Micro and Smart Systems
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Lecture - 24
Modeling of Microsystems: Scaling Effects

Hello as part of the Micro and Smart Systems Course we were discussing the modeling techniques in the last several lectures. This is the last lecture on the modeling of micro systems and we are going to talk about something slightly different from what we have been discussing in the modeling part by highlighting the scaling effects that we find in micro systems.

As we discussed the scaling effects we will try to look at the modeling issues and it will serve as a review of the modeling that we have discussed so far.

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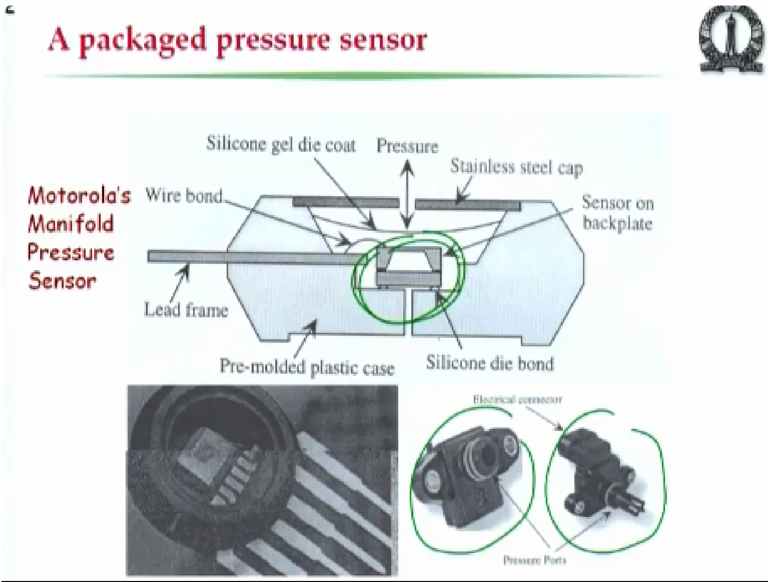

Let us look at this pressure sensor device that we have discussed in the lecture that we had on sensors micro sensors. If we look at that slide here we see that the sensor is over there. In fact, is an exaggerated picture where the chip is shown to be larger than what is surrounding it. It is not a scale drawing per se, but if you just see that the final product which is shown here is a pressure sensor made by Motorola is a commercial device.

The chip will be quite small that is over here this is a chip, but the final device is going to be big because it has to be interfaced to something at the large scale where human beings can handle it. So one can ask the question if the final product is going to be big as big as we can hold in our hand. Why should the chip be so small?

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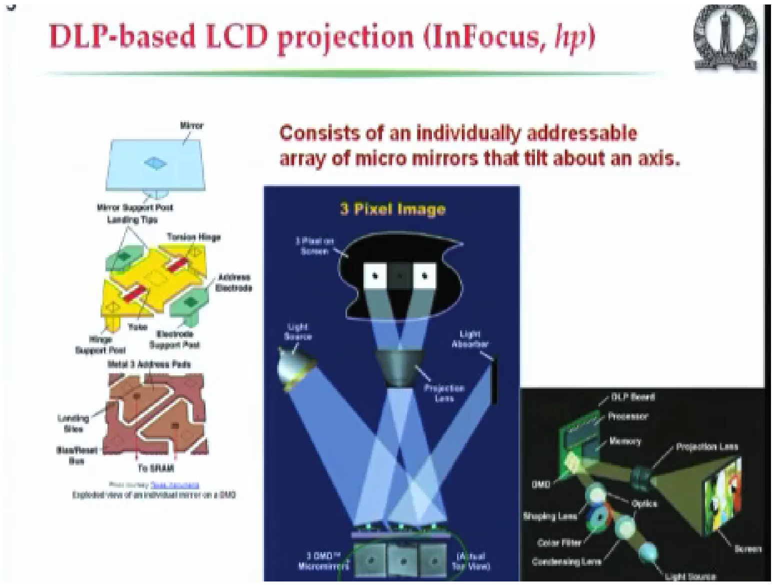

The same question can be asked about some other devices. For examples this array of micro mirrors which we had discussed earlier in one of the lectures where we had talked about modeling where the torsion beam and how to take care of the modeling of the torsion. Now if you look at this device there is an array of mirrors small mirrors as you can see. The ones that are shown over here several of them will be there and they tilt and project the image.

If you look at the computer projector that uses this array of micro mirrors again a commercial product that is a quite large box and one can ask the question if the final box is going to be that large why should we make this mirror array at the micro scale. Again a pertinent question the final device is going to be big, but the chip is small why should we do it?

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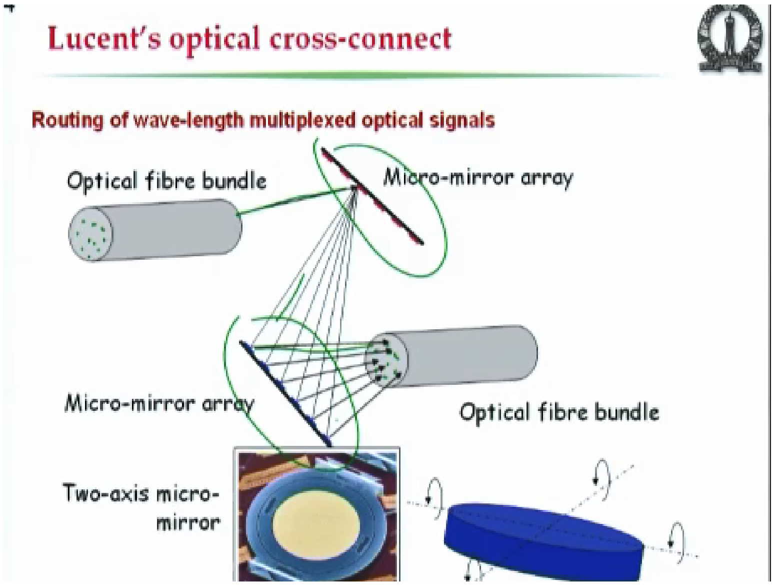

Here is another example of another mirror array. The previous mirror tells about only one axis whereas this one can tilt about two axis and here the purpose is as again we had discussed in the earlier lectures we have a number of fibers here and they all need to transmit to a number of fibers in the output fiber bundle. So these mirrors that are over here and here tilt so that everyone of them can go tilt there and come back and address any one of them.

So if you think about how big this system is going to be or device is going to be, the switching device is going to be it is going to quite large because they are going to be about a 1000 fibers here, 1000 fibers in the output. So you need to connect all of them if you take the connector size and the whole alignment fixture that is made to position this micro mirror chips is going to be quite large definitely of the order of tens of centimeters.

Whereas the chip itself will be quite small a centimeter by centimeter. So one can ask the question why should we make the mirrors so small.

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This has to do with the scaling that depends on many things. So let us look at motivation for miniaturization. Now that you have heard a lot about a micro system and their fabrication techniques and modeling. Now let us look at the reason for why people try to miniaturize things. The first reason of course that you would have already guessed by that time is the economy that is associated with making things small especially if a product that we are looking at has a large volume.

There are lot of products are made if you make several of them on a same chip and subject it to the same processes one after the other the cost per chip will come down in that batch production mode and for the same reason IC chips have become very inexpensive. And the cost of them keeps going down. The same thing is likely to happen for micro systems as well and that is why there is a strong reason for making thing small even when all applications do not require that micro size.

The second reason is that some of these micro devices might not even work if they are made any larger okay so that a point. So there are some phenomena which work only at the micro scale through miniaturization. Whereas in some others the scaling is such that it favors miniaturization there are few devices of any kind as well and if you think about what are the really driving factors for making things small.

It would be the weight which is very useful in consumer applications where you carry like a mobile phone and watch and things like that or in aerospace applications where weight is of concern. And power and energy are critical for almost any application. So if you make things smaller to do a job that can be done by a larger one if it consumers less power which is always the case then there is an advantage.

So there are a number of reasons and one of the most important reasons is that if we use an array of identical element we basically get the advantage of VLSI very large scale integrated systems like imagine an army of ants actually lugging a big insect or food that they eat. So that is kind of an analogy we would like to take and a lot of them like a micro mirror array one mirror probably will not be of much use there are array of mirrors it has a purpose.

So these are many reasons for miniaturization that is why we make it small, but really the driving factors are the scaling. So if you make things small things do change and there are advantages most of the times sometimes there are also disadvantages.

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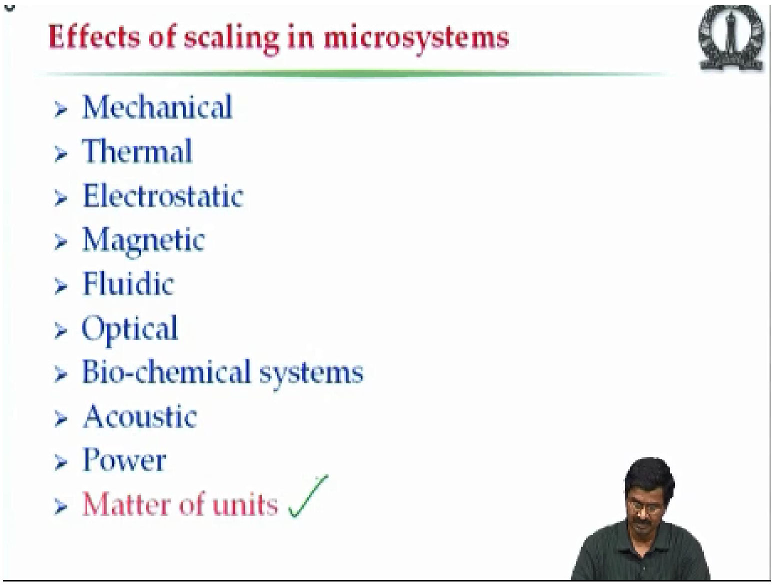

We will look at this scaling issues in a number of domains today and this will serve as I said at the beginning of today’s lecture as a review of the modeling that we have discussed. The first is mechanical domain and then we look at the thermal domain, electrostatic, magnetic, fluidic, optical, biochemical, acoustic and power. So all these domains have something to do with scaling and we will discuss that.

And then see how we can use very simple modeling arguments to answer this question why miniaturization in all of these sub fields? And finally we will spend some time talking about what units to use when you do computations because that is a question that arises whenever we try to do some modeling because even numbers may become too small if you start putting one micron as 10 power -6 number in a computer. So we will discuss that a matter concerning the units to be used in calculations.

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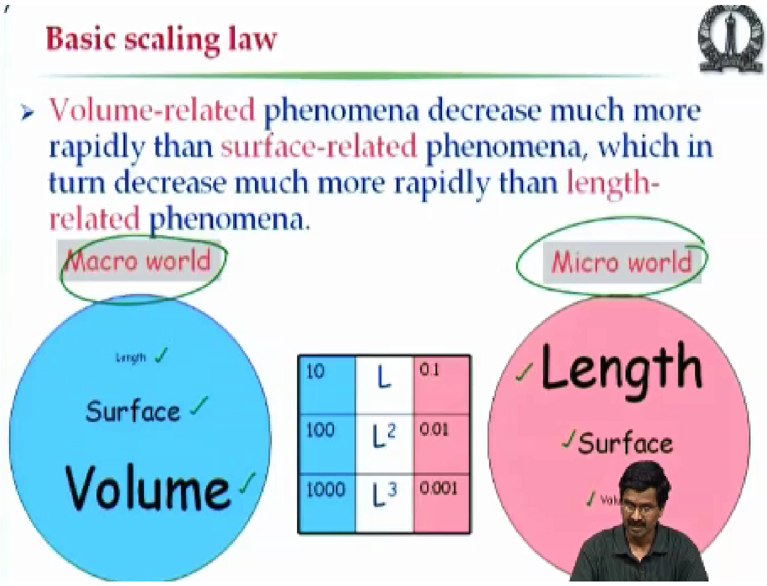

Okay the first thing when you talk about scaling we used to realize one very simple scaling law and that says that volume related phenomena decrease much more rapidly than surface related phenomena which in turn decrease much more rapidly than length related phenomena. So if you look at this scaling law pictorial is illustrated here you have the macro world here these is our blue world and then the pink world is the micro world.

