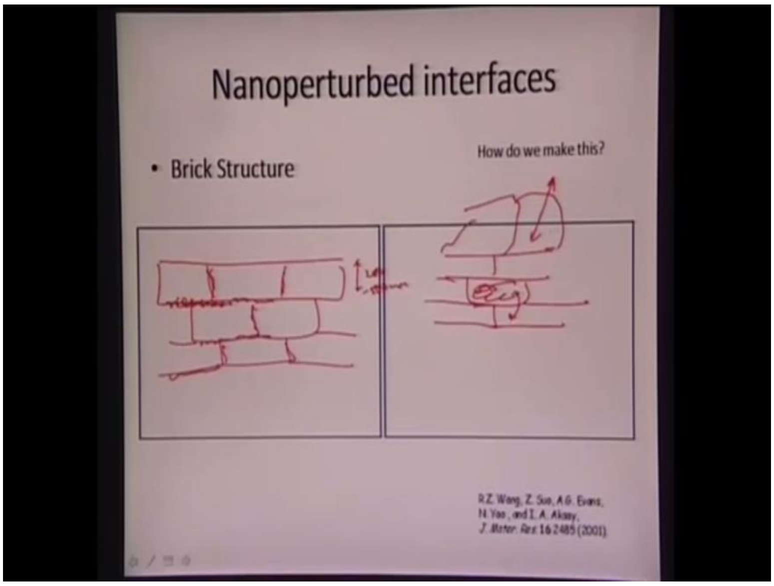

And how this particular layout has been generally generated? It is something, it is something called a brick structure, so we have something like this, and then brick structure basically emerges out of it. And this brick structures are, they have a glue or a protein layer between them.

So, we have certain protein layer which is kind of holding the, all the bricks together and these are around order of let me say, 200 to 500 nanometre. And you have certain regions of glue which is very-very thin couple of nanometres out here. But, this architecture gives them very much toughening. And how does it do it as basically? The protein is nothing but a very complined material, so upon any shock it can absorb the shock very easily.

And all these are glue in a region of around 2 to 5 nanometre or so. So, we have certain bricks as we see in the construction and upon any impact all this bricks can also come out to take the particular shock. So, it is not that if a crack is it has to propagate through. No, the crack may just get restricted at a certain brick, one of these bricks. And this brick itself may come out in order to comply to the particular shock or an impact. And that is the reason that, this particular material becomes very-very tough, and if we see that one of the bricks can just come out, like they have architecture like this.

And then one of the bricks in this particular brick may just kind of slide away. These are nothing but something like platelets, these are platelet and this whole plated can come off and make the structure very-very tough. So, that is the beauty of this particular structure, that all these are tablets or platelets, and apparently impact they can just slide over one another in terms rendering or absorbing certain energy and then becoming much more tougher.

So, these are, these are called nanopart of interfaces because that interface is the one which is allowing the tablets to move over one another, or tiles to move over one another. At the same time, this glue or the protein glue which is holding them that also can absorb much shock, and it will try to hold the bricks above itself and below itself together. So, that is a beauty of this particular nanopart of interfaces.

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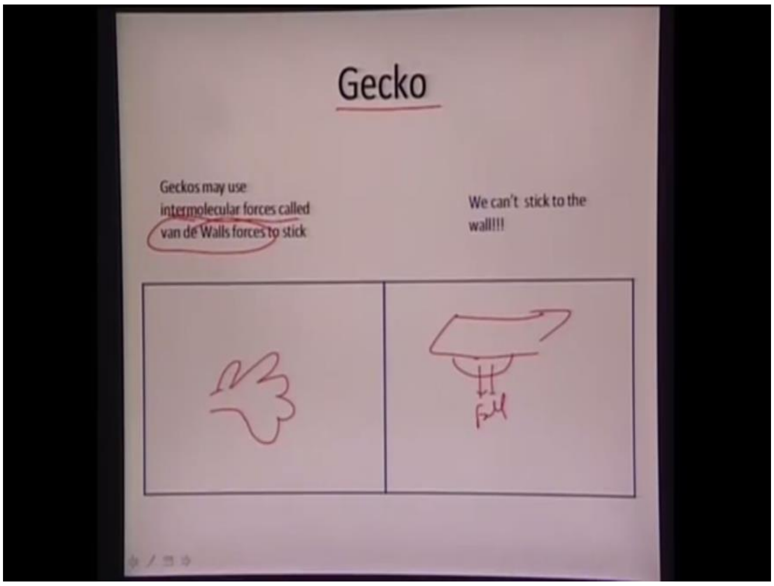

Again coming to a second example, like in gecko. In gecko, basically gecko has a very nice ability to walk on any of the surface, at any, on any surface, even when they walking upside down, see on the roof. Still it is able to, still it is able to stick itself and walk very easily. But, we cannot really do that because we do not have that much, we cannot really stick to the wall, why because we are we have so much weight that even if you want to create certain vacuum or something like that we will not be able to stay.

