Micro and Smart Systems
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Lecture - 25
Finite Element Method and Microsystems

Today, we would be talking about introduction to finite elements and it utility in MEMS design and manufacturing. Microsystems are quite complex the analysis and design of this requires a tool and finite element is one such tool that can be used so in next series of lectures about 6 of them we would be talking about finite elements its basic science and theory, Now the question is what is finite element so finite element is a computer aided tool to solve complex equations involve calculus.

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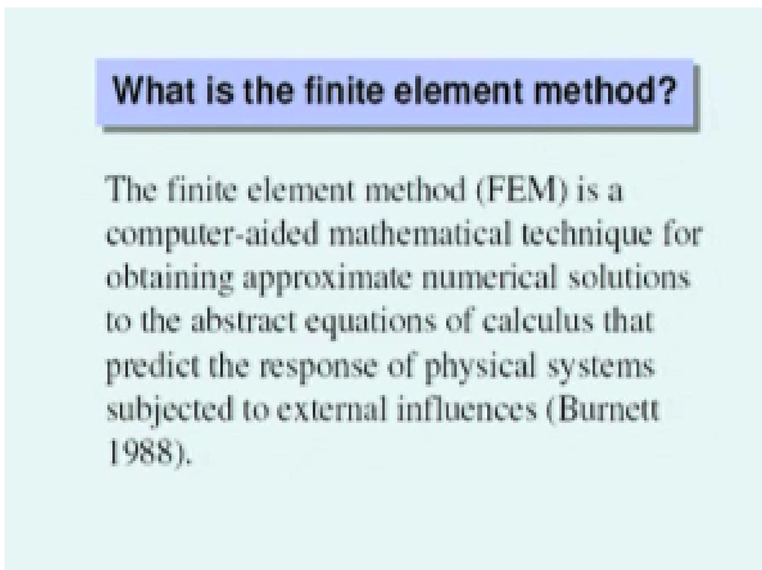

And finding out response of this physical to system subject to some external influences such as loads currents etc.

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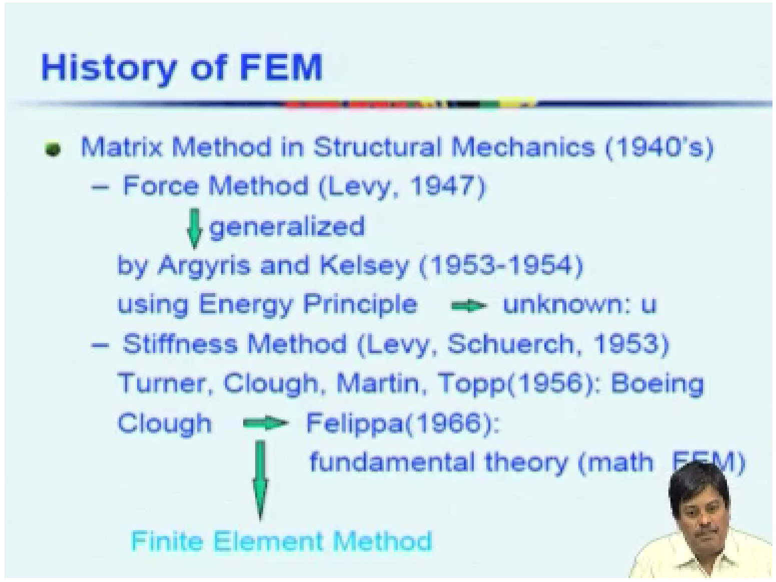

Let us go into the history of finite element method, the finite element method were started by civil engineers as a part of the structural mechanics problem solving, it was initially developed by John Argyris from Germany and Levy as early as 1947 to 53 and then the method was called stiffness method but by Turner and Clough in university of Berkeley and that was the starting for component element method.

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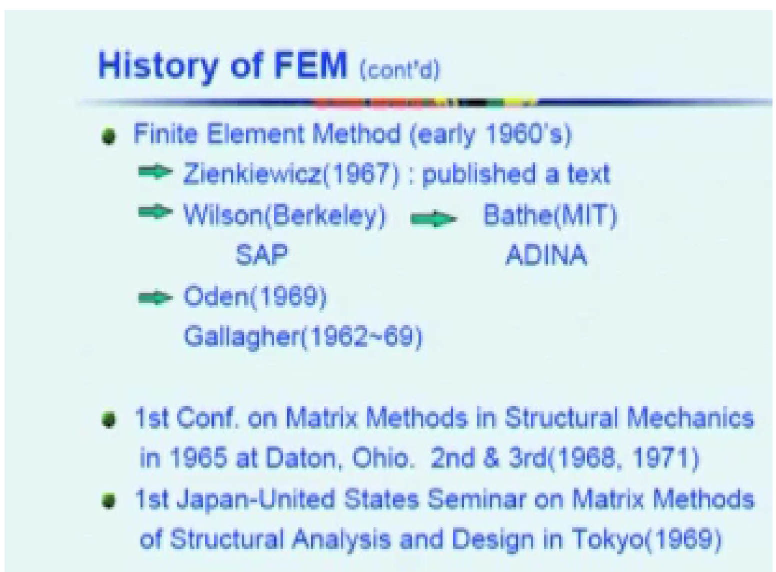

Since then rapid advances were made on the first book was published in 1967 by a single it and there were many pioneering works in this area was made by Zienkiewicz, Wilson, Oden, Gallagher and many such people many commercial packages had came out starting from this the works of these people the first conference was organized in FEM in 1965 Asia, in Japan, United States seminar was organized in 1969.

Since then there was a rapid progress that has been made and many standards were developed for finite element and it has become a tool as a design and analysis tool for very many areas of engineering and science.

