Nanotechnology Science and Applications
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Lecture – 04
Discussion on Feynman’s talk on Nanotechnology Part II

Hello, we will now look at this class today on Discussion on Feynman’s talk on nanotechnology. As mentioned, it is considered by many and acknowledged by many as one of the first if not the first systematic discussion on the idea of nanotechnology, the concept of nanotechnology, the various issues that one might see if you were to deal with this field and also the potential of this field.

So, in fact, even in his talk, he does not necessarily use the word nanotechnology, he simply tells you about the huge potential of this arena of small things and I know some fascinating views that we can look at and consider. Its particularly very informative because of various things including his ability to see so, far forward in terms of what is possible in that area.

And also, the ability to think differently from what was being done at that time. So, many times in science that is one of the first starting points that we are supposed to look at the literature and they have done all this what can I do that is different. Often, we find many of us will find that we tend to look at improvement in an area based on the framework that already exists in that area.

So, you have some framework and within that framework, you are looking at some improvement. So, it is not often easy to look at a framework that is drastically different from the framework itself that exists. So, in his talk that is sort of what he does, I mean at that time nobody was really looking at this arena and he was still able to set aside the idea that most people are thinking at the macro scale and keep that aside and now let me think at a much smaller scale and see what is possible that.

So, that is thinking would like they say in English outside the box, out of the box thinking this is sort of that this is a very good example of that everybody else would have sort of looked at what was already in place for macroscopic things and see ways of improving that and here he was looking at something no completely different from that.

So, we already had some discussion on his ideas with respect to data the way in which you could handle data at a very small scale, how you could put a tremendous amount of information in tiny spaces. And also if you did that how you would perhaps look at the computers trying to access the data and therefore, what issues those computers would face and what issues computers in general at that point in time we are facing and how those issues could potentially be overcome by looking at extremely miniaturized computers.

Both the data there the way in which the data has been miniaturized as well as the miniaturization of the computers, both of those are now realities. I mean today we carry most of us carry a laptop with us and even that may change with time, but most of us carry a laptop which is phenomenally powerful and we carry huge amounts of data with us both of which were completely alien to society in the 1950s and 1960s and at that point in time the best computers used to be at least a room-sized computer or even a building-sized computer that is like the best that you could think of. So, we have come a long way and many of the predictions he has made in those areas have come true.

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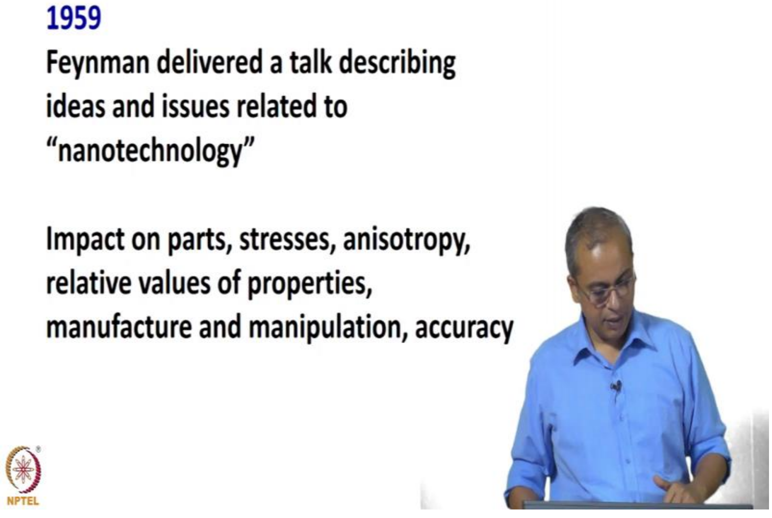

In today's class, we will particularly look at ideas that he discussed on this concept of small scale associated with its impact on parts that you might make, on stresses that might exist anisotropy that is there in materials which or at least anisotropy that may end up coming up more dramatically in materials. And then some ideas on relative values of properties because again scale changes and therefore, the impact of relative values of properties is important to look at some things on manufacturing and manipulation of parts that small scale and aspects related to accuracy with this area.

So, these are all interesting points the sort of maybe relate to each other at different levels and so, as we discussed these topics, I think some in some aspect of the interrelation of interrelationship of these properties is of value for us to sort of think about.

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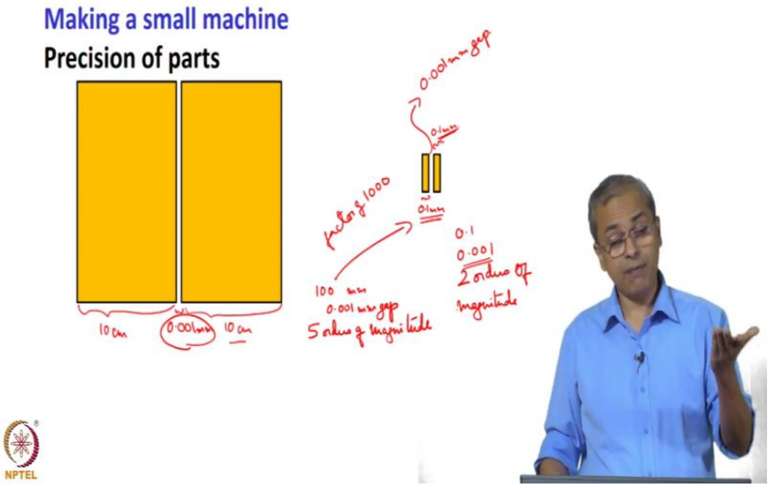

So, for example, we will look at two aspects of this precision and accuracy and so, on the point that he brings all very nicely in his talk is that I mean our alerts us to is the fact that if you made some component I know you have a cylinder and you have a piston going into the cylinder and the gap between the cylinder and the piston is points 0.001 millimeter.

So, or point 0.001 millimeter let us say. So, if this gap is 0.001-millimeter. So, that is 1 micrometer. So, that is the accuracy with which you have and these parts are now in that scale but I do not know if this is I mean this is not drawn to scale, but you may have a piston which is 10 centimeters another and some other housing interest in the wall of which is another 10 centimeter.