Macro world length looks very tiny you can hardly see it there. Surface looks a little bit bigger, volume looks very large and it exactly we are around at the micro scale. Length looks really big, surface medium and volume is hardly felt. So the way to see is that length is L, surface is L square where L refers to the size L cube refer to volume. If there is a large number 10 becomes 100 becomes 1000 for volume.

Whereas if it is point 1 it becomes point 01 and point 001. So anything to do with length related phenomena is going to be dominant at the macro scale and then come surface and then volume and the reverse is towards the macro scale where volume related phenomena is going to be very influential, surface less influential and length related phenomena will be least influential.

This is the basic scaling law that we should keep in mind as we discuss the modeling related to micro systems.

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Some of the these is very well embodied in if you call it science friction in Gulliver's Travels which many of us or many of you would have definitely read about and enjoyed the amazing travels of Gulliver's. And if you just think about and read that book between the lines now you will see that there are lot of nice scaling arguments that were put forward by Jonathan Swift the author of Gulliver's Travels.

Where he says that when Gulliver arrived in Lilliput Island they had to decide how much food to give them if they eat certain amount of food since he is 10 times taller than them does he eat only 10 times more food or is it more than that and they decide that it should be 1000 times more food because compared to what they have their size is 10, but volume which is the volume of the stomach to fill his need for saturating his hunger has to be proportional to the volume and that is how the food has to be decided.

So there are many more arguments in that book and people have thought about this scaling for a very long time.

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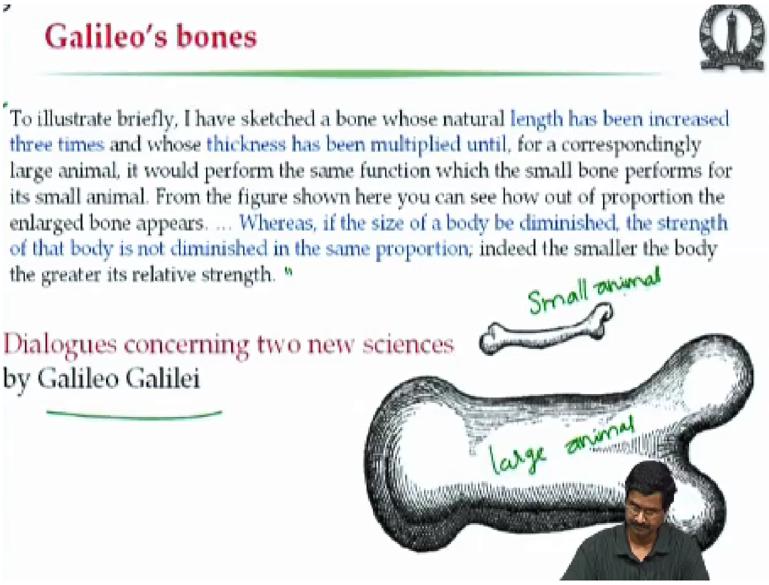

And here we are showing a couple of sketches that were taken from a book by Galileo Galilei who was the first people to conduct experiment systematically in gravity. He would also thought about scaling because he observed that compared to the animal bones in small animals. This is the bone in a small animal and this is the bone in a large animal. He made one observation Galileo made observation which is quoted here taken from this reference dialogues concerning two new sciences.

He says that the large animal bones look bulkier compared to their length aspect ratio is quite reasonable whereas the bones of small animals in the same body part let say in a leg it looks much slender why is that, why is the proportion changing from length to the area of cross section in small animals and large animals. We can answer this question from the mechanics viewpoint as we will see.

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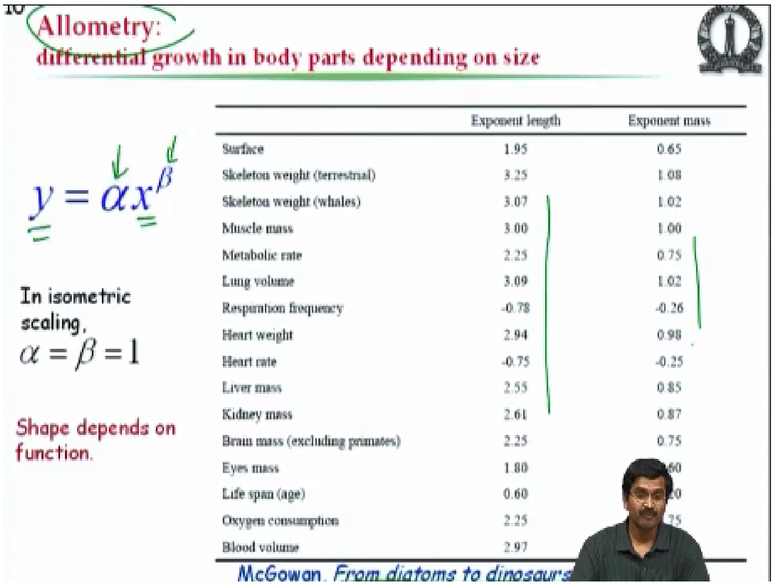

And this kind of analysis is actually there in almost everything not only in nature scaling analysis, but also in engineered structures which goes into the name of Allometry differential growth in the body parts or even engineered things depending on the size. So they say that everything let say a parameter X if you take it is going to vary with an exponent better and there will be some proportionate constant alpha as if we take X as the size a different sizes Y will vary.

So they have given this exponence in this particular thing a nice book by McGowan from diatoms to dinosaurs the reference if you want to look up more on this topic how surface area changes in the biological things exponent is 1.95 almost to as it should be and heart weight, heart rate, liver mass they all have different exponents and for the length as well as for the mass.

So this Allometry also helps and one can do this allometric things for pressure sensor compare the large scale ones and the small sized ones and then see that they also satisfy allometric relationship such as this one.

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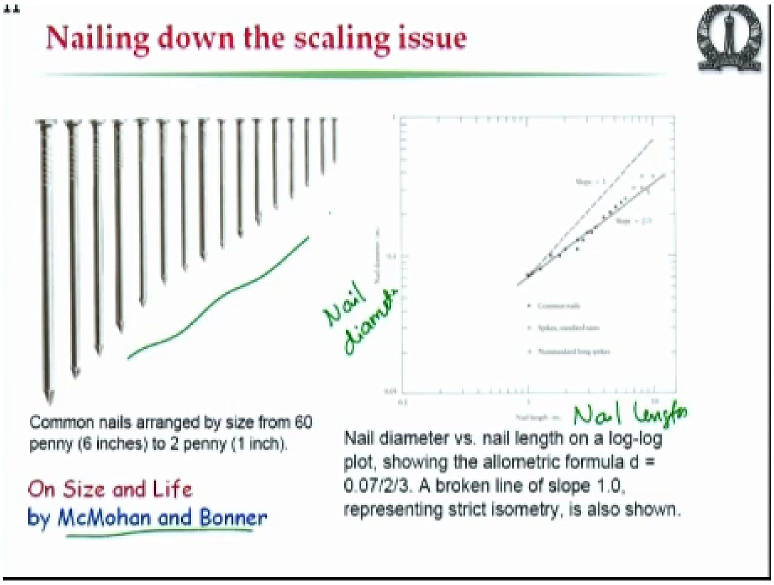

This allometric relationship exist for nails also. If you look at the diameter of the nail compared to its length it is not linear. So if you plot it, it is actually a log-log plot which you cannot see very well. This is the nail length and this is the nail diameter. This are log-log plots. So if something is linear log-log plot actually it means that there is exponential relationship in reality for the normal thing.

This again another nice book on size and life by McMohan and Bonner where they say that even for engineered thing such as nails there is allometric relationship. So there is a scaling law involved in things that are made in different sizes.

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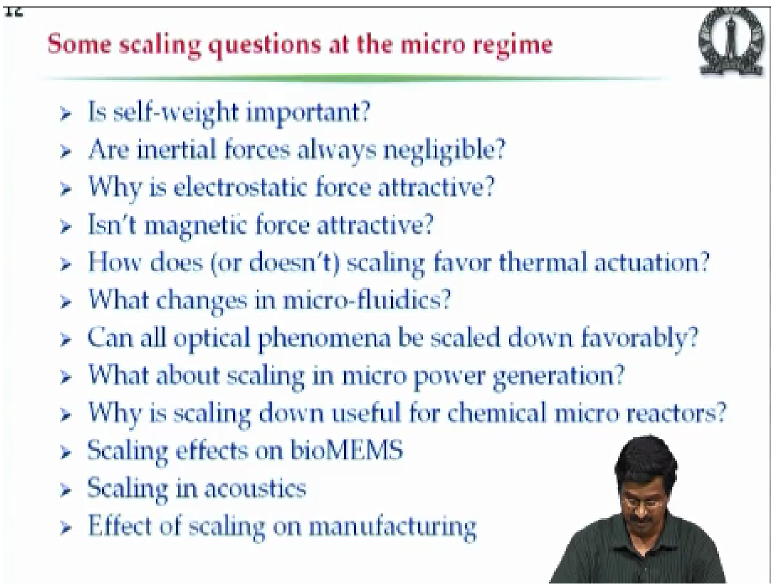

Now we will first post some question and answer them now. The first one is when you think of micro systems should we worry about the self weight? Civil engineers you know have to worry about self weight, but should micro system design as worry about self weight or inertial forces always negligible. Why is electro static force attractive and how about magnetic force is it attractive and thermal actuation is it favorable or not and micro fluidics.

We have one lecture on the fluids, but now we will see some more examples of modeling issues in fluids as it pertains to micro systems and optical phenomena. Optics and micro systems go very well hand in hand, but there are places where miniaturization does not make sense in optics at micro scale and we will look at power generation and whether the scaling is favorable there or not and chemical and micro reactors.

So what does scaling mean there and biological applications and acoustics and even manufacturing and power and so forth.

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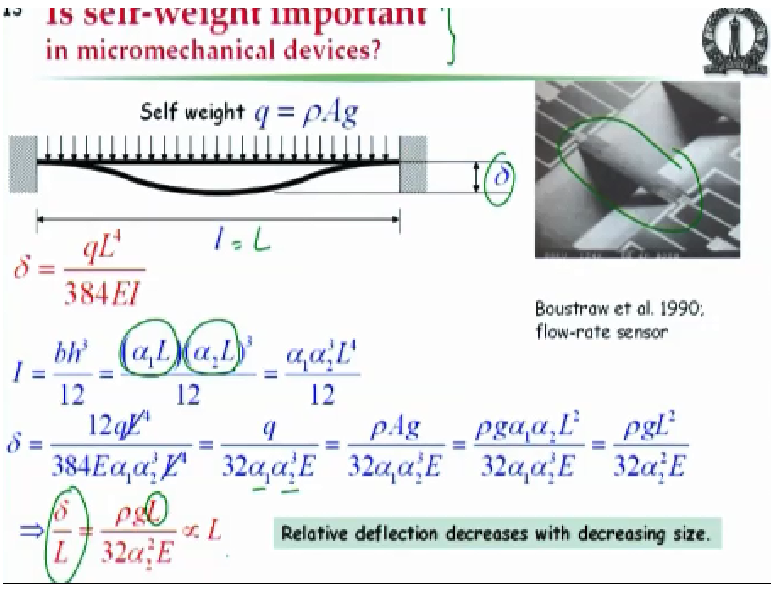

Let us start with the first question. Is self weight important in micro devices? Let us say I am making a bridge like this anisotropically (()) (15:44) and there is a bridge over this should we worry about self weight in this case. So here we show that delta is equal to some formula that we know from strength of material or from Castigliano's Theorem that we had discussed in the earlier lectures. So if I try to get this delta as a relative deflection by dividing it by the size L of the beam here.