And there had been a concept that gecko stick on the wall because they create certain vacuum on their feet, but that is not true. They stay because of inter molecular forces which are called vender waal's forces to stick on the wall. So, if you have a roof, let me try to stick below it, we will basically fall down. But, gecko what it can do? Gecko can really stick, can stick on the, on to the walls because of something called vender waal's forces.

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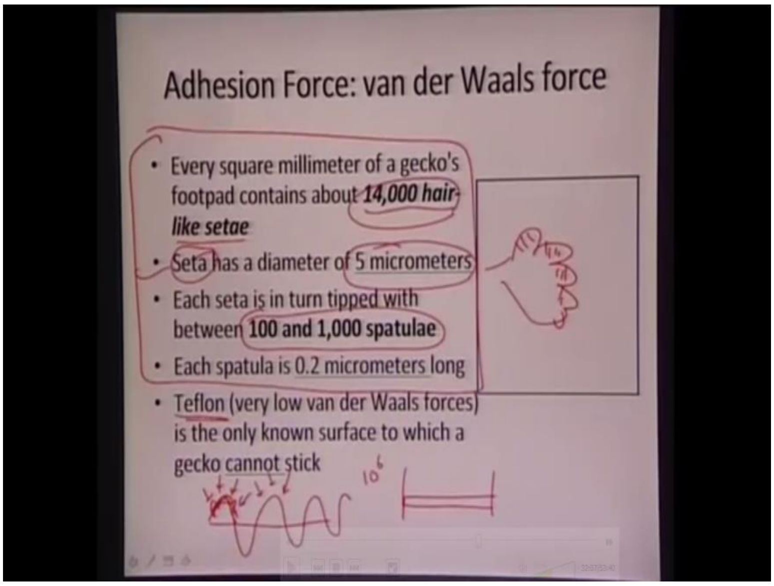

And how does this vender waal's forces arise is because that every square millimetre of a gecko footpad contains about 14000 hair like setae, where we have feet of gecko which have around 14000 hair like setae. So, they have certain lamellas on their feet and they have, and their lamellas will have some setae around 14000 hair like setae.

And setaes are very fine, they are to the other of 5 macromere diameter. And each setae will have in term more than 10 to 1000spatulae. So, it is more like this, at a surface which is very flatter in nature than I create some micro roughness. So, if I give it certain ((Refer Time: 29:45)), we are seeing that this surface is acquiring the surface area is gone up dramatically because this is no more a projection area, it is more of a surface area which is providing it the vender waal's forces.

So, initially we have flat surface. So, flat surface is sticking over to a flat surface is nothing but like 1 to 1 contact, but once it has a setae, that setae will have some roughness to it, because it has a diameter of around 5 macron which is couple of microns longer as well. So, we get some extra roughness on to from this because it has some setae on a surface. And again, all the seate there in turn again tipped with more than 100 to 1000 spatula.

So, what it is doing? Just by inducing the micron size roughness, the surface area is going up by say around 1000 times. I am going to a next level, one more level of nano because it the spatula is around 200 nanometre. In diameter it is more like nanohair. We are inducing one more level of roughness over this micro roughness. So, we have overall surface going by order of 10 to the power of 6 times. So, 1000 into 1000 that much at least it is going up the surface area.

And once it has so much surface area, that can automatically induce vender waal's forces because there will be automatic to atom to atom, atom to atom contact and that can easily have very high vender waal's forces, and it can go upto say around 15 Newton or so around it can go up to that much load it can easily take. And similarly, one company have 3M has been able to manufacture, the able to mimic what is there in the gecko's feet and is able to take on 15 Newton's load out there.

So, we can stick a very huge even a person of around 5 around more than 5, more than 5 to 10 kgs, and we can easily stick onto the wall without letting it drop, just within via 1 centimetre square tape. So, that is how, that is how the particular structure can really give out much-much very nice aggressive forces to be able to stick it. But, teflon is the only surface on which gecko cannot stick because Teflon has a very low surface energy and it does not allow anything to stick over it, means it will not allow anything to stick over it.