So, you are looking at two tenths in 10 centimeter or objects the gap between them is 0.001 millimeter. So, in a macroscopic scale, you could have easily have a component which looks like this. Now, if you are trying to replicate the same thing in very tiny scale, it is important to understand that this level of accuracy with which you are building those parts may not suffice if you go to the small scale.

Because at the small scale if this is now only 0.1 mm and this is only 0.1 mm then here you have gone from a 1000 mm part. So, 100 mm part and 0.001 mm gap. So, you are looking at 5 orders of magnitude. So, 5 orders of magnitude difference is there between the gap and the component. On the other hand, if you have something that is 0.1 mm part and you still maintain this 0.001 gap. So, then what you will have is you are basically seeing a difference of 0.1 to 0.001. So, we only looking at 2 orders of magnitude. So, the difference between the two parts and the gap between the parts is only 2 orders of magnitude.

So, the point is if you are making something in the macroscopic scale which is only 0.001 mm accuracy and it functioned in a certain way wherein you had this long piston and this long cylinder and things did not wobble you could move see it moving up and down uniformly. If you now go to; so, you have gone from 10 centimeters to 0.1 mm. So, 100 millimeters to 0.1 mm. So, you have gone down by a factor of 1000. So, you are reducing everything by a factor of 1000. So, the size of the components has come down by a factor of 1000. So, now, what that scale if your accuracy is still 0.001 mm if that is the gap that you are providing then you will find that on that scale the piston and the cylinder will have much more wobble.

So, they will have much more wobble given the relative scale of things and so on and so, if you just continue maintaining this, if everything else keeps becoming smaller and smaller and smaller, but the gap remains the same. You could very well have even a situation where the component is 0.001 mm and the gap is also 0.001 mm it is the same as having a 10-centimeter cylinder wall, a 10-centimeter piston and the gap between them being 10 centimeters. So, you see that there is a need that the relate the gap should be very tiny relative to the cylinder sizes size of the components. So, if you are just reducing the size of the components, but you are not improving the accuracy. If you are not impure increasing the accuracy with which they are getting closer and closer to each other then you will have a situation where the parts will wobble.

And therefore, so, that is something that you need to be alert to it does not mean that you cannot overcome it, but it means you need to be alert to that is. So, when you are designing something that is going down and scale, you have to keep this in mind. Please also remember that at the time that he gave this talk many of these technologies were not currently built and at that point not built.

And then and therefore, many of the examples that he gives has a certain association with mechanical objects that you can relate to and that is fine I mean, but that is the way he has presented it and he has given wide range of examples, but some of the examples tend to have this mechanical frame of reference and that is how you see this reference. So, when you go down in parts the explanation, he the idea that he alerts you to is that your precision should also be something that you need to pay attention to.

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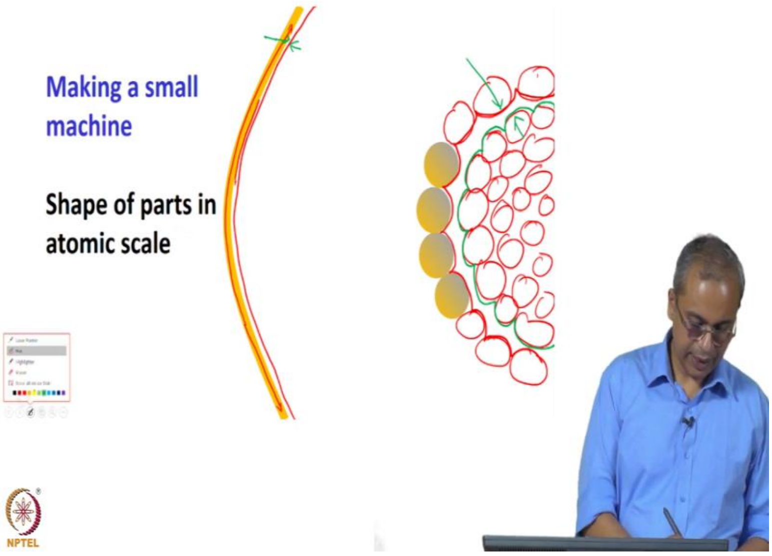

Similarly, if you go extremely small in parts. So, there also you are end up having some other issue. So, that is also something that you have to keep in mind. If you are making a very small machine where we spoke about a scale of 1000s supposing you go to a scale of 100000 down in size. Then again you are putting the cylinder and wall together etcetera and this is the wall of there this is the wall of the piston now what do you see here.

So, at the macroscopic scale, it is a nice smooth wall. So, it is a nice curved wall. So, it is forming the cylinder is forming if the this is the wall of the cylinder, if the cylinder is forming tubular structure cross-section would be a circle and this is part of that wall there. So, you are seeing that wall and therefore, you are seeing a nice smooth curve and then the cylinder that goes inside it will also be a nice the piston that goes inside it will also be a nice smooth curve.

Now the same thing if you were doing in nanoscale, I mean you are going down in scale to a nanotechnology scale, then if you had a piston and a cylinder the surface of the piston is no longer millions of atoms or billions of atoms it is several individual atoms. So, then atoms of course, you can think of them in different ways, this is a rudimentary way of thinking of them as hard spheres, but you can think of them in so, in some sense that is a picture that could still work for us. So, now, even if you make a curve like this even if you are trying to make the wall of a piston a wall of a cylinder.

So, then the wall would consist of a series of spheres like that. So, you will have a series of spheres. So, you see here while you had a smooth surface here you no longer have a smooth surface here you have a surface that looks like this. So, this is the surface now you that you have. Similarly, even the piston that is inside this. So, the piston would have been like that part of the piston we will draw here and that would continue. So, you have a piston-like that and that is the piston that is sliding in the cylinder, here the piston itself would also consist of atoms and so, the piston itself would have this kind of shape. So, you have a bunch of atoms most importantly the surface of that piston.

So, the surface of the piston would then also be like that. So, you can immediately see that what was a pair of smooth surfaces here is no longer a pair of smooth surfaces here. So, this is something that we have to pay attention to when we go into the nanoscale and because that makes a difference on how well the two parts will now behave with respect to each other. So, that is something that we need to keep in mind and relative to the scale.