This is the deflection relative deflection due to its own weight and we see that it is proportional to L all others here alpha 1, alpha 2 are proportionately constant. So B is alpha 1 times L and age is alpha 2 times L. So it depends on alpha 1, alpha 2 and finally we see that relative deflection is proportional to size that means that relative deflection decreases with size. If I look at there is a beam of 1 meter length and a beam of 1 micron length.

The 1 micron one is going to have much less related deflection. So that is if I divide this delta deflection by this L then I would see that it does not L on capital L and these slide are the same that little deflection will be much smaller when you consider micro world. So you can say that self weight does not matter so much when it comes to micro systems devices, but then is inertia force because weight is inertia force can it always be neglected.

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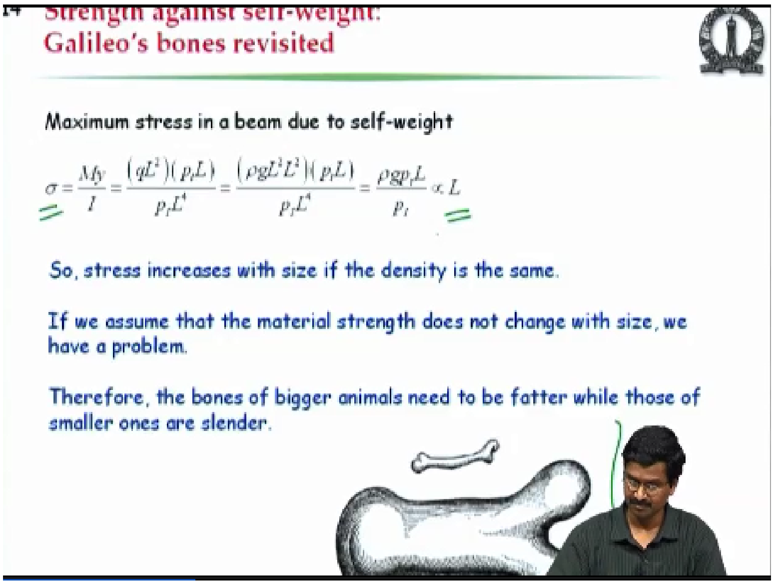

And before that let us come back to this Galileo's bones and then see whether Galileo was right in his observation that large animals have bulky bones as well as small animals have slender bones. He looked at in fact in his passage. He refers to the strength because generally if we take bones whether it is a large and small animals the strength is not going to vary much. It is the same bones and bones strength will be pretty much the same, but he observed that the stress is proportional to the size.

That is a duly self weight. If an elephant is standing on his 4 legs it has to hold the 4 legs have to hold its weight and the same thing is true with the mouse, but then this stress is proportional to the size meaning that if you say from mouse to elephant it is a 10000 let say factor in term of its height. Now the stress in elephant is going to be 10000 times more than what is there in the mouse.

So you have to have bones of elephant much bigger and bulkier than that of mouse and that is what is the scaling argument that tells us when you design something at micro scale you have to keep in mind the scaling argument. Otherwise we could make mistakes. If you say that the self weight which is an inertia force is negligible. We do not need to worry about it at micro scale, but what about other inertial force or like centrifugal force.

If something goes let say spinning there will be centrifugal force on it in the context of their scopes we have discussed that, should we worry about this inertial forces that come because of rotation structures, structure that are rotating.

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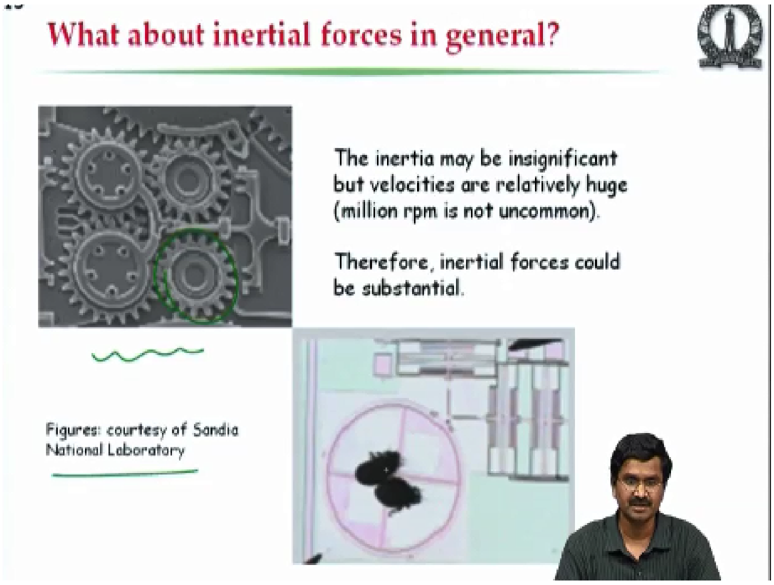

Here is a picture from Sandia labs which is a gear trial. These gears turn at a very high speed even though their weight of inertia is quite small. The inertial force is going to be quite large because the speed is very large. So if you think of this wheel going at a very high speed when these might sit on them then actually fly off because the inertial force is very high on them because of the speed more than their own weight.

So when you consider dynamics which we had a very small introduction in the context of vibrations and resonance frequency and other issues in this discussion modeling, but if you consider the dynamic response in general we have to include the inertial effects otherwise again we get a wrong answer.

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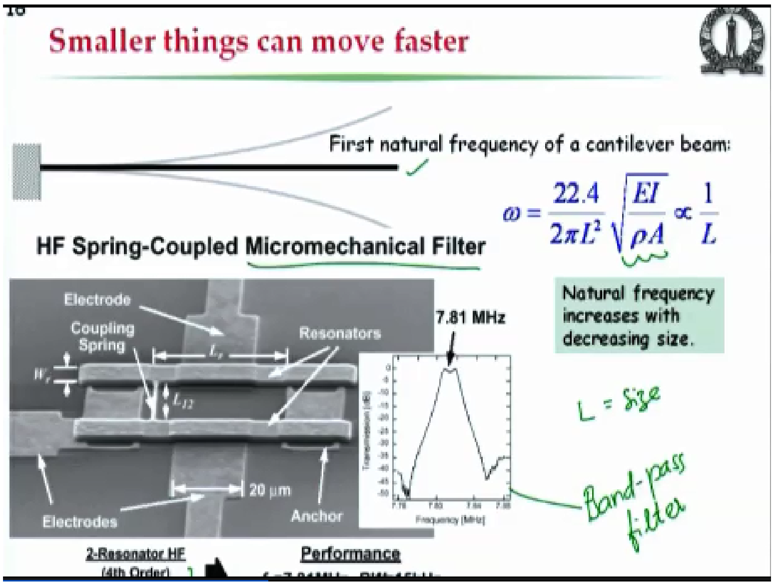

And another thing that we need to remember when you model micro systems is that smaller things move fast, faster than the macro things. It is a everyday experience for us that compared to its body size and ant or any other insect moves much faster than the animals including (()) (20:32) that we know that is because whether it is a solid or a fluid things tend to move much faster at the small scale.

They can be understood by looking at just this cantilever beam that we see here that vibrates like this that is a frequency of vibration that we had taken as a natural frequency and discussed in the context of modeling the vibration effects in micro systems that frequency if we look at substitute the values related to the size. We see that frequency is proportional to 1 over size where L refers to size.

That means that when you go for small scale systems your frequency is going to be large. If the frequency is large things tends to move fast that is the notion of something oscillating if you take. If the frequency is high it will go very fast if the frequency is low it will go slowly. So consequently because of his favorable scaling people have built a number of dynamics devices such as this micro mechanical filter such a band pass filter as shown here.

This is a band pass filter which is a mechanical filter which goes to very high frequency the one that is shown from the (()) (21:56) Professor Clark Nguyen at the university of Michigan, but here it shows that the bandwidth is 15 kilohertz and the base frequency is 7.81 megahertz, but people have gone much beyond that if you use gigahertz just because of this scaling. The smaller you make it the large the frequency becomes.

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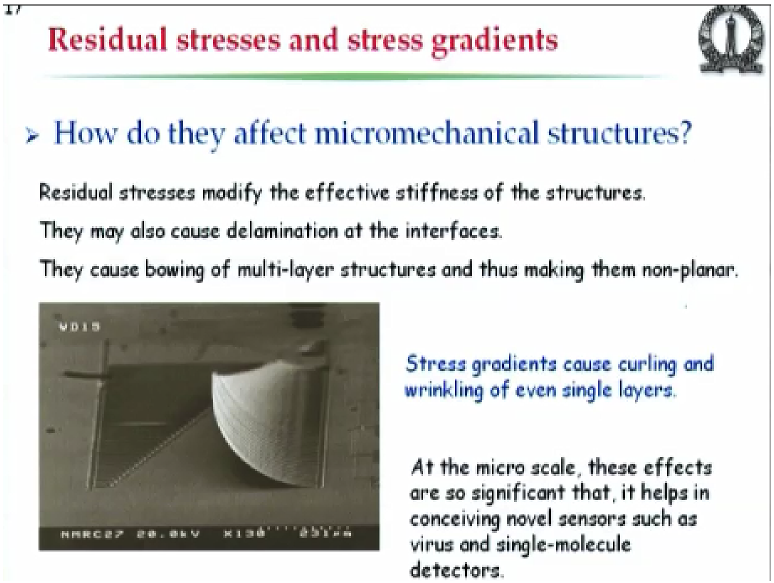

And we have also discussed the residual stress effects in the context of modeling and we said that residual stress or stress gradients are not so important for the macro scale structures whereas for macro scale structures they are very important you can use them to your advantage or when you do not want any bad effects due to residual stress we have to definitely model so that the effect is not felt significantly.

And we had discussed earlier in the context of actuators whether we should go for electrostatics or electromagnetic or thermal or other types of actuations. We have argued that electrostatic force is favored at the micro scale or for the miniaturization and for that we had taken this comb drive or other type of electro static actuators.

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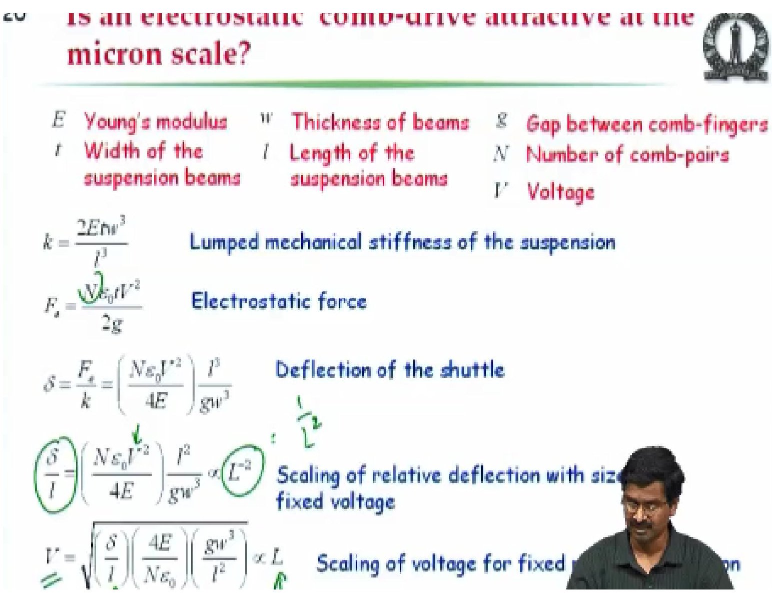

And made a simple calculation. So in the discussion we had on modeling electrostatic we had derived formula for deflection due to electrostatic force. Now we are just recalling that formula for the comb drive where there are number of combs and things going between and this kind of motion we have said that the force is proportional to this quantity there a number is equal to that quantity, number of combs, permittivity, thickness and voltage square.