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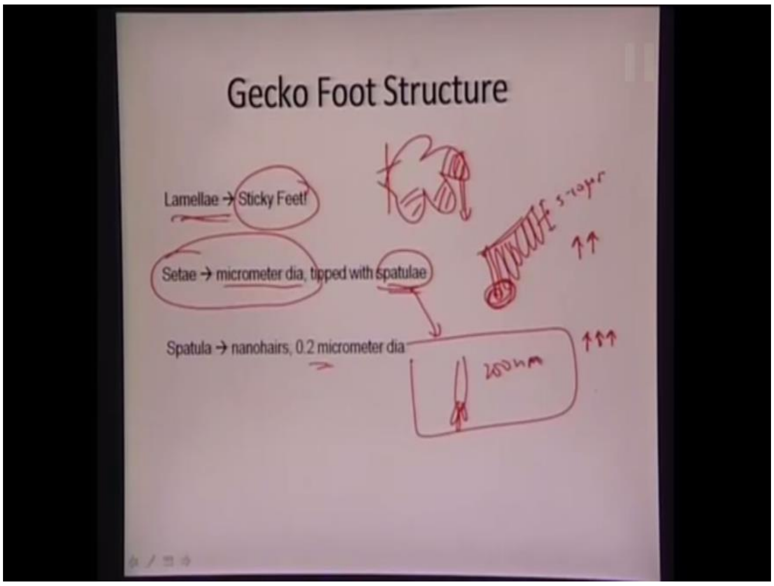

So the gecko generally falls while walking on the teflon surface, but it is because, it is a very low vender waal's force out there. So, how the gecko foot structure really looks like? First of all the word chemistry of a gecko foot. It is, it is a sticky feet because it has something viscous and sticky. So, it can provide a certain ankle to it, so we have its gecko feet.

So, we have, we have certain feet, and it is itself, the chemistry itself is very sticky. Over that, we have certain lamellas, so the gecko's feet has certain lamellas, which will provide extra roughness to it. And then all this lamellas will have setae. So, setae are nothing but micrometre diameter, they have a micrometre diameter, so lamellae then have certain setae. So, we have seen there are certain micron size setae on to which are lined up on each lamellae. So, this one, this one lamellae.

Then we have many-many setae which have couple of microns in diameter 5 to 10 microns, of 5 metres in diameter, and couple of microns long. And then the tip of each setae is, it has spatula. This spatulas are nothing but kind of nanohairs with a diameter of around 200 nanometre. So, the tip of this particular setae will have nanohairs all right. And as we have nanohairs on it, we are increasing the surface area by millions of times. So, from lamellae, it is a sticky feet, the conclusion itself is very-very sticky. Thrn lamellas will have setae, it gives out it render some micrometre diameter.

So, the, so the surface area increases dramatically. And the tip of the spatula will have again some tip of setae will have spatula, and spatula are nothing but 200 nanometre diameter. So, that is, that has one more advantage that is providing extra roughness to it and then gecko can easily stick on to it. But, one more quality with the gecko is, it can not only stick, it can de-stick itself as well with very much ease. Whereas the manmade adhesive were able to stick them, but de-stick or deboning them is very-very difficult.

So, how gecko does it? It basically slides itself, it basically sheers itself, and then now it has to remove only one by one by one setae from its feet. So, the overall, the net force, the net vender waal's force which is dominant on a single setae, it is not that high. So, the gecko feet is able to de-stick or de-bond itself from any wall surface. So, sticking also is very easy, de-sticking also becomes very easy, and which is not so easy in the manmade structure or the manmade adhesive which are mimicking the gecko feet. So, that is the overall thing about this multi scale structure in the gecko foot.