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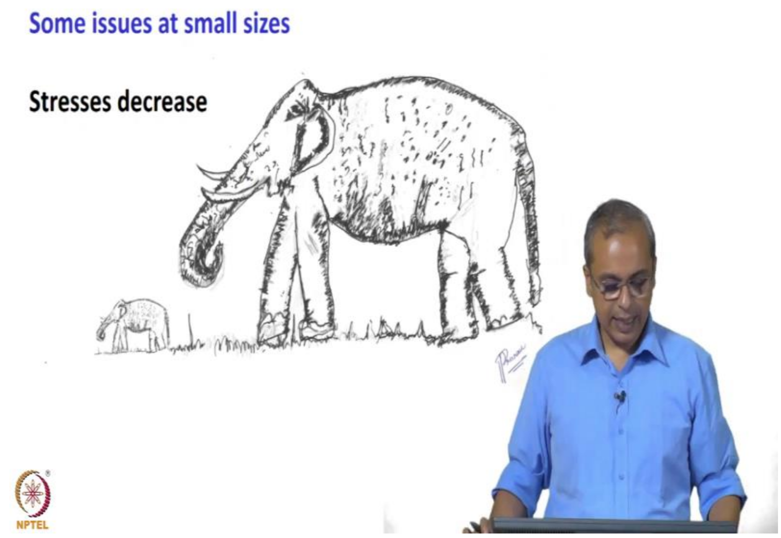

We also discussed in the last class the other issue with respect to sizes and which is about the stress. In this case the it is no longer an issue for us in the sense that you can see we discussed in detail last class that when you go from a large elephant and you make it a small elephant as long as you proportionally bring everything down in size, the stresses faced by the bones of the small elephant is actually vastly less than the stresses faced by the bones of the large elephant.

And that is got to do with the fact that as the size increases the volume increases as a cube of the size whereas, the area increases only as the square of the size. So, if you are going from small to big the weight goes up fast, the area that is holding the weight goes up slowly and therefore, the stress on that same area is higher. Opposite direction you go you are going in a favorable direction because weight is decreasing faster when you go from large to small, but the area is decreasing relatively slower it is decreasing a square of the value of the length, that is decreasing as cube of the value of the length and therefore, the stresses are distinctly lower in this case lower stresses are there here relative to what you get out here. And therefore, with respect to stress you are moving in a favorable direction.

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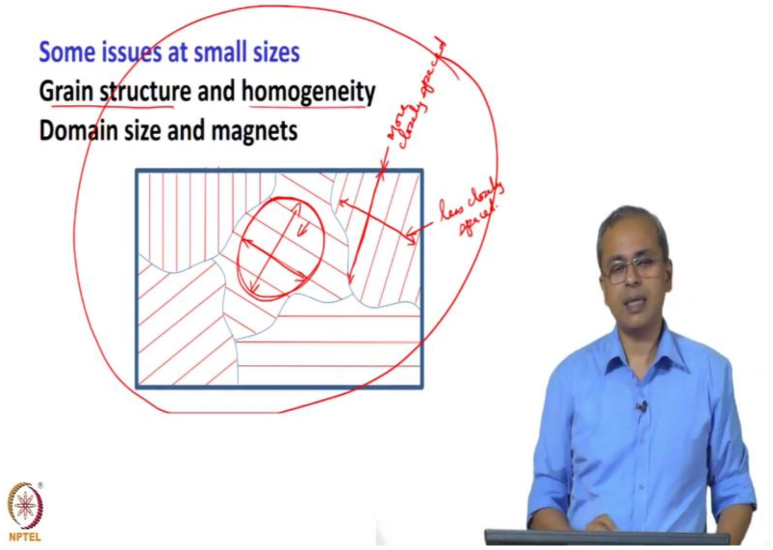

Yet another very interesting issue that comes up when you go to very small sizes is the issue of isotropy or anisotropy. So, now, if you actually go to a hardware store right if you go to a hardware store and you buy a sheet of some metal, you buy a typically some stainless-steel sheet or some other sheet for some application at your home.

If you just buy the sheet or even if you go to a vessel store a utensil store you buy a utensil. If you actually look at it in the light you will see a lot of patches on it. So, even if there is no, I mean this is I am not talking about rust or any such thing, but a good vessel, you just look at it carefully in the light and it is nicely polished you will start seeing a lot of patches.

Those patches are actually grains typically they are grains especially in sheets you will see this very clearly because it rolled in flattened out in various directions and therefore, the grains look larger. So, now, what typically happens is when you buy a sheet. So, you have grains oriented in different directions and what is there within a grain is that you have a series of atomic planes in perfect order. So, now, what happens is the idea of these planes being in perfect order is that sometimes the atoms are more closely spaced along this direction and less closely spaced along this direction.

So, the atoms may be more closely spaced here whereas in this direction they are less closely spaced. And that is just one aspect of it to some degree that spacing is indicative of the type of bonding that is present in the material in other words in many materials bonding in one direction is different from the bonding in another direction. So, and even if the bonding were same if it just has one bond on the x-direction one on the y-direction and one on the z-direction or two each on the x-direction y-direction and z-direction if you go along the body diagonal the situation is different.

So, the position between atoms is different. So, generally, you are unlikely to find a solid except an amorphous solid, typical crystalline solid you will find some crystalline order which means the spacing in specific directions is usually different. And it also means the bonding is different therefore, the properties are different.

So, if I take a single crystal of almost any material there is a good chance that in the single crystal if I measure a property from front to back right from front to back information of property anything it could be electrical conductivity, it could be mechanical strength, could be thermal conductivity. If I measure it from front to back the value that I get will usually be different from the value that I will get if I measure it from top to bottom or from right to left. So, from your right to left. So, if I do it that way depending on how that single crystal is and what kind of atoms are there, bonds are there, generally in a crystalline material you are going to find that the properties are different.

However, if you buy something macroscopic from a hardware store and you bring it to your house and you make measurements, generally you will find that this is not the case you will find that you take this block of metal and then you measure the conductivity from top to bottom, you measure the same conductivity from front to back and conductivity from right to left. So, if you do all this from your right to left if you do all this you will find generally the value is the same.