And this is the gap and now again if you take the relative deflection we find that the relative reflection due to a given voltage, voltage is specified is proportional to L raise to -2 or 1 over L square that is = 1 over L square. That is when the size is small relative reflection is very small, very large because 1 over L square whereas if the size is large 1 over L square is very small so you do not get much deflection.

So if I use electrostatic force at the large scale that the scale that we live in we are going to get a very small deflection relative to the size, but when we make things smaller and smaller we tend to get a large relative deflection. Other way of saying it is that the voltage required to achieve a certain delta/L a relative deflection then that voltage is proportional to the size. The size becomes more voltage is more.

If I need 1 volts at the micro scale to actuate something to get certain relative deflection when I move to let say meter scale I have to multiply by 10 power 6 1 micron to 1 meter then the voltage required become instead of 1 volts here a million volts. Million volts we will not use it as an actuator for day-to-day things. So there is clearly an attractiveness for electrostatic at the micro scale and we had discussed this magnetic actuation. So we will not talk about this again.

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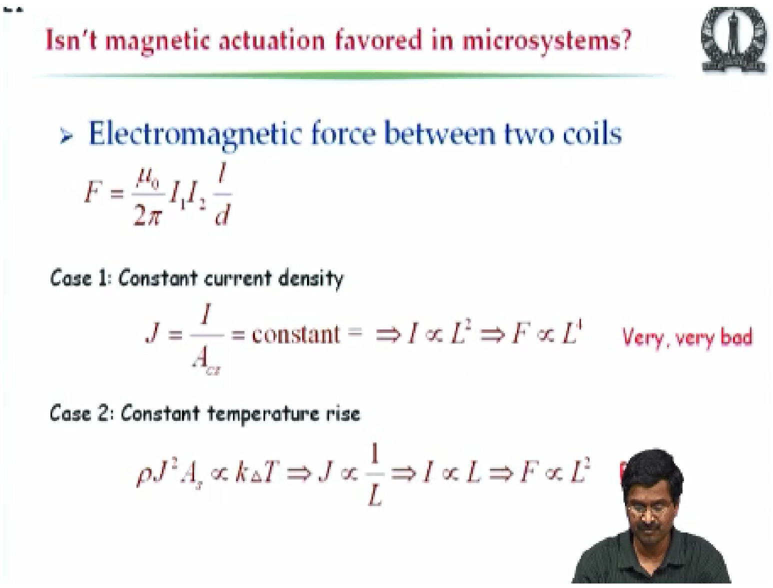

It turns out that if you look at magnetic force between two coils then proportional to the size raise to 4 and R proportional to square of the size which is not attractive for miniaturization.

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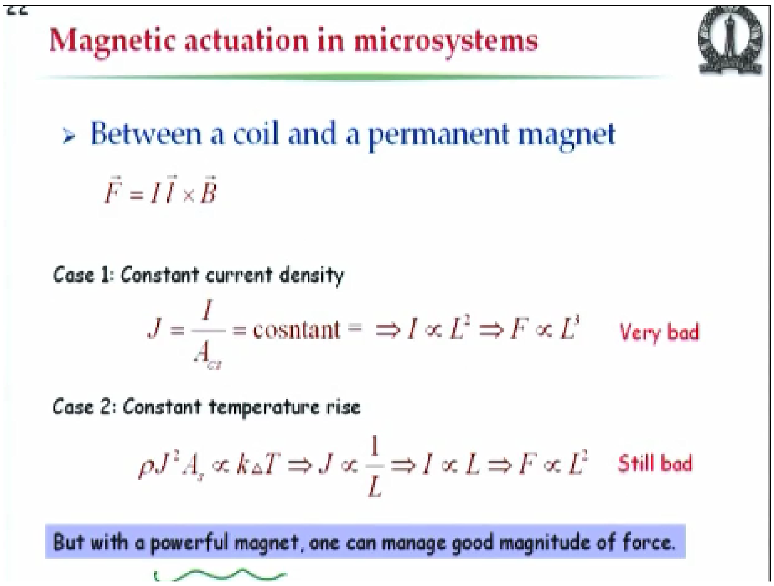

Whereas if we use a powerful magnet then one can manage and get a large magnitude or force with micro things and that is the trend that we see where you put a permanent magnet and put a coil degenerate magnetic field in the presence of permanent magnetic field and you can get some magnetic waste actuation force.

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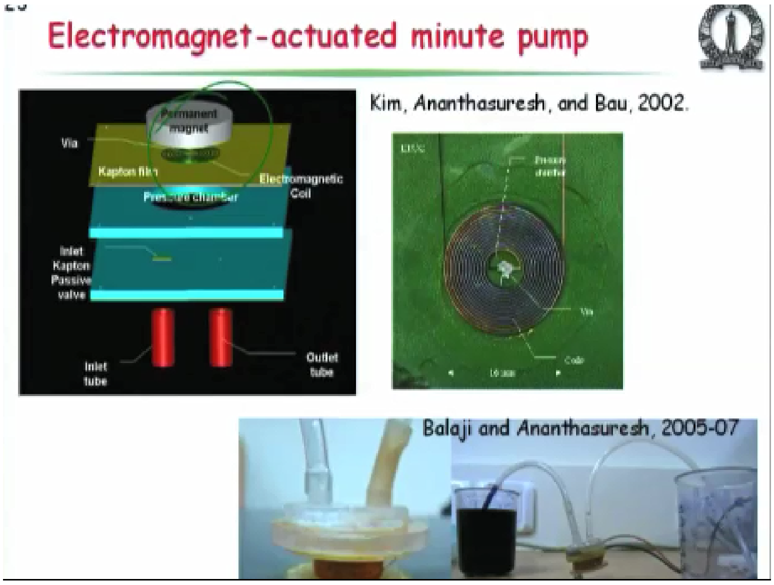

So it does not really scale well, but one can make lot of pumps and valves and so forth such as the ones shown here by using a permanent magnet that is the key to making magnetic actuation work in practice with substantial force.

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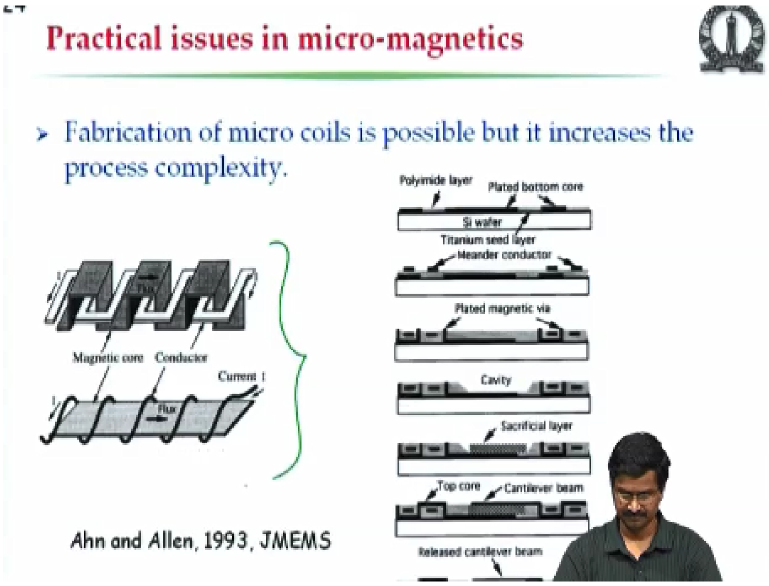

So we can actually make coils as we had discussed earlier with a trick in micro fabrication process topologically equivalent to what is a coil can also be obtained at the micro scale.

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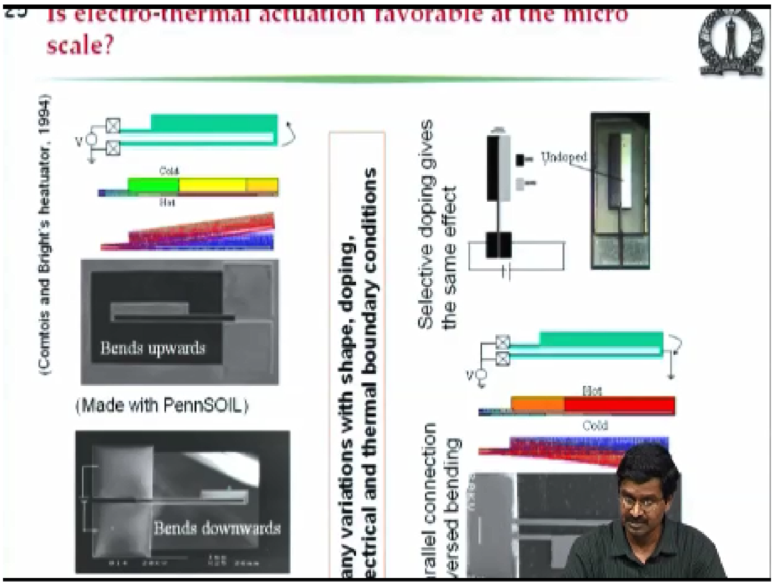

Let say we consider thermal actuator something that we had discussed briefly in one of the last lectures in the previous lecture. Here thermal actuation also has it is favored at micro scale if the absolute force is quite large and it is easy to achieve which we do not use that much at the macro scale other than using (()) (26:53) material.

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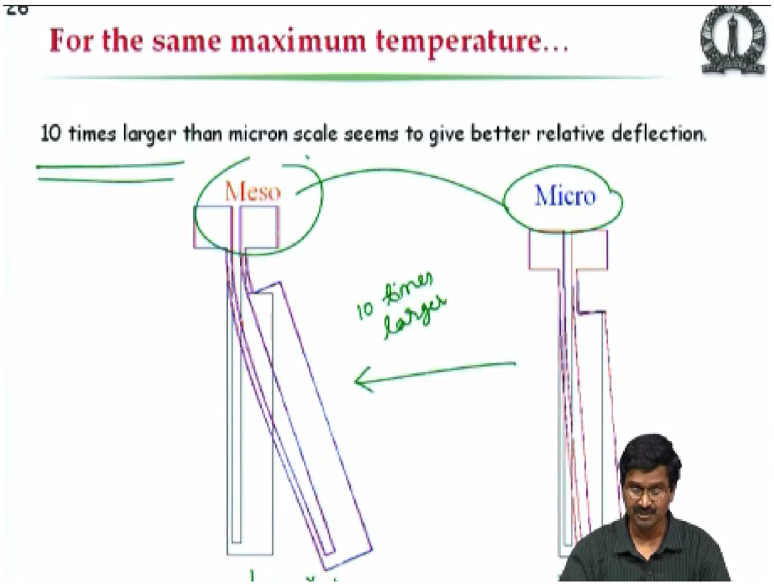

But here as we had discussed this particular device in detail earlier, but one scaling effect that we do not mention then is that if I want to make something thermal actuator 10 times larger than what it can be done at micro scale you get that much more relative deflection at the Meso scale which is a 10 times larger from here to here 10 times larger than the micro scale compared to little reflection here this relative deflection is 10 times more.