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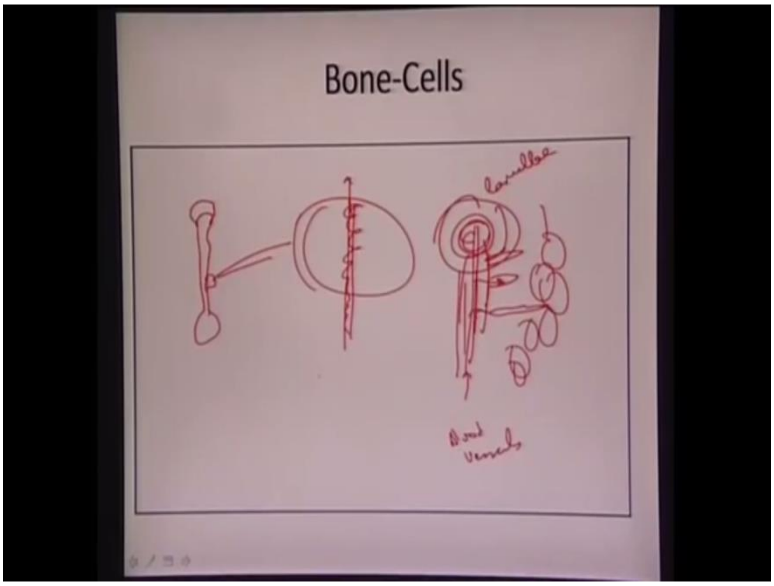

And coming to the bone cells, bone cells also perform variety of, variety of functionality, that it has to bare load for certain duration of years. Like since we, since we have born, we walk and walk and walk, the same time we jump and all that we run, we do sports and play a lot, and at the same time we walk a lot.

So, the bone has to take so many cycles of say any impact or any load, the same time they has to keep the bone alive, so it has to also provide certain nourishment. So, we see that, that the bones will have some central Haversian canal. So, in the, in the centre we have Haversian canal which is nothing but which applies supplies certain arteries or the blood to the particular bone. And then we have a system of something called lamellas around it.

So, each have certain ((Refer Time: 36:06)) canal will have certain lamellas around it, and from there even the arteries will basically extend to certain other location. And the outside of it is basically more porous. And again if you see there are certain something called lacuna or canaliculi which is, which are around it, which are nothing but different kind of, which are nothing but kind of a porous regions which are extending from the central ((Refer Time: 36:33)) canal. And it has basically blood vessels which are flowing through it.

So, we have blood vessels and certain lamellas, and then we also have canaliculi which is nothing but a central region out here. And then it has to basically the bone, the bone itself will have to perform under a certain load and all that. And the bone itself shows a micro structure which has a something like this. And then again it has certain lacuna and all that to take care of the food supply, the nutrient supply. And how do they basically work is?

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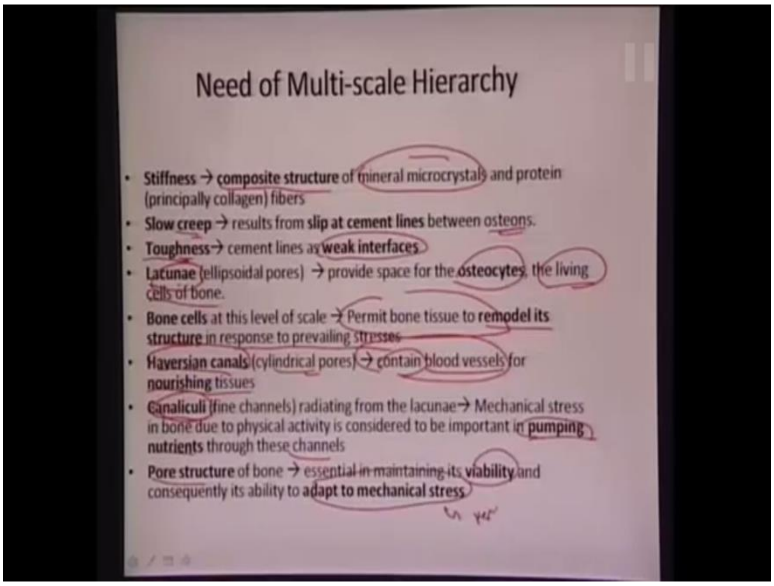

That, bone is nothing but a structure of which is comprising collagen protein, and then certain microcrystal of hydroxypetite. So, stiffness basically comes from a combination of either, combination of how this particular collagen and how the crystallites are the mineral part is basically being from all together.

So, this component session provides much toughness to it because of the mineral micro crystals hydroxypetite, also it impact, it also needs to creep sometimes because to reuse it itself it also needs some weakness or some cement lies at the weak interfaces to take care of the toughness part. There can be crepe as well because its time and all that, it might want to sleep, it want to sleep, so there will be sleep at the cement lines which are between the osteons.