The reason that is the case is that when you go from top to bottom, you have you do not have a single crystal, you actually have a polycrystalline sample like the one that you are seeing in your slide and there are many crystals between the top and the bottom. And each crystal is oriented randomly, therefore, what you see as a property value that you are measuring from top to bottom is an averaged value across all these single crystals from top to bottom that is the value that you are actually measuring and recording; same will happen from left to right from front to back.

So, in all these cases you are seeing an averaged value of grains pointed in all different directions, different sized grains may be somewhat similarly sized grains, but they are all in different directions and that is why it becomes an average value. This is particularly useful if you are trying to put the material to use in some condition where you want that averaged value. So, that is the point you need to remember and also it also means that when you machine the material, you can sort of not worry about the specific position in which you are keeping the material as long as the machining will get you the shape that you want.

Because in general, the properties are going to be the same any which way you want. On the other hand, if you go to a sample that is smaller and smaller and smaller and smaller in size you may reach a point where the sample that you are trying to machine is actually so, small that it is within the scope of this grain.

Let us say you are trying to machine a cylinder and this is the top view of the cylinder, you are now going to machine a cylinder that is within this grain. Within this grain it is no longer a polycrystalline sample, it is a single crystal sample where there is a dramatic difference in property between this direction and this direction. So, what you got is an averaged property for a large sample of that size, average property that you got for a large sample that size it is not the property that you will get for a small sample that is size.

So, suddenly you will find that for the large sample everything was the same whether you measure it this way, that way, top to bottom everything the same, you come to this sample here and suddenly you find that it is no longer the same you are finding something may be the property is three times as strong in one direction compared to the other direction.

And this could completely throw away your I mean completely disturb the kind of machinery you are trying to make or the kind of product that you are trying to make your product may it’s a cylinder on which something has to be loaded. And you assume a certain average value of strength for that material suddenly you find in one direction it is very weak the only in one direction it can hold whereas, when you made it in the macroscopic scale, you did not care it was a cylinder you could roll it and any in any direction you could load the sample, it would hold. you are making a ring your ring of some sort you can hold the ring this way, you can hold the ring this way whatever way you hold it the load it will take perfectly, but as now with the smaller material you cannot load it any which way.

In one direction you load it will break another direction you load it will stay strong. So, this is something that you have to keep in mind when you go to a small scale. So, this is got to do with grain structure and homogeneity, I mean composition and so, on and grain structure is this. This structure that you see here is this grain structure this is a grain these are the grain boundaries. So, this is a grain that you have seen and so, if you go to the scale close to the grain boundary grain size you no longer can expect this averaged property and therefore, this is called as long as it's averaged in uniform across all directions it's we described it as isotropic.

Isotropic means the properties are similar in all directions and if it is not similar in all directions then we say it is anisotropic. So, when you go down in size you are increasing the chances that your sample is anisotropic. Similarly, we also have domains in magnetic materials you are making a magnet for a fan using an electromagnet for a fan. So, when you have a field developing because of a coil or there is a static magnetic field there that magnetic field is based on domains of the magnetic moments lining up with each other.

So, but if you go below the domain size then you are increasing the chances that the magnetic moments will not align with each other. You are increasing the chances that they start randomly orienting because they do not have sufficient numbers to sort of build on each other’s alignment. And then get you a domain which is where all the magnetic moments are aligned.

So, if you are trying to make a magnet that is very small you may run into trouble. You may start with the material that is magnetic, but as you go smaller and smaller and smaller in size suddenly it will show you properties that are not exactly what you are expecting from the magnet at a larger scale it may behave very differently it may stop being magnetic and so on. So, if you are trying to miniaturize a fan, the fan works perfectly fine when it is large you miniaturize it, suddenly it no longer works properly. So, that is the problem you have.

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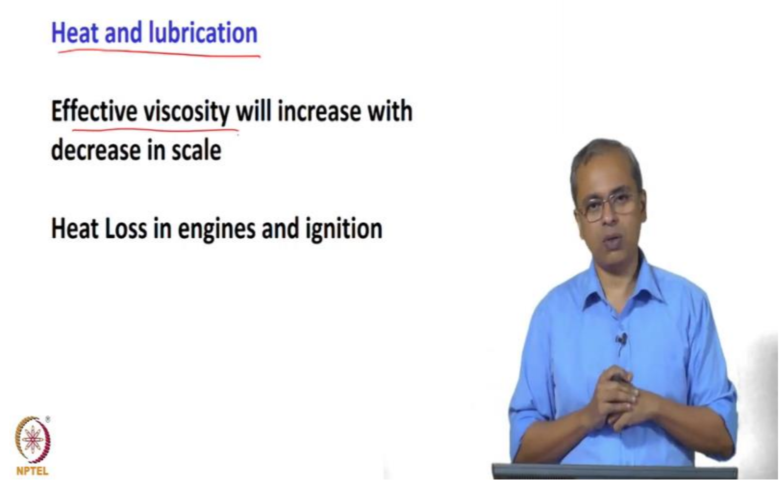

Again, another interesting problem with respect to heat and lubrication. So, these are all by the way again as I keep saying this is very nice to see his talk you can look up a talk I mean transcripts of that talk at various places, he just looked at a wide range of issues that you will see at small scale and no consider options and issues with respect to the heat and lubrication.

This is with from the context of you are trying to miniaturize and internal combustion engine. you are trying to make an extremely tiny motorcar for some demonstration purpose some purpose you are trying to make an extremely tiny motorcar. So, you have an engine which is inside which has all the shape and features of an engine that you would see in your car that is a full-sized car except that it is all 1 million times smaller if that is the case. Now in our cars in our automobiles we are always typically using some oil as a lubricant.

So, that otherwise the engine will overheat and seize and so on. So, you have to have some lubricant. So, now, what happens with lubricants as you go down in size? What happens is relative to the size as you go down and smaller and smaller sizes, the effective viscosity of that lubricants will become higher and it with us if you take a tiny drop of that lubricant and put a tiny metal two tiny metal pieces and try to move them, you will find generally find that they stick more they do not move that easily.