So we are now considering the fact that sometimes you do not need to be at the micro scale actually you need to go to what we can call Meso scale that let us say 10 times larger than this. If the maximum size here is 1 millimeter. Here you can go to 10 millimeter centimeter size and you may actually get better performance. There are examples of that kind also you do not need to always miniaturization that answer through modeling.

Here we can do thermal modeling based on the previous lecture you can related to this device where we have different temperature distributions that tell you how this actuator is going to move and by how much it is going to move.

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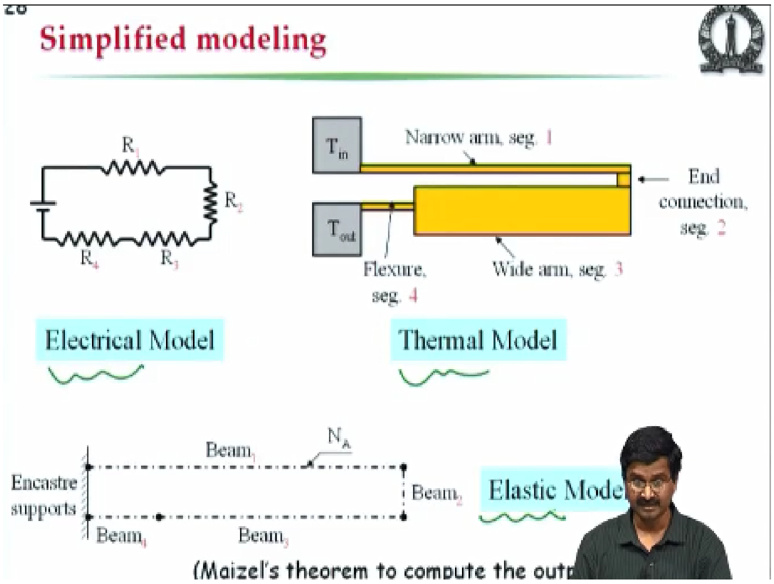

There are modeling techniques for it, very simple modeling techniques both actually electrically, thermally and elastically. Mechanically we can have small models to understand this effects and accordingly design the device. If something is not suitable for miniaturization that should not even be attempted at the micro scale. Now let us discuss a few more things with regard to the thermal aspects.

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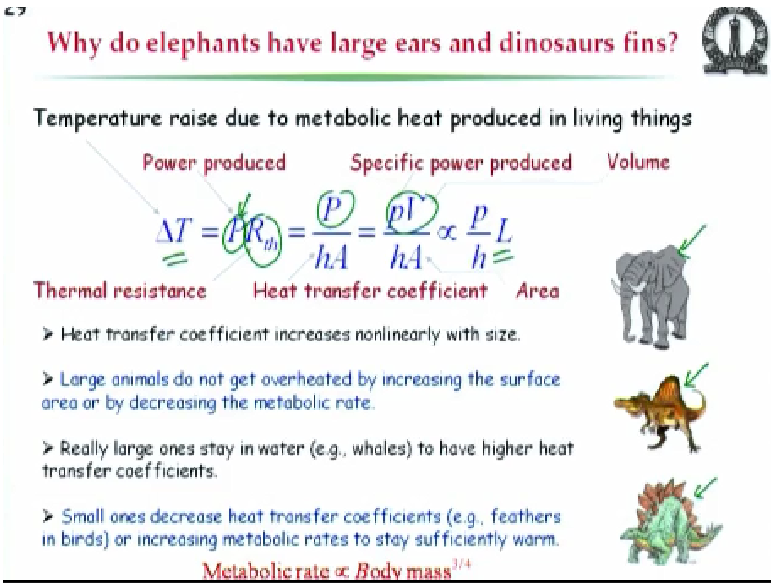

You might have wondered why do elephant have large ears and dinosaurs fins. Why do they have? Large animals tend to have large ears. The reason for that is it has to do with the dissipation of heat because temperature rise due to metabolic heat produced in animals you can approximate it. This modeling is all approximation a good approximation it is the power produced P and the thermal resistance that the animals has and that is equal to the thermal resistance is 1 over HA where H is the heat transfer coefficient.

Because if you are producing heat you need to take it out it is through our skin that it goes out our surface area. So a large animals will have lot more heat generated P the proportional to specific power that they produced times volume of that large animals will have larger PV so larger P. Then HA if the area as we said at the macro scale the volume looks much bigger than areas you do not have sufficient area.

One way to have sufficient area is to have this large ears for elephants and other large animals as well as with fins that are there for dinosaurs. That explains why we need to worry about cooling at large scale at small scale it may not be when it really depends on the application. So we have to look at the scaling carefully. So this heat transfer coefficient in animals increases actually nonlinearly with size.

Here our simple relation based on the temperature rise we said is linear that is not true in practice. We have to take all this modeling more carefully to see how it varies. Large animals have larger surface area in the form of ears and fins and other body features to keep them cool, but small animals have the other problem. They have lot more surface area then the heat that they produce so they lose heat and they cannot be warm-blooded animals anymore.

They will get cold so they have to increase the metabolic rate that is a P has to go up there in order to make the temperature reasonable. So they should not get too cold. So some of these small animals will eat a lot to have the high metabolic rate and that is something that again is given as an allotropic law the size related scaling.

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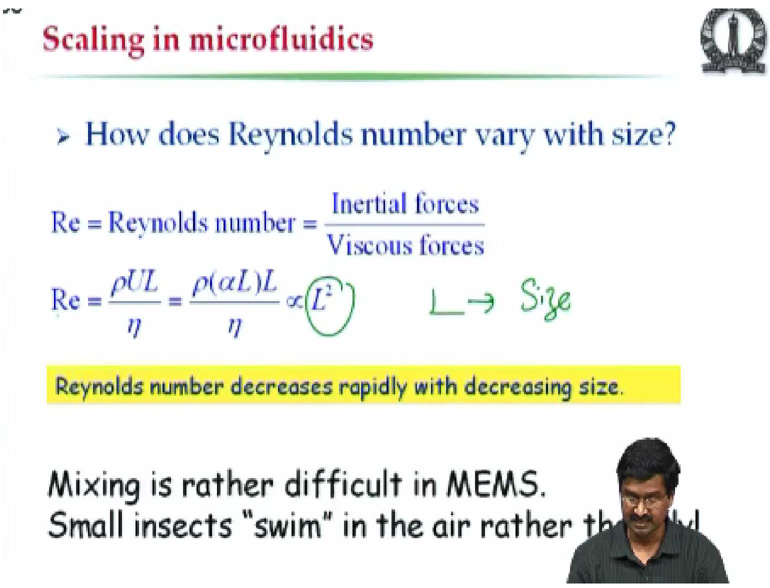

And it is there in fluidics. In fluids normally there are lot of non dimensional numbers which do not have any size related to them, but then the value of that number makes a lot of difference. So one example is the Reylond’s number. It is the ratio of the inertial forces to viscous forces and that is proportional to L square meaning that if L is small the size. So again remember that L refers to size.

If L is small for small sizes Reylond’s number is going to be extremely small. One consequence of Reylond’s numbers being small is that turbulence does not occur. So when you put two liquids together they will not mix very easily. It will go side by side for a very long time and whatever mixing that occurs if we do not any special care occurs only by diffusion. So mixing is a very difficult problem in micro systems.

And in fact people say that insect actually swim in air rather than fly because inertia forces are not big compared to viscous forces and they feel really sticky. It is like swimming through honey for any small insets although we think they are flying in the air.

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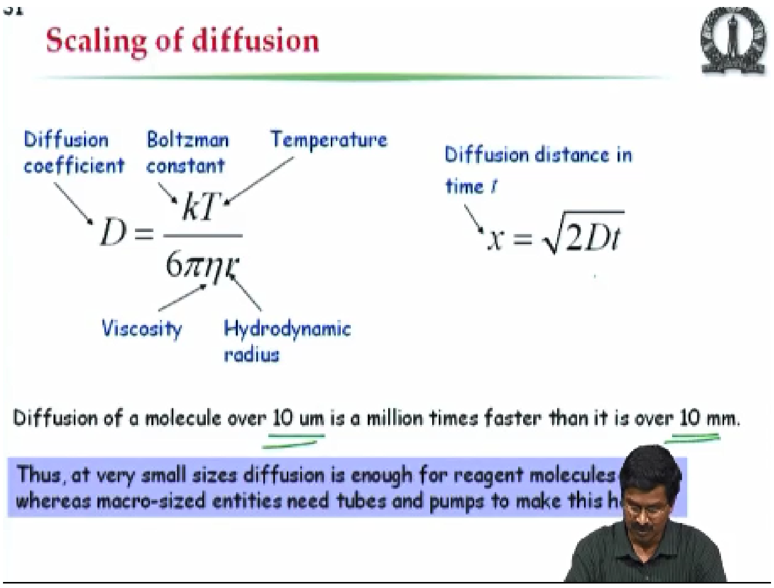

And we mention diffusion. If things were to mix on their own it is because the diffusion between two different liquids (()) (32:56) interface things go back and forth and that diffusion coefficient if you think that depends on Boltzmann constant K temperature viscosity between the property and have dynamic radius. And if you consider the effect of diffusion if you consider a molecule that diffuse over 10 micron distance.

It goes a million times than it goes over 10 millimeter first 10 microns it goes very fast after that it takes a long time for it which is embodied in this formula. You can see here X is proportion (()) (33:33) T, but square root of T and square root of this diffusion coefficient D. So at very small sizes diffusion is enough for simple mixing to occur, but if they have to happen at large distances we have to have some special techniques for stirring things and mixing things at the micro scale.

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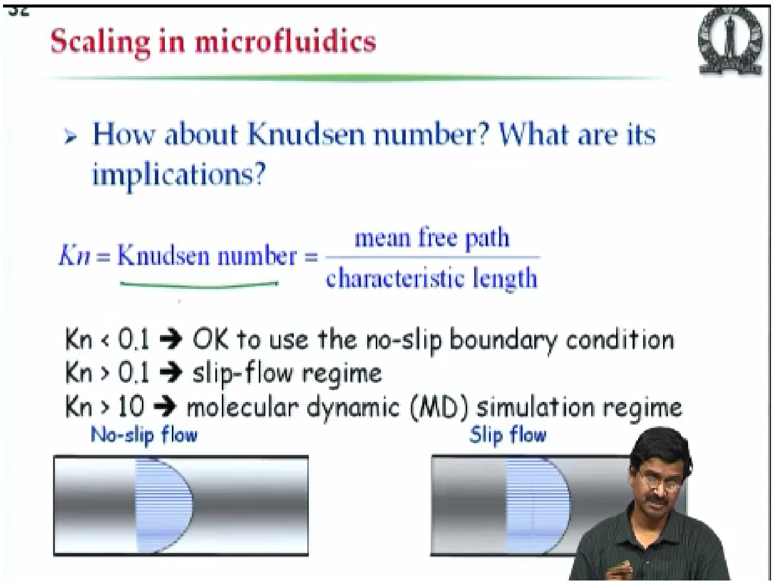

One more thing in fluidics that we had mentioned in the context of modeling fluids is that there is no slip condition. This no slip condition is a very important one that again depends on the a non dimensional number called Knudsen number which is a ratio of the mean free path of the particles. That is the distance average travelled by a particle between its successive collisions with other molecules.

So this Knudsen number if it is very high or very low we go from very rarified things that were used single atom or single molecule based simulation As opposed to very small Knudsen numbers means that mean free path is very small compared to the length or size of the part there we can use this no slip boundary conditions whereas for other ones we have used slip boundary conditions or otherwise modify the fluid mechanics behavior.