At the same time we have some lacunae of the left side post, we should provide osteocytes because upon impact, the bone has to reshuffle, reaching itself. So, it needs to a certain location where osteocytes can really survive, and they are the, they are the living cells of the bone. And bone cells basically they are able to remodel its structure because of the weak interfaces or because if this osteons, they are able to re reshuffle itself or remodel itself to respond to the prevailing stresses, and that basically permits the bone tissue to remodel.

There are certain cylindrical pores to allow, which will allow blood vessels to nourish the tissues because the all these tissues will need some chemicals and all that, some nourishment to be given through the blood vessels, and blood vessels can go through really. This Haversian canals or the cylindrical pores of the bone, which can contain blood vessels and they can provide nutrients. And there are certain very fine channels of canaliculi. And basically it is help, it is help for pumping the nutrients to this particular channels.

So, we have canaliculi which will help distributing or pumping the nutrients, the haversian canals again which will allow the blood vessels to go through it and provide the nourishment. We have certain pores, pores or the lacunae to provide space for the living cells, so that is what we see here. And the pore structure also helps to maintain its viability and adapt to a mechanical stress by allowing a remodelling of the bone.

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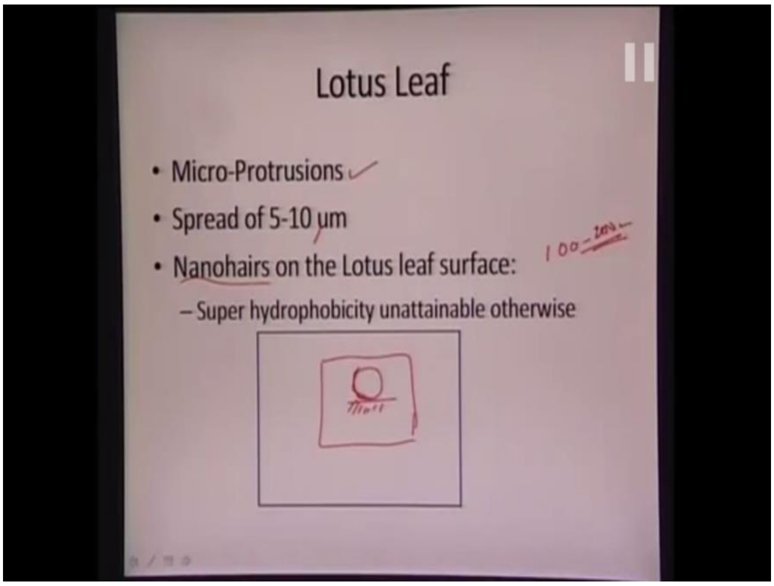

Now, coming to a next example of lotus leaf structure, we see that lotus leaf has known for its super hydrophobicity. So, we see a lotus leaf, and that we, over that if we take it, if you take it a particular water droplet, we will see that it will basically it will not wet the surface, it will, it will remain sitting on the lotus leaf without wetting it. So, that is the non wetting of lotus leaf.

But, ideally we can also see that once we have a lotus leaf, if we put a water droplet, it basically comes and basically without wetting the lotus leaf it basically rolls off on the surface. And that arises because it has certain hierarchy in as a micro protrusions. So, that are some micro protrusions with which the order of 5 microns as a globules of, globules which are setting on the lotus leaf surface. And then they split across with a distance of 5 to 10 micro apart. And around 5 nanometer, 5 microns in diameter. And those basically provide extra roughness to it.

So, that basically is given it extra or additional hydrophobicity in terms of, to the lotus leaf surface. And more than that, there are certain nanohairs which have diameter of around 100 to 150 nanometres. So, they basically provide much more order of 100 to 200 nanometres, and they provide additional or additional surface. So, the opponent contact angle goes even beyond 150 degrees. So, the transition from hydrophobicity to super hydrophobicity is very-very drastic, even though the difference might be a couple of, couple of theta value of around 30 to 40 degrees, but still the property itself it is from hydrophobicity to super hydrophobicity.

And there is a group of Michigan, they have basically tried that, they burned the surface without damaging the micro protrusions and just removed the nanohairs, and that from that they could see the contact angle has reduced from 165 degree to less than say for 140 degrees. So, the additional 14, 15, or 16 degrees which is coming out, it is only because of the nanohairs and that is important in super hydrophobicity. It means the contact angle has to be access of 160 degrees. So, that part is being provided by the lotus leaf surface because of their nanohairs or nano roughness which is in hand in the, on the lotus leaf surface.