So, but there are solutions to it you can go to lower viscosity oils and so, you can try to mitigate this problem. But interestingly why are we actually doing this lubrication, I mean we are doing it because otherwise the parts become hot and you need some of this to lubrication to handle all that heat and movement and so on. Interestingly when you go down in size, the heat loss from that engine is actually quite high.

So, in other words, you are trying to normally engine this large size because of its mass it also has a thermal mass associated with it. So, it takes certain amount of it will it has to release some amount of energy to the environment for it to cool down, but if you go to smaller and smaller sizes and the environment is the same, the amount of mass of the engine is extremely small.

So, correspondingly its thermal mass is also very small and therefore, it loses heat very easily to the surroundings. It’s no different than you keep a small a small bead you heat one small bead and once a big block of metal to the same temperature and you keep it out the small bead will cool very fast, the big bead will take a big block of metal will take a long time to code.

So, that is got to do with thermal mass. There is so, much heat inside it is all got to come to the surface and leave when a small bead it happens very fast. Same thing large engine block small tiny engine block large engine block will take a long time to cool small engine block will lose heat very fast. Therefore, the interesting thing is if you are making a tiny engine you may not have an issue with lubrication because you can you probably can run the engine without any lubrication because it is just not heating up it is not heating up so, you do not need any lubrication. And so, this issue that you have a lubricant and that you need to have a lubricant of appropriate viscosity at extremely small scale can actually be worked around you no longer need it because this heat loss is not there.

Interestingly now this creates a new problem. So, we have we started off with something that is large scale we try to miniaturize it, we saw that there is a problem with respect to viscosity, we recognized that actually maybe there is no problem with respect to viscosity because heat loss is faster, but this creates a new problem what is the new problem? In any engine, you need to have a certain amount of heat to be present for the fuel to ignite. So, only then the fuel ignites.

So, now, if the engine is losing heat very fast their fuel will not ignite. So, therefore, the engine would stop working. So, it is not stopping to work because it is overheating this is this engine is going to stop working because it is cooling too fast the small engine.

And therefore, you have to now work around it, you have to provide some electronic ignition to it only then it will start functioning. So, this is an interesting cycle of problems that arises as you go down in scale. One seems to be a problem it actually is not a problem then you find it creates another problem and then you have to find a way to deal with it. So, that is some that process that thought process is something that you have to keep in mind.

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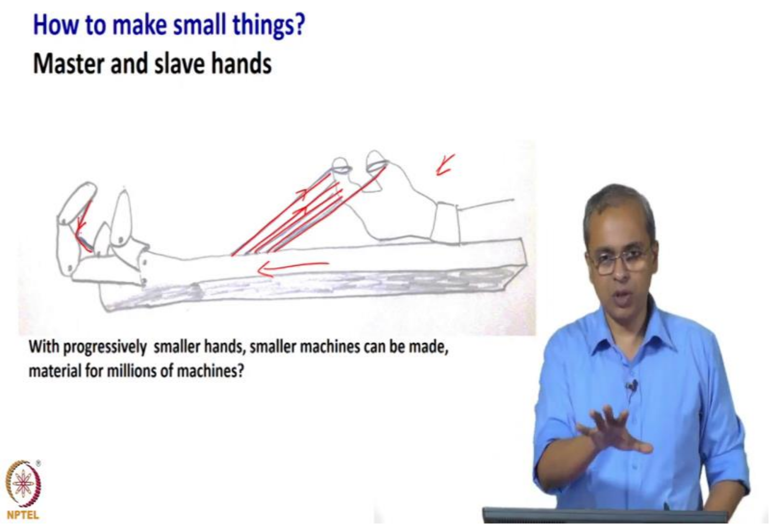

So, then a Feynman also considers the idea that you have to deal with making machines at a small scale. So, while just talk deals with lot of things at the small scale he also explores the idea of what should you do if you want to make things at the small scale. So, that is an idea that he explores. So, he takes this broader picture of a master hand and slave hand.

So, this is something that has existed in the nuclear industry, where you are working with materials that are radioactive and therefore, you cannot have as easy contact with the materials that you are working with as you would do in any other non-nuclear energy-related laboratory. So, what they would do one of the ways in which they can deal with that, is to have some kind of a robotic hand wherein another location which is not radioactive you attach some things to your hand and then you try to open a bottle this robotic hand will actually be elsewhere it will go grab a bottle and do exactly the same action that you are doing.

So, in other words, whatever you are doing with your hand it will repeat. So, that it will do and so an example is here this is a macro mechanical kind of example which you can easily make even at home as a toy and this is like a mechanical version of it. So, this is that a real person’s hand here and this is the robotic hand you can think of its just a block of wood with some joints and here are some threads.

So, these are all threads at each going to a different finger in your hand. So, now, when you pull one finger in it will pull the thread closer to you and that thread which you pull this thread back closer to you and then that there will that will pull this finger inverse or this thread you are pulled in, it will pull this finger it will pull this thread in and therefore, it will curl the finger.

So, when you curl your index finger, the index finger of that robotic arm will curve. So, this is a very simple mechanical way in which you can make this slave hand. So, you can easily use this as a hand extension. So, at your home you can make this gadget very easily and you have a cup of water in front of you, you can easily curl your fingers as though you are grabbing the cup your extended arm will grab that cup and then you can hand it off to somebody.

So, this is the way you could do it. Now, what Feynman’s says is that like this idea you can also consider the possibility that your hand is at a certain size and that the slave hand that you are making is at a much smaller size. And therefore, you can go from something that you are making at your scale and you will be making it at your scale but your robotic hand will make it at one-tenth the scale.

If you that robotic hand is one-tenth your hand whatever you do at your scale, the robotic hand will do it one-tenth the scale. So, he uses this idea to say that you can make machines which make copies of themselves and so, you have a lathe, a lathe can be wired so, that it makes a new lathe, but that new lathe is one-tenth a one-fourth its size. And that lathe makes another lathe which is one forth its size and so on.

So, like this you can make starting with some macroscopic machine you can make a very microscopic machine and then if you have several of those, you can create a factory of smaller tiny machines which if they are in a position where if those machines have been made in such a way that they can do some activity together, you can have this set large collection of tiny machines which are going about doing some activity and then they create no more machines and so on.