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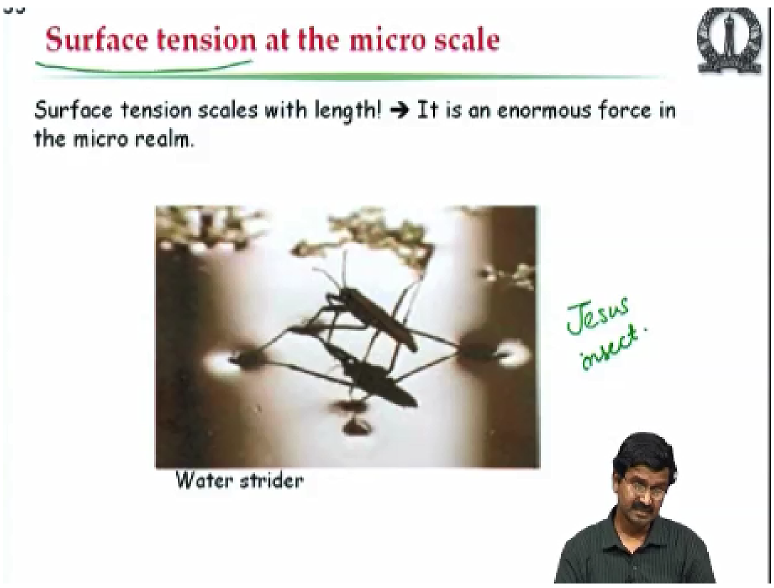

And we had said that any actuation force that is proportional to the length related phenomena is going to be dominating at micro scale and that is why this insect can walk over water. Some people call it Jesus insect because it can walk on water. So this happens because of surface tension at a small scale since a length related phenomena it dominates over the centrifugal force and several others. So the viscosity effects and surface tension affects are very important in fluids.

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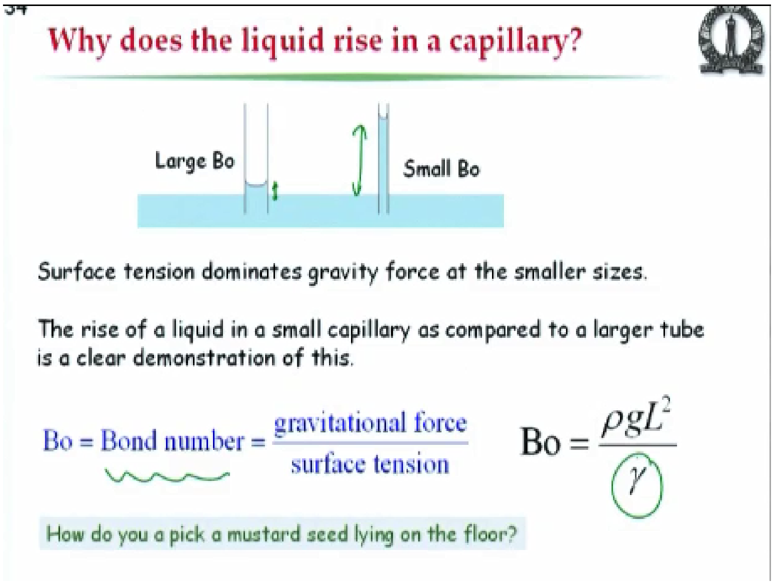

And in capillaries when things rise in a small tube it will raise to a higher height than a bulky tube. Again a consequence of sizing or scaling where we have other non dimensional called bond number which is a ratio of gravitational force to surface tension. If surface tension is high then the bond number will be lower and the scaling effects becomes not so important. But the surface tension related forces dominate at micro scale.

So you can actually make things move using surface tension. To relate to a daily experience if there is a small mustard seed lying on the ground how do we pick it up? We put our hand over the mustard and pick it up it will stick Imagine doing the same thing with the football you have to put may be thick glue and stick the football to a hand and take it up, but whereas just a little bit of wetness or moisture with water can pick a small mustard seed or cuscus seed.

That is happening with actually surface tension force because a small scale not with the football with the mustard seed you have the advantage of using surface tension affect to pick things up very easily.

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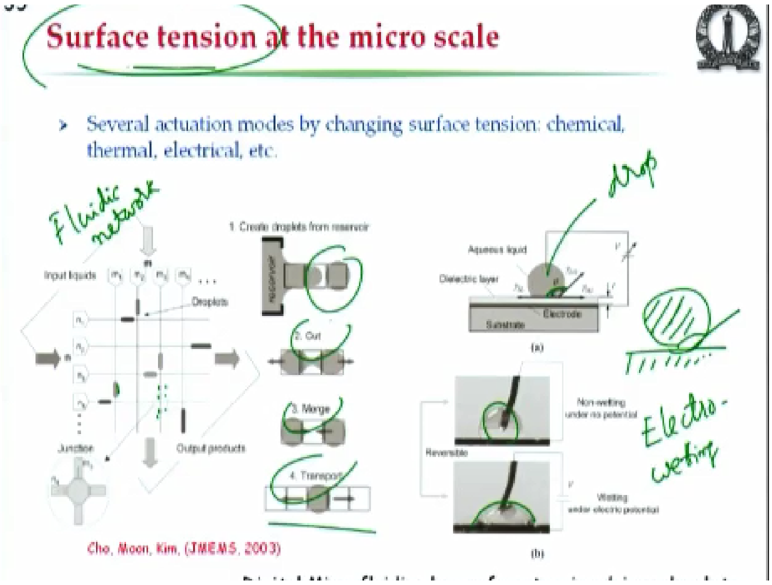

This surface tension being a phenomenon that is proportionate to length that means it is very favorable at micro scale. A number of researcher have used it affectively to move things at the same scale making a pump and a valve is not easy at the micro scale because they are moving members and there are ceiling issues and lot of performance issues, but if you can move it without having to use pumps and values it will be of advantages and that is what several groups have done.

You can look up the papers published in several journals where surface tension is used effectively and here we need to talk about the contact angle. So if I take a sub straight and put a drop this is just a drop of a liquid of some kind it could be even water. If the contact angle which is this angle. So if I have the surface and if the drop is like that only mercury and normal surface will be like this, but even a water can be like this in a hydrophobic surface if I take this angle that is the contact angle.

If that is a large then we have an advantage in the sense that this drop does not wet the surface. And one can actually change this drop takes this shape because of surface tension want to minimize surface tension in the contact angle depends on the drop what is inside the drop and what is there in the sub straight usually need to be like this. Now if you apply either in a electric field or a thermal field this drop might become shrink like it is shown here or can bulge also.

So using this effect of creating drops making them smaller and larger you can have a grid here and make this each of these bubbles go anywhere in the fluidic network that is shown here. This is fluidic network. In this fluidic network, we see that the drop can be moved by just varying surface tension by applying a electric field. This is called electrowetting. So if I take a drop sitting on a sub straight and apply electric field I can change the contact angle what is like make you drop here becomes flatter that means it is flown.

Now if I put these electrodes all across these things and activate one at a time we can make these drops move the drops can be cut, they can be merged then they can be moved. So merging, cutting and transporting all of these things can be done (()) (39:54) to begin with. So you can use this drops to move things around on the chip and that happens only because surface tension we cannot do at the micro scale. So that is really a consequence of scaling.

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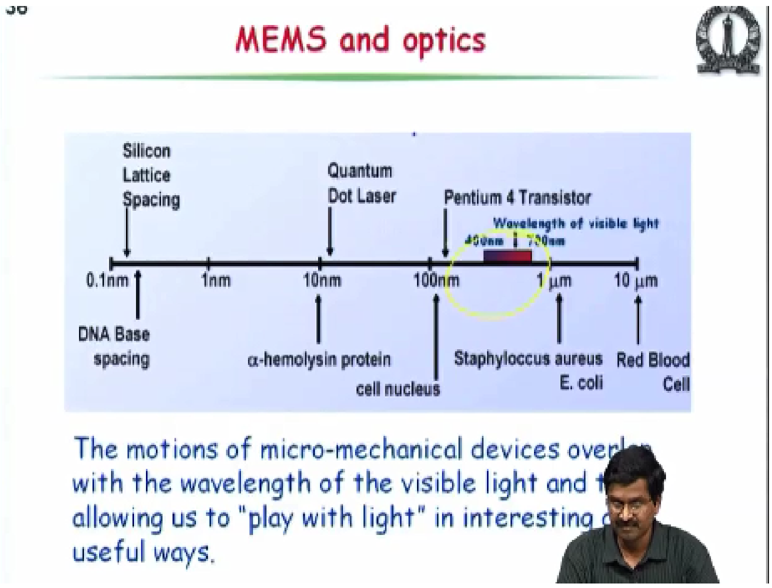

Now if you look at optics. This is let us take a different color. If you look at this, this is really the visible lights spectrum, wavelength it goes from 400 nanometer at point 4 microns to point 7 microns 700 nanometer and that is exactly the range where microstructures can move. So you can manipulate light like it was not done before and there are lot of devices.

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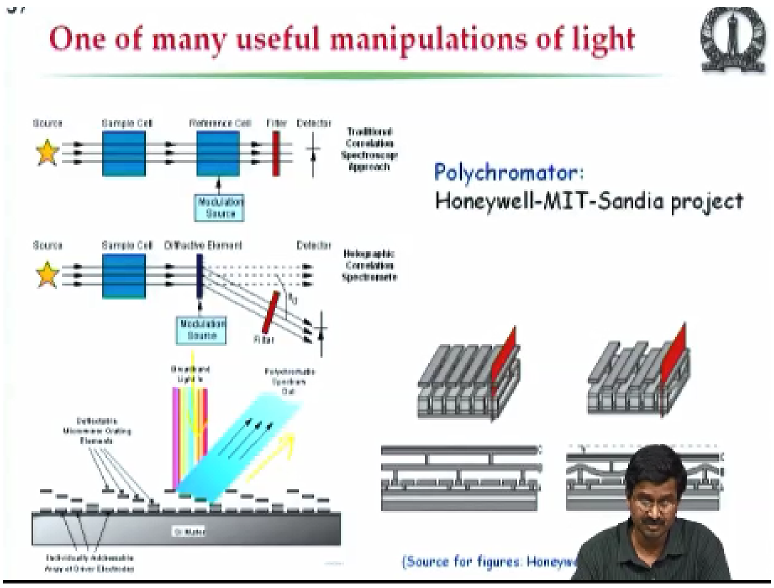

So we had mention this Polychromator application in one of the lectures whereby just moving these beams up and down we can get this interference based way of generating from white light any light of sudden wavelength that you desire. So with that correlation spectroscopy done and that is the principle of this Polychromator.

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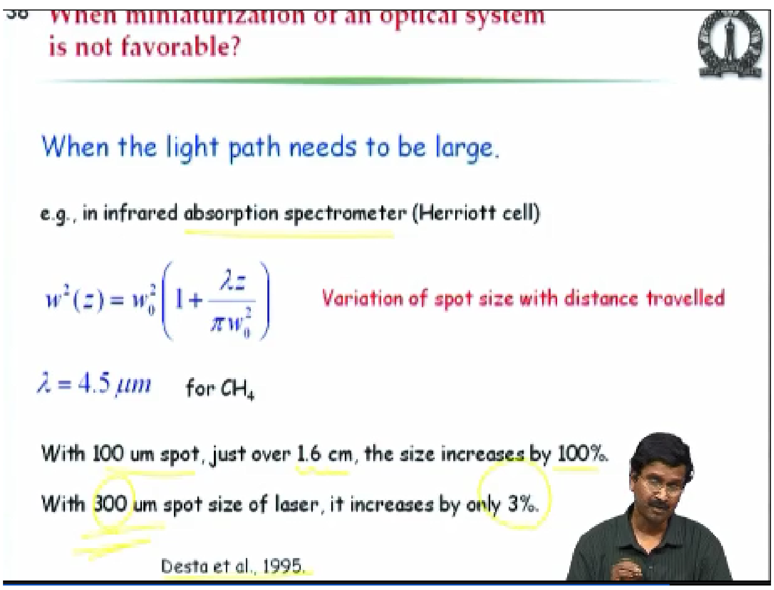

And there are many other examples where optics or MEMS or Microsystems go so well together that there are lot of advantages. But here is an application where miniaturization is not favorable for an optical application. This has to do with an absorption spectrometer that is you send a light of certain wavelength to a chamber that has certain gas that you would like to detect then it goes through that.