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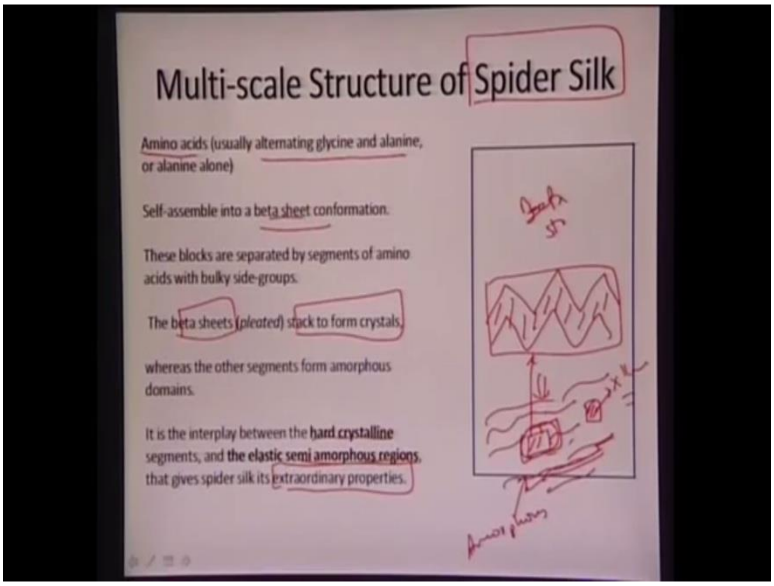

And again there is, there are, the spider silk is also want to be very strong, that is because there are certain amino acids which are alternating layers of glycine and alanine. And then they have assembled into a beta sheet.

Beta sheet is nothing but kind of a zigzag structure with a bulky side group, so they form certain crystalline regions and those basically comes as a, they form of kind of a crystal, and all this crystals basically come as certain crystalline regions with a amorphous amino acid, amino acids kind of hoarding around it. So, basically we have a certain crystalline regions and certain non-crystalline regions or amorphous regions. And these are basically, they basically have a beta structure.

So, this is a beta structure, beta structure around here, we see the beta sheets, and they stack to form crystals. And other segments apart from, apart from these crystals they remain amorphous. So, we had a combination of amorphous and a crystalline region, that basically gives it much more strength. And it is basically the inter play between the hard crystalline segment and the elastic, semi amorphous region. And that is a region which gives it additional or extra ordinary properties of basically strength, and that is what defines the spider silk.

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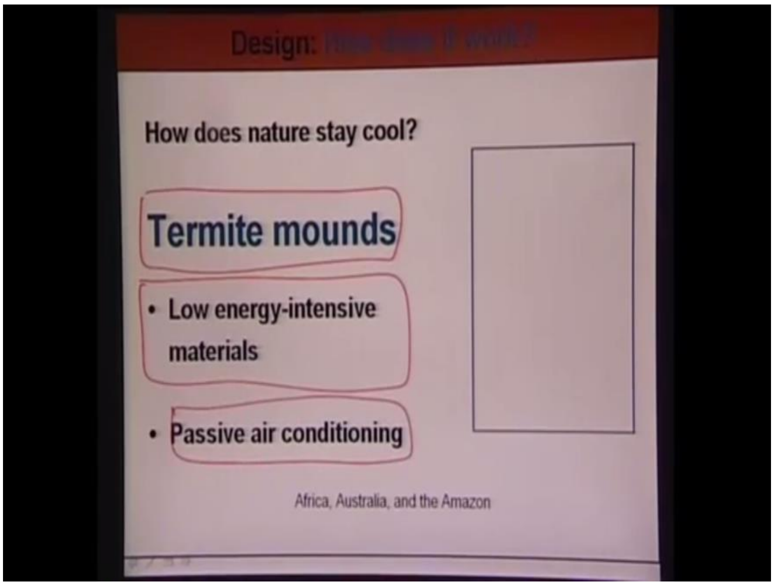

And basically when coming to one more example of termite mounds, termite mounds are basically seen in Africa, Australia, and Amazon. The advantage they have is that, they are basically, they can stay cool in, they can stay cool in summer, and they can remain hotter here in, they can survive the cold even in, even during nights and all that. Because the, because of the energy they have stored during the day time.

So, they can say cooler for longer times. And this basically forms a basis for engineers because it can serve as a low energy, low energy intensive material. If we have this particular material, we can provide passive air conditioning. So, we are not basically losing any energy in terms of providing this particular air conditioning. So, that is the advantage of this particular thing so again coming back to the slide.