So, this idea he explores on how you can do this if you go from large scale to small scale and he also points out that in terms of material, this is actually very convenient to us because if you had to make 1000 lathes for doing some machining, they would occupy a very large building amount if you had to place them in some building.

Whereas, if you made tiny lathes which are 1000 the size of the original lathe, the 1000 lathes will just occupy the size of one lathe. So, that is the beauty of doing something at extremely small scale, the amount of material you need also will be extremely tiny the amount of material you need would be just the amount of material you need for one lathe. And therefore, this is a very interesting direction to go in and he says that if you have this large army of small machines, they can do something very constructive together.

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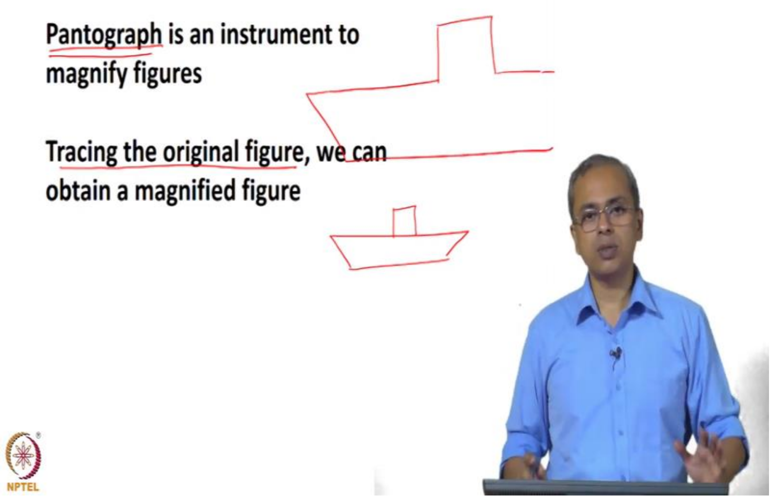

So, he actually looks at again how you could do this physically. So, he looks at a machine called a pantograph, in these days we have photocopy machines where you put in some document and it makes a copy of the document almost instantaneously; you can take photographs you can print out your photograph so, many such options we have readily available to us these days. If you go back 60 years 1960s and so on, they did not have such facilities even a photocopy machine I do not know if it was really available at that point in time.

So, but they did have ways of making copies of different diagrams and not just copies you could also have ways in which you could magnify the diagram if you wanted. And so, one of those is this device called a pantograph where the idea is that on that machine you will trace the original figure. So, whatever is that original figure. So, let us say; it is a boat some boat like that.

So, you would trace this on the pantograph you would you take the pen of the pantograph and move it along the lines of this boat. It would then create a copy of this boat based on how the pantograph is designed, it would create a copy of the boat which is much bigger. So, whatever is that size know whatever it is designed to magnify to it would make a much larger boat for you. So, part of it is visible here, but you could make a larger boat. So, that is the idea that with which it does and with the manner in which it does is something like this.

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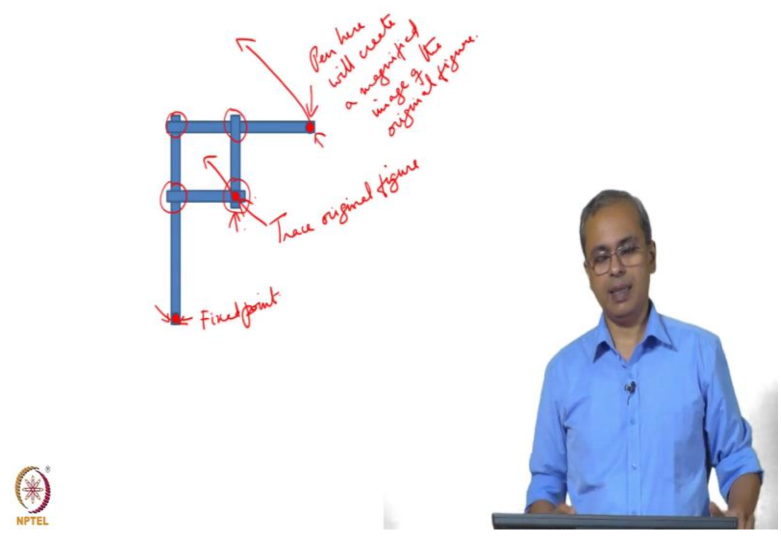

So, this is a pantograph and so, there is one point that is fixed which is this point, for example, this is a fixed point, this joint is movable or at least they are they can slide with respect to each other this way that way and so, all these joints can move. So, the idea is that you will take this as a fixed point. So, this is your fixed point with this point you will trace your original figure.

If you put a pen on this point, it will create a magnified image. So, if this were moving along this direction this would move along the direction and it would correspondingly make a larger image. You could do the opposite if the if this region was the tracing the original diagram, then a pen in this region would give you a miniaturized image.

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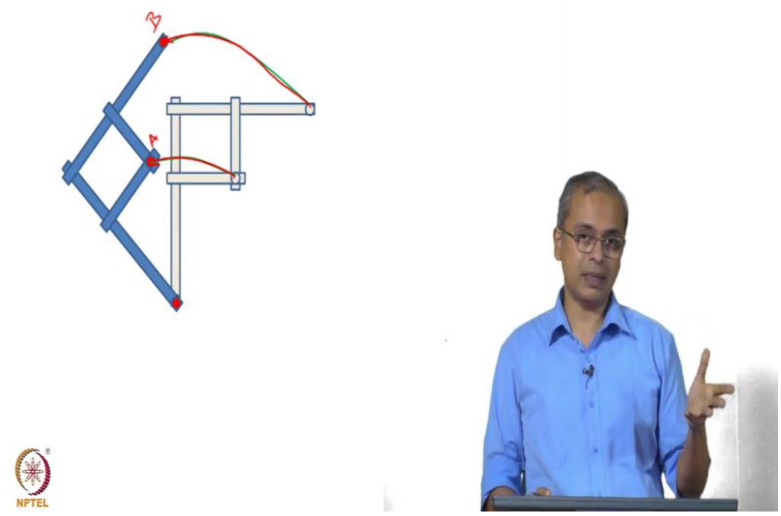

So, for example, I am just showing that to you here. So, this is how for example, this arc has moved. So, I have traced an arc in this direction, the pen here has traced an arc which is much larger. So, by moving the location A I am getting a much larger arc from location B. So, you can make any shape because the joints are all flexible joints. So, you can actually get you can trace any shape that you wish with point A and you will get a magnified image of it using the pen at point B.