This light is observed by the molecules of that gas that you want to sense and that can be detected. So the light has to be inside that chamber for enough time. If we make it small does not have that time so we may not going to do reliably detect. So if we look at what happens if I miniaturize this with some people have tried to do. They found that there are problems. So if you look at a 100 micron spot of laser beam let say just over 1.6 centimeters you can put a lot of mirror and increase the paths inside the chamber that is not a problem.

But as it reflects of one mirror to another mirror and so forth it spot size is going to be diffuse and become bigger if size increases by100%, but if you take a larger spot size it increase only with 3% or the distance 1.6 centimeters. So it makes sense to go for higher spot size here than lower. So it is an example of miniaturization that is not favored in optics it is very rate but there are examples.

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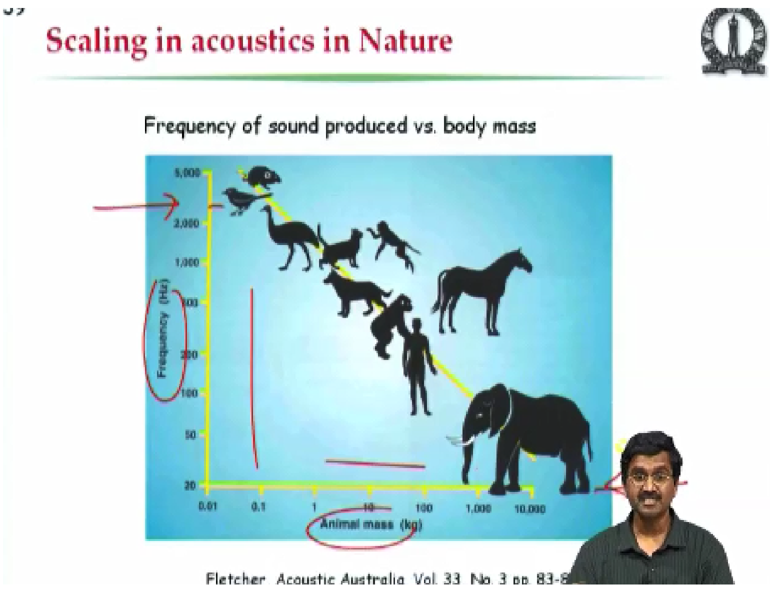

Now when we go to acoustics there is again there are lot of scaling and the way microphones are designed. One has to keep in mind that as you make microphones are micro machines, microphones we have to keep the frequencies and other things in mind. So you see that the elephant trumpeting will be very different from a mouse chip or a bird chip you got a mouse making its own noise. So there are very, very different frequency.

This is low frequency and this is high frequency. We have the frequency on this axis and the animal mass here. Small animals have high frequency and large animals have low frequency. So we have high frequency here and low frequency that has to be kept in mind when we look at caustics.

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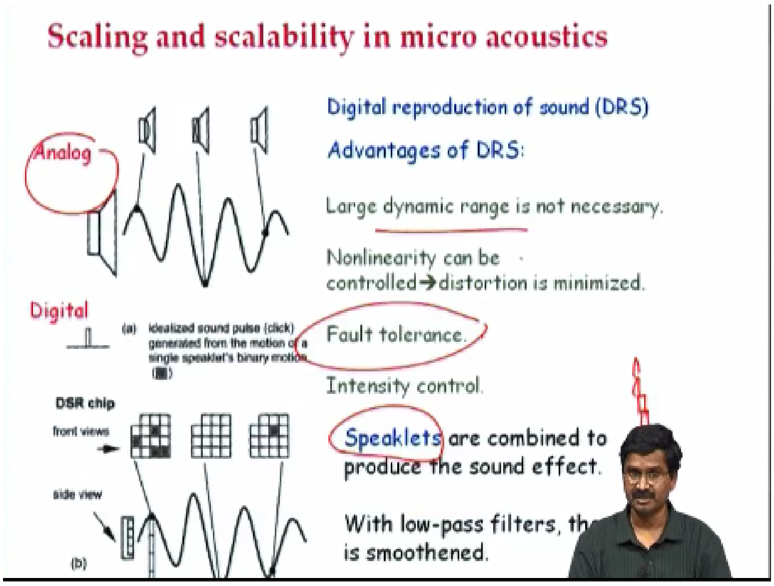

And here is an example where the scaling was exploited with micro systems and this has to do with the digital reproduction of sound. Normally when we say sound is digital it is only in the way it is stored, but not in playing back. Here we normally use this analog micro phones where there is a membrane that moves back and forth as it is shown here to generate a signal it has some problems because dynamic range and bandwidth is not very high and non linearity is a problem.

And fault tolerance because the membrane breaks you do not have a speaker or micro phone and controlling intensity is also not so easy. So somebody came up with an idea that if we have speaklets each of them gives a small sound little quantum of sound. If I want to have 4 times that I will make 4 of these go off at the same time and if I want to have a no sound and make it 0, 1, one of them any of them.

So you get the fault tolerance that was not there here varies with the digital production of sound. Here as again we have array of identical thing doing something useful. One speaklet that is speaker small thing you call it a speaker for a little membrane all other linear range, but they can produce any signal with respect to time. So an advantages of using miniaturization one because you can do all this tricks.

Individual speaklet membranes that can produce any sound of any frequency and amplitude and still there is redundancy and the fault tolerance that comes with it.

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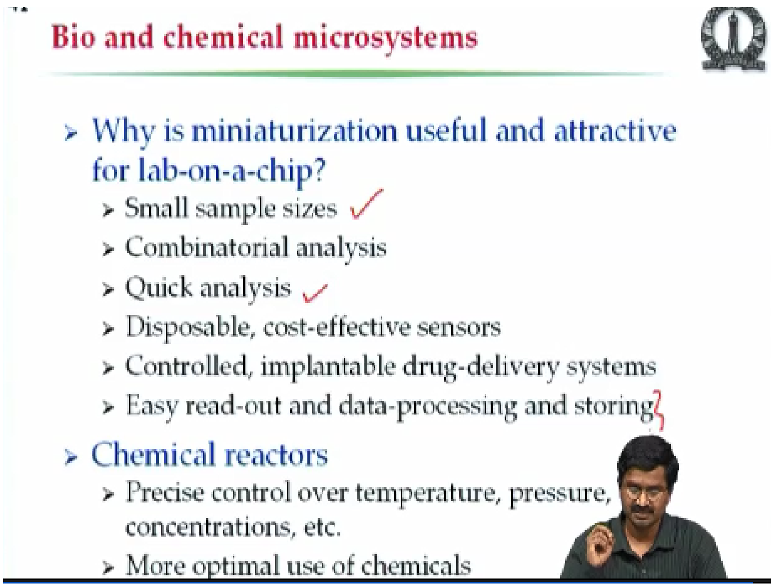

Now let us look at the biological and chemical Microsystems. Why is miniaturization necessary there? One when it comes to biochemical analysis is that you can get away with small sample sizes. So we can do combinatorial analysis that they did not want to see one drug and want to test it on number of combinations of drugs we can do that. And we said that things move faster small scale we will have quick analysis.

We had looked at blood sensor which is a hand health blood sensor which is a commercial device there you can get the result in a matter of minutes as opposed to now going to the lab giving your blood sample and going the next day letting the day you collect the result this will be much faster almost at the point of care that is doctors office itself you would know the result of a blood test.

And cost effective disposable that is another advantage of making things small as we discuss there is an economical advantage because there are small material is there you might as well throw it away then keep it. And drug delivery can be done by implanting and you can have all kinds of integration that can be done when it comes to why you want to be miniaturize chemical and bio reactors.

In chemical reactors if you want to get the optimum rate at which chemical reactions takes place getting precise control over temperature, pressure, concentration other factors that are there is much easier at a micro scale or small size than at large scale. So you can use the chemicals in optimal fashion.

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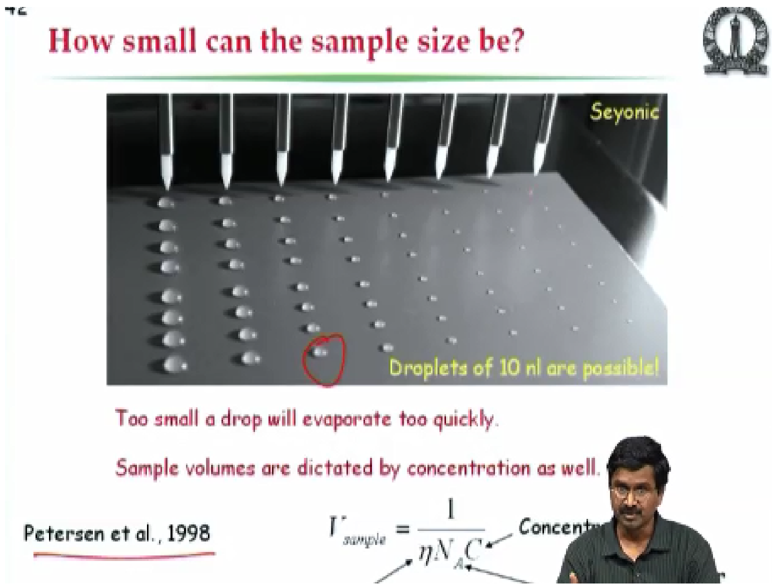

And sample size cannot be too small also. There is a simple calculation that we can do the sample size that you need to take is given by in a work published in a literature. They say that it is one over efficiency of the sensor Let us say that is sudden efficiency that also varies with size. The same sensor mirror large scale, small scale efficiency will not be the same let us keep us that aside. How many species you want to detect something in this small drop that we have here how many if you want to detect a virus how many virus will be there?

That depends on the Avagadro number and the concentration. So if you want to take a V sample that is very small if it is very small then a concentration also is going to be very small. So for a given concentration you are not going to have many species so you might actually miss even it is present and that will be a problem. So we cannot make sample very small. There is advantage in making it small, but too small will lead to problems.

And here there is a small capillary putting all these drop the last rho is quite difficulty you want to photograph the paper says because even before you take a photograph this droplet operate because if you take a small volume because the surface area is more than it is at the macro scale. So it will just lose its moisture or water content and it will dry up so that also needs to be kept in mind. So there are lot of scaling effects what we need to keep in mind in analyzing these micro system.