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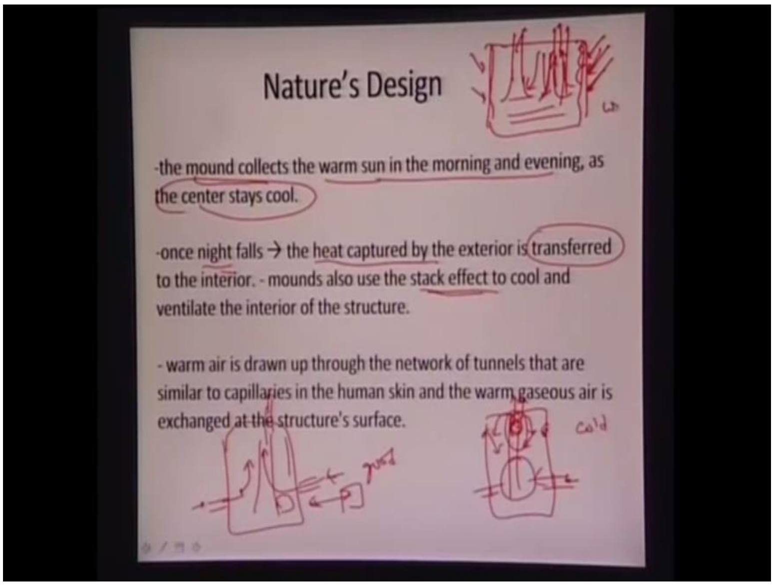

And how does it work is, that the mounds they collect, the warm sun in the morning and evening and the, and the centre stays cool. But, when the night has fallen, the heat which is been captured earlier is not transferred back to the interior. So, it is not transfer to the back to the interior, and also it uses as stack effect to cool and maintaining the interior of the structure.

So, it is a basically stack structure more like this, with certain closures and all that around itself. The overall idea is, that the ventilation is dependent on the temperature outside inside. If it is very hot then the ventilation will go stronger, if it is hot the ventilation will go stronger and the air will keep passing and it will get released from above itself. So, we will have very good ventilation, very few airflow during the overall climate is little warmer, but when it is very-very cold, it is very cold outside.

Then, basically what is happening is, the heat which is being trapped outside, it starts flowing in inside because there is no ventilation anymore. There is no difference between the temperature outside and inside. So, the ventilation, overall ventilation is basically slow and cold during the times of cold. So, overall ventilation is slowed down, so heat which is being captured here, it cannot go out. It basically comes back because of poor ventilation and it starts warming the interior of the warm.

And now warmer is drawn up to the network of tunnels that are similar to capillaries and the human skin, and the warmer gases here is exchanged at the structure's surface. So, that is what the overall thing is about termite mounds that, how the overall ventilation can occur, that burns the, once the temperature are very-very hotter. There will be very nice ventilations, very nice ventilation which will be available from termite from this particular structure. And also there are certain designs, which are able to be such as east gate, that they have, they have designed structures like this, that they have some kind of stacking effect. It is also utilised in either material processing, that it can retain most of its, most of it heat during the material in process. Or even some structures or the buildings that take care of this particular heating effect.

In winter, the sun in warming the side walls, so this is basically heating the overall surface. And as the heat is very-very high, the ventilation will go, will go to a good extent and then heat will get release from the top channels. But, if the climate is very-very cold then what will happen? That the heat which is been connected from the walls, or from the surface, or from the roofs, will stay inside and it will, and because of poor ventilation it will again warm the chambers of the building inside.

So, that is how the overall thing works, that it stays warm because of poor ventilation in winter. And in summer what happens, because of a better ventilation, the air basically goes away.

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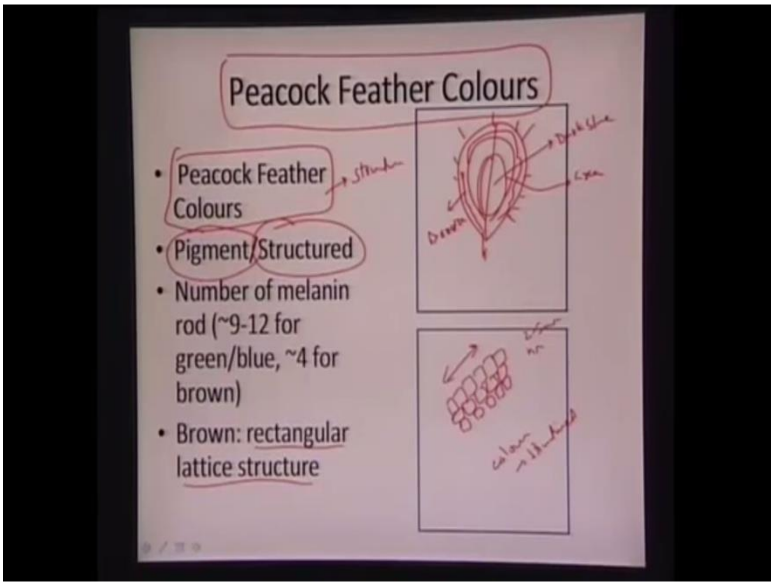