So, that is basically what this pantograph is. So, you can see here original position and it has move right original position is here that is moved. So, this is the pantograph and so, he says that you can actually use this kind of an idea to make something smaller. So, he talks about how you would go about making something smaller and this is an idea that he provides us with.

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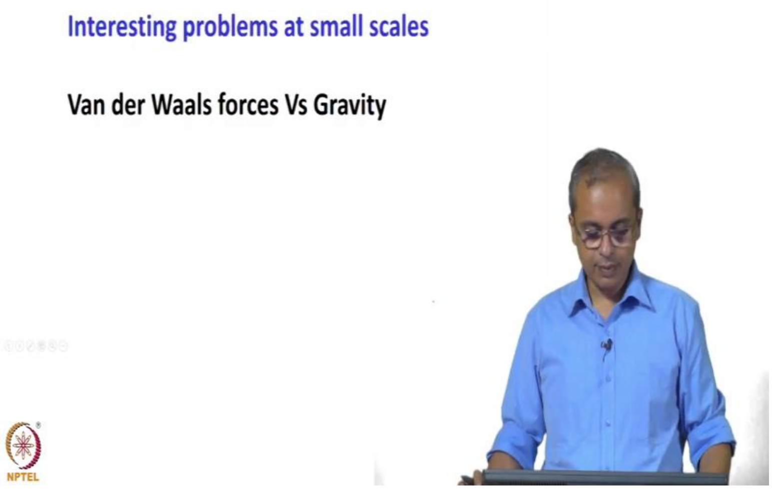

Some more interesting problems at small scales. So, what is this problem on Van der Waals forces versus gravity? So, he talks about this idea that you are trying to fix something you are fixing a bolt to a nut in a small in a small scale. So, when you actually do it in a macroscopic scale. So, when do it with your hands you have a bolt and a nut and then thread them one into the other it fits?

If you remove the thread you unscrew it and then it comes to the edge you remove it will just fall right off right the bolt just falls off. So, the nut and bolt just fall apart once you remove them. But if you go to extremely tiny scales they fall apart at the large scale because gravity is there right gravity is there at the large scale and it has that much mass and so, it gets attracted by gravity and it falls right off.

Now, when you go to extremely tiny scales the mass is so, small that if you have any attractive forces I mean chemical bonding forces which are also acting between the nut and the bolt, they start taking relatively higher I mean relatively they start matching the value of the gravitational pull on the nut and the bolt.

So, that force also exists in the large nut and bolt except that the weight of the nut and bolt is. So, large that it completely overwhelms the attractive forces say Van der Waals forces of attraction between the various atoms in the nut and the bolt. So, the gravitational force on the nut and bolt is very larger than that of the Van der Waals forces between the nut and the bolt.

When you go to the very tiny scale the Van der Waals forces remain the same, they are exactly the same value, but the gravitational effect on the nut and bolt becomes extremely tiny because the mass of the nut and bolt is extremely tiny. So, they do not fall off as easily they are competing its weight is competing against the pull from the Van der Waals force and so, it sorts of it might sort of get stuck.

So, he describes that as though you are working with something that is sticky right it is just like putting some gum on some adhesive on the nut and bolt and so, as you unthread it does not come off it is still sticking your nut and bolt are still sticking. So, it is that kind of a situation that you can have at when you go to extremely small scales where you now have to look at the relative values of different properties.

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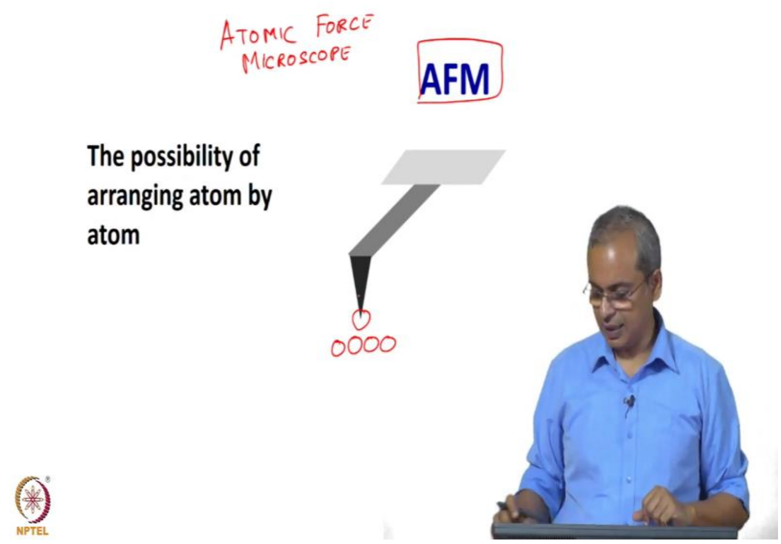

He also talks about this idea of arranging something atom by atom and so, again this is again significant extrapolation on his part which has been know very nicely shown to be true in these days is that, today we have this thing called an atomic force microscope AFM Atomic Force Microscope. That does exactly this I mean you have actually a very pointed tip that is very small it is shown in large scale here, but extremely small almost two atomic dimensions you are going with this tip and so, when you bring this close to a set of atoms you can exert a force on those atoms and people have shown experimentally that they can carefully move an atom around.

So, you can make a collection of atoms arranged in a certain manner, then you can use this atomic force microscope to actually image it. So, there is a way in which you can use this in an imaging mode. So, in that case, it will show you the image of those atoms and tell you where those atoms are sitting, then you can use it in a slightly different mode where the tip comes very close to an atom and then starts dragging the atom. So, you can drag the atom and now position it at a different location relative to where it was originally and then again change the mode go back to the original mode and then take an image of that set of atoms.