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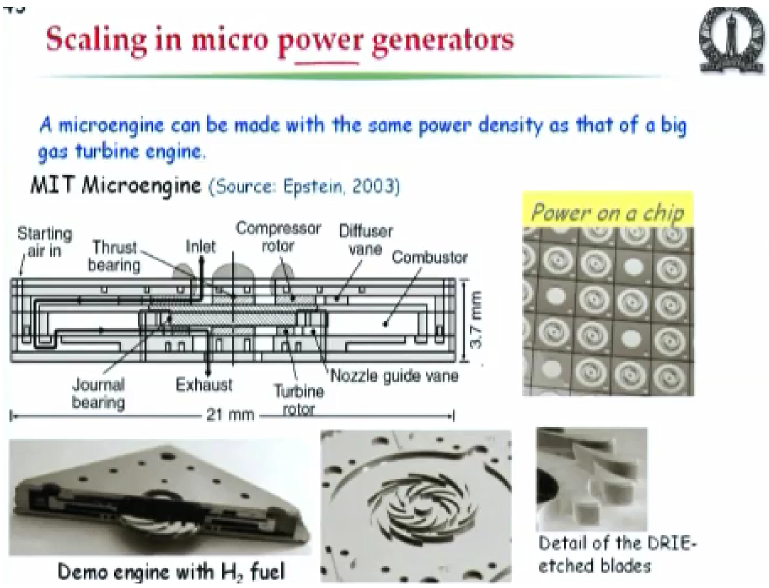

Here is a slide that we had talked very briefly in the context of actuator discussion where today you can generate power on the chip. There is really power on a chip because you have one chip the several chips on single wafer is a complete gas turbine engine that has made on a thing that is like a shirt button size 21 millimeter in diameter 3.7 millimeters thickness something which has a turbine compressor, combustion chamber everything.

So there is a lot of interest now to produce power on the chip with some fuel that is convenient to carry so that we do not have to rely on batteries. Now if we look at miniaturize devices battery occupies a significant size in the device, mobile phone being a classic example because the battery if you remove it feels much lighter and in fact if you can make the batteries small mobile phones can be made much smaller than what they are today.

So if we can generate power somehow or come up with a fuel for the power this one is hydrogen is a fuel. Some other fuel it is much lighter that you can carry and put it there is a engine right on the device to produce the needed power that will be very interesting and that particular aspect that is this designing power generation on the chip requires modeling that is very, very sophisticated.

And it would not have been exaggeration to say that it is as sophisticated as the designing a Pentium chip or MD chip that does this fantastic computation that we see on the computers today.

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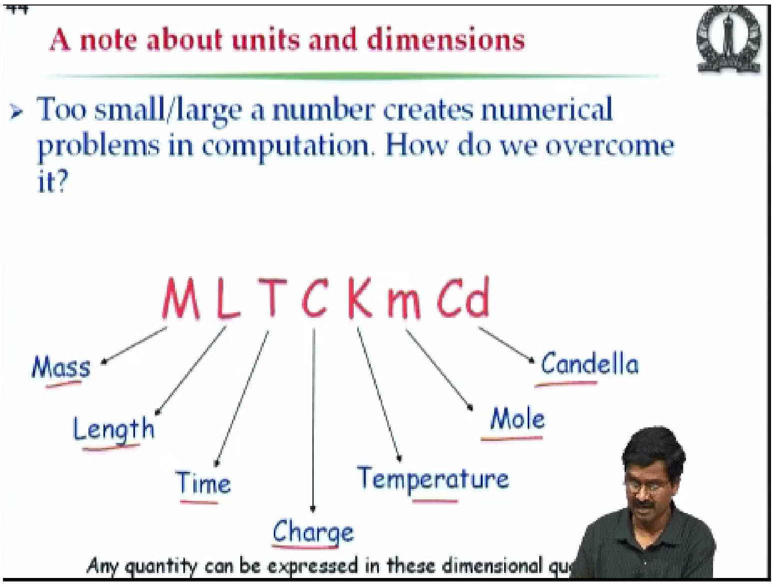

And finally we said that we will discuss the units that we need to use when we do calculations or when you model numerical calculations of the micro system modeling. So if you take a meter as a meter or a micron as 10 power -6 meter you have to put in a very small number into the computer and that might make when you square it cube it for example in width if I take moment of inertia goes as let say depth of the beam cube.

Depth is taken in micron that is a5 micron we have put 5*10 power -6 that raise to cube it will become 125*10 raise to -18 which are very small number and if we multiply another small number that will be round off errors, truncation errors. So we have to use appropriate scaling for the length and the best way to do that is to go to dimensions. There are 7 fundamental dimensions the mass, length, time, charge, temperature, mole and candella. Mole for the quantity of atoms molecules and candella for light.

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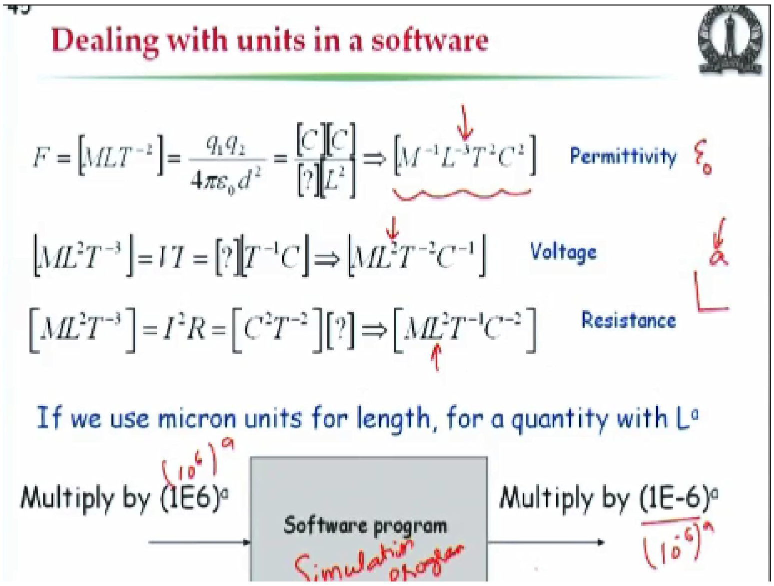

So now if we take any quantity and express in terms of this dimensions we will know our interest is to see how we depends on the length if I take let say permittivity that is epsilon 0 because I would decide that let say microns I will put 5 micros as 5 numbers in the computer then what factor do I put for epsilon 0. The best thing is write down what are going to be the dimension epsilon not in particular for the size (()) (52:18) -3.

That means if you put something to be in micron as the unit then you have to multiply this by 10 power 18 because it is L raise to-3. Similarly, voltage will be the size is L square if we have let say one old actually you should put it as if you are doing the scaling of the length by a factor of 10 power 6 you put it as 10 power 6 raise to the power of 2 or 10 power 12 as a voltage.

Similarly, resistance has again L square. So 5 (()) (52:58) will become 5*`10 power 12 because if you are scaling the length by factor of 6 that has to be done. So you have to multiply whatever that L raise to A whatever that A is for when you write the dimension for other particular quantity when you put into the software program or any simulations program you have to multiply by this factor 10 power 6 that is what you are doing.

10 power 6 raise to A you have to multiply and put it in when you take it out you have to do 10 power -6 raise to A so that your calculation should be correct. Deciding the right scaling factor scale factor when you do computations is very important and some of the software programs do it on their own it is always good to watch out so that we do not fall as a pray to numerical truncation and the round off errors.

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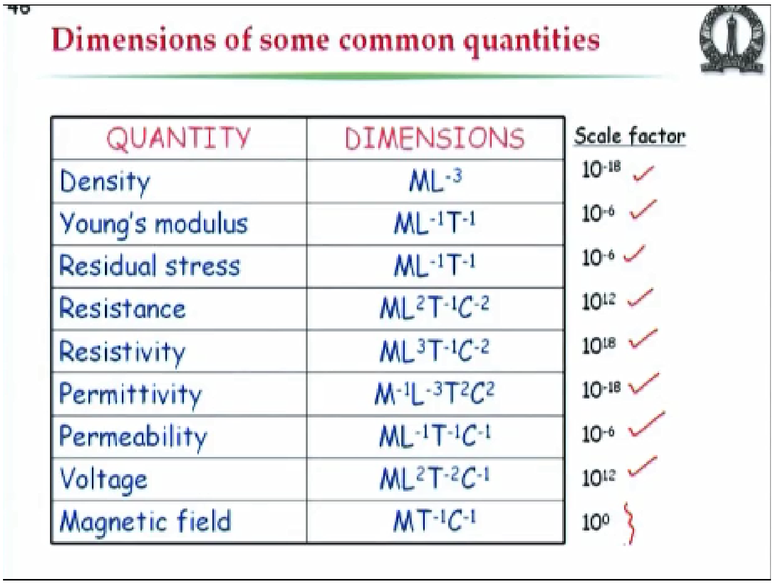

Dimensions of some common quantities

QUANTITY	DIMENSIONS	Scale factor
Density	ML^{-3}	10^{-18}
Young's modulus	$ML^{-1}T^{-1}$	10^{-6}
Residual stress	$ML^{-1}T^{-1}$	10^{-6}
Resistance	$ML^{2}T^{-1}C^{-2}$	10^{12}
Resistivity	$ML^{3}T^{-1}C^{-2}$	10^{18}
Permittivity	$M^{-1}L^{-3}T^{2}C^{2}$	10^{-18}
Permeability	$ML^{-1}T^{-1}C^{-1}$	10^{-6}
Voltage	$ML^{2}T^{-2}C^{-1}$	10^{12}
Magnetic field	$MT^{-1}C^{-1}$	10^{0}

So there are these scale factor that we have for density, Young's Modulus, residual stress, resistance, resistivity and permittivity. Permeability in the case of magnetic and voltage we have already discussed and magnetic field which does not depend on the scaling which goes back to the point that we had made in the case of magnetic actuation or if use external permanent magnet it actually makes sense to make things at the same scale.

So it comes out from a dimensional analysis that we show here.

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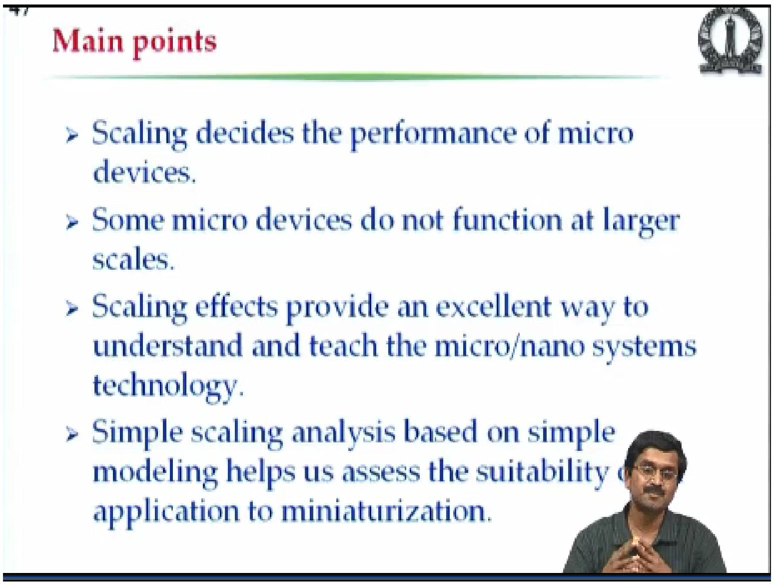

To summarize what we have discussed scaling decide the performance of micro devices and some of these will not work if they are made larger, but many of them they are going to perform better because of miniaturization and another thing is that the scaling effects provide an opportunity to look at modeling in a very insightful way. It is an opportunity to learn modeling of electrostatic or other coupled systems at micro scale as well as understand the scaling effects.

And answer the questions what happened when you make something very small and in this modeling lecture that we have discussed in the several lectures in the past few lectures of this course we discussed the coupled modeling because when it comes to micro systems several energy domains interact with each other and that leads to certain challenges in simulation and we have discussed just a little bit I must say because this is introductory micro system course.

We have just seen the tip of the ice fall there is a lot more to be learnt in the modeling, but one thing to remember is that we have to know the domain knowledge strength of material you have to know, fluid mechanics we need to know, electrostatic we need to know, electromagnetic we need to know knowing all of that is difficult. Yet we have to make an effort to understand the basics and put it all together to have a complete understanding to micro systems.

Before we model and stimulate and eventually design make and test the device. Thank you.