And this basically brings us to something called peacock feather colour. We know that the colour can be given either, it can be the pigmented, or it can also be through some structures. It can ((Refer Time: 47:55)), it can be transmitted through the, through the corners and it can provide certain colours.

But, the problem with the pigment colours is that, they do not stay longer, those chemical colours they do not stay longer. The life time is couple of years, 100s of years, but again it basically does not last eternally. Whereas, this colour which is been provided by the structure it stays forever, so does not require a, require any dies or any chemicals to provide itself a new colour, it just remains there as such. And as we know that peacock feather colour, and the butterfly feather colour, they are not pigmented, they are basically structured.

So, we can see that pigmented colours, they basically die out of time whereas, structures they remain eternally because that is the structure which has given out the colour. So, we see that a peacock feather will have certain regime like this, and then it will have certain colours around it, maybe very dark blue, then will have certain fringe of kind of green, a certain fringe of brown. So, all these colours are, these, all these colours are provided just by the way the structure or the number of melanin rod which are making this particular feather, how they are basically structured.

So, we see that there are certain number of melanin rods, which are all 9 to 12 for green or blue, or around 4 for brown, and they have certain very nice regular structure. So, these all structures which are, which have positivity as well of a controlled size, or a controlled distance between them. And these blocks are around couple of nanometres, around 2 to 5 nanometres in length and breadth. And those particular form a kind of a rectangular lattice structure, and this particular lattice structure is what which is responsible for providing a colour which is kind of a structured colour to the peacock feather.

So, this is the, this is the overall thing what we learned in this particular multi scale, that initially we need to have fundamental building block which can go into forming something at different scales and at different hierarchies. And each length scale let say coming to micro, it can have a different structure, at nano it can have a really different structure. Say in case of a gecko or in case of a lotus leaf, we can have a nanohair which is pre-dominant at nano scale.

But, once you come to micron scale, in gecko we have more something called setae or spatula. And then those going to form something lamellae whereas, in lotus leaf we have nanohairs, and coming to micron scale we have something called micro protrusions which are more like a microspheres. And then they go into forming a super hydrophobicity. So, we can see that gecko can stick onto an any surface whereas, hydrophobicty is coming out via non wetting. So, very drastically different properties how they can be engineered by utilising this multi scale hierarchy.

And then we realise how differently, how a, what a hierarchy can classified, say in terms of cracking, so what kind of interaction we see more at atomistic scale. And it basically define single atom and what is the electron structure and all that to give it certain bonding properties. How it can go on to forming a molecule, and how it can go on to forming molecular chain, which will have certain interactions between them. And how it can go on to forming certain localized eeled regions, and how it can on to forming more plastic regime which can extend to certain grains to many-many grains. And what is the overall bulk eelding which can define the bulk property of a particular material.

So, we see the how the hierarchy or how the length scale is basically deciding the what is happening differently at each scale. So, we had different hierarchy at each scale and that is what is the finding a mechanical properties. And also we saw that, how the nature has been, the master engineer starting from, starting from termite mounds, or gecko feet or ((Refer Time: 52: 10)) structure. How nicely the platelets of calcium carbonate are arranged with certain protein layer to render such a toughness which is to the order of 1000 times more than the its ingredient ceramic material, which is calcium carbonate.

So, how well it can go on to forming something very tough, or how it can be really arranged to provide a colouring effect such as in peacock feather, or butterfly features. Or even providing warmth in winter and be able to manage the energy or the heat around it, such as in termite mounds. So, this gives us the overall feel of the multi scale hierarchy. And if the building block itself is to a order of nanometres or atomic scale, we can realise that we can go on to forming something very-very complex, and that will give the advantage that we can control the overall structure much more precisely. And that is where basically I will end my lecture.

Thanks a lot.