So, today we have that capability to rearrange atom by atom. So, you can really think of some set of atoms in some arrangement and then sit with an atomic force microscope and within reason actually, do something very similar actually create that collection of atoms in that orientation. So, this is the idea of arranging something atom by atom which will help you again at the nanoscale in some very interesting ways. So, for example, this AFM when I would spoke about it being used in imaging mode, it actually does surface topology. So, if you have a surface like this it will slide along the surface and as long as it is smooth it will remain smooth, then it will climb up go downslide up this slide down this go up and down as it is moving in this direction.

So, then it will record that it has moved straight it is moved up, it has come down moved up come down. So, it keeps track of XY and Z locations of this tip the microscope physically move a sharp tip on a surface and then as the tip goes down it notes that the Z value has gone down, the tip goes up no ZZ value has gone up and so, on. So, XY direction it already knows because it is moving the tip accordingly z direction it picks up the information and so, it gives you a surface topology so, to speak of that sample.

So, all the hills and valleys of that sample are nicely captured by it and so, if there are atoms it can actually show you, it will go up over and above the atoms and give you some approximate idea of how those atoms talk. So, this is how the AFM works and using this you could arrange things atom by atom and then you can create something that is interesting.

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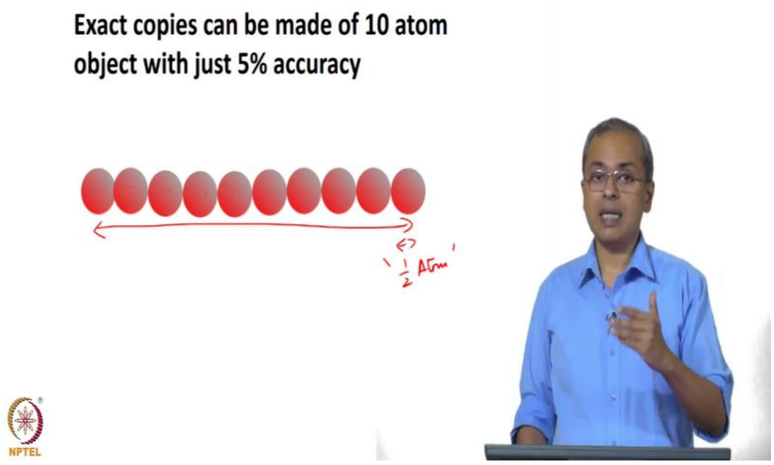

And one final point that he makes is that one of the advantages of when you of doing this at an extremely small scale is that when you do at large scale. If you want to make an exact copy of something, you start with some object and you want to make an exact copy of it your accuracy has to be some 0.000001% accuracy only then you can get something that is an exact copy of the original.

Interestingly, when you go down to atomic scale if you are trying to make an exact copy of 10 atoms, you have here one let us see 10 atoms are here. So, I have 10 atoms here. If I want to make an exact copy of these 10 atoms. So, what do I need? I when I say an exact copy it means I should not have 9 atoms I should not have 11 atoms I should have exactly 10 atoms.

So, for this, I should have more than 9 less than 11. So, even if I get nine and a half, I am at I cannot have nine and a half atoms if I cross 9, I will reach 10 I cannot have 10 and a half if I cross 10, I will have 11. So, if I drop below 10 and a half, I am at 10. So, essentially, I have to be accurate only with respect to about half an atom because half an atom will not exist if I am anything better than half an atom accuracy naturally one full atom will be there.

So; that means, out of 10 atoms I need to have only half an atom accuracy which is 5% accuracy. If I have 5,10% accuracy is one atom, 5% accuracy is half an atom if I am better than 5% accuracy anything more than 5% accuracy, I am around 5% accuracy I will get this 10-atom sample done correctly. So, therefore, suddenly it is actually easier in some ways to do an exact copy at an atomic level. So, this is again another thing that he highlights.

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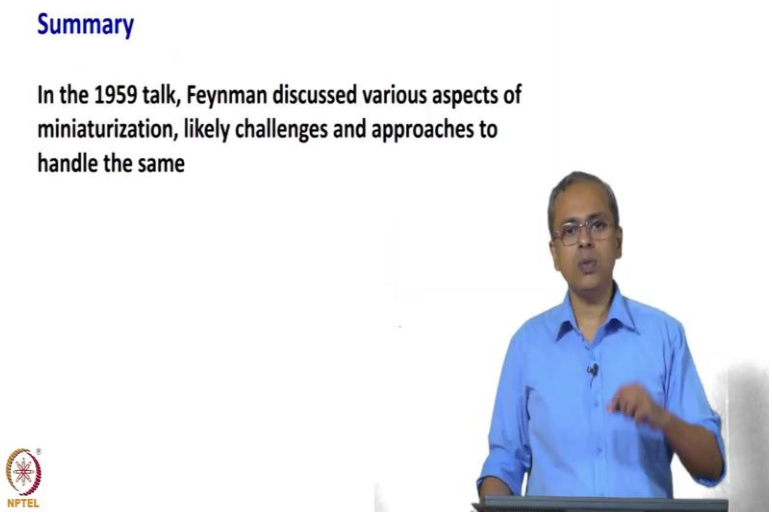

So, in summary, today we looked at the other aspects of the talk that Feynman gave again it's a 1959 talk and you can see through what we discussed today a variety of issues he has highlighted we are sitting in 1959, he could think so, far forward in a field that did not exist in a field that nobody had spent enough time on, he could think of such a wide range of issues that may be there and such a wide range of possibilities, such a wide range of concepts and ways in which you can address those concepts and utilize those concepts and what beautiful things we might have available to us if we went down that path.

Today in nanotechnology in all the science that happens behind nanotechnology all the products that we have with respect to nanotechnology. In many ways, we are doing exactly what Feynman had the very beautifully put out in his 1959 talk. So, he gets a lot of credit for this and as you can see from what we discussed in the last class in this class its very justifiable, I mean it's very nice it's not simply that some famous person said something if you sit and analyze what all he said it certainly sounds so, clear and so, it's so, much foresight he has managed to say these things.

So, that is the reason why we have so, many people referring to his talk as the sort of this philosophical start of nanotechnology and I think that is an extremely justified position to take. So, with this we conclude this class we will look at new topics later.

Thank you.