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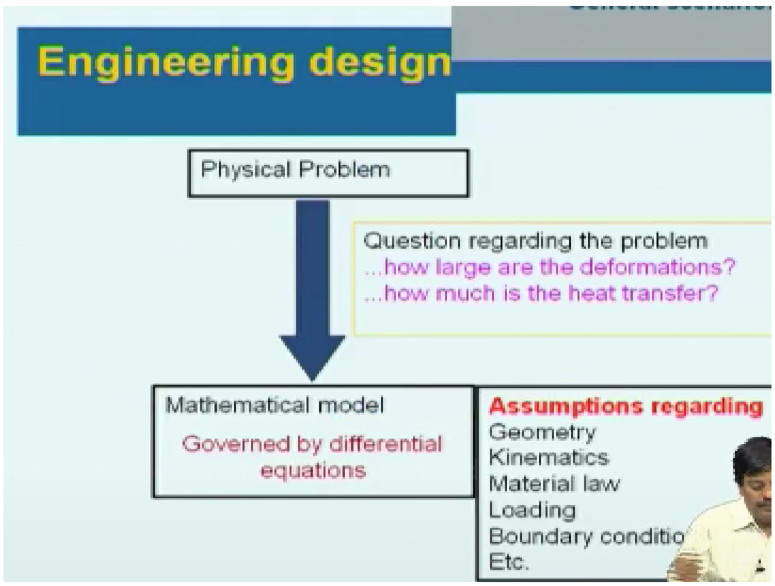

Now coming back to the whole concept of engineering design, we have a physical problem and the physical problem, we are requested we are required to find answers for example, How large the deformation in a structure? How is the heat transferring? What is the level of capacitance in a circuit? What is the level of vibrations in the mechanical system? So in order to solve this physical problem first of all we need to come up with a mathematical model.

And these mathematical model has to be developed based on certain assumptions regarding its geometry. The kinematics, the material law, loading, boundary conditions and many such parameters, so based on this we develop a differential equation that requires to be solved.

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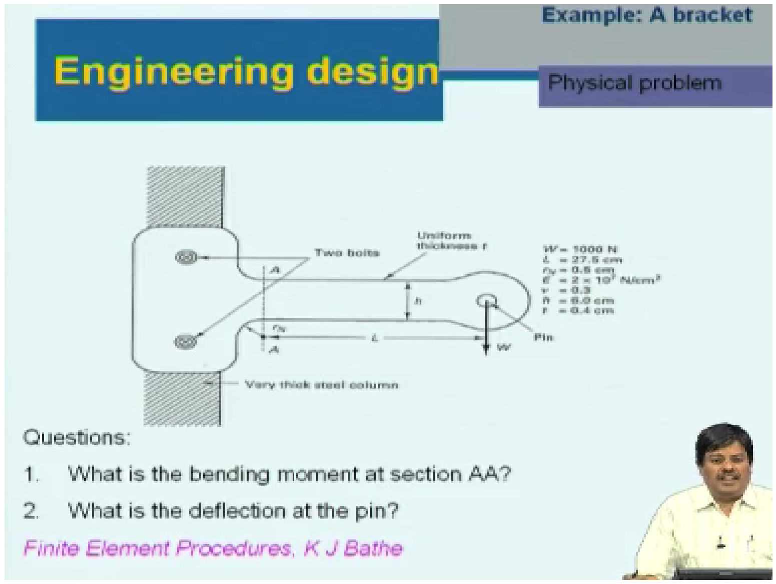

Let us take an example of a simple bracket which is found in many mechanical engineering systems and this bracket we are now required to find what is the bending moment at section AA, we know the beam theory beam theory was developed way back and using the beam theory we can really find out what is the bending moment by taking the product of the load and the distance and we also want to find out what is the deflection in a beam. We still have a beam theory here, so we can use the beam to beam approximation to find out.

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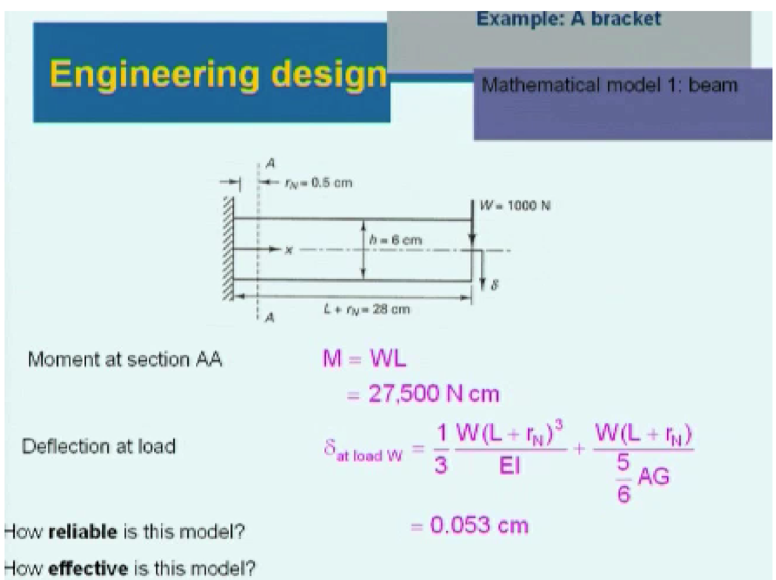

Let us see what we get here, so as is said by taking the product of the load on the lever on distance which is the length of this section they can find the bending moment and we can take the tip deflection from our strength of material and we can find out this is nothing but W into length cube/3/ flexural rigidity here and we also had the shear deformation of proximation which is coming from this stuff. So if you take the sum of this we can get the deformation.

Now the question needs to be asked is, how reliable is this model? Is this what we get in the actual structure? How effective is this model? So in order to understand this we need to introduce some more sophistication into this model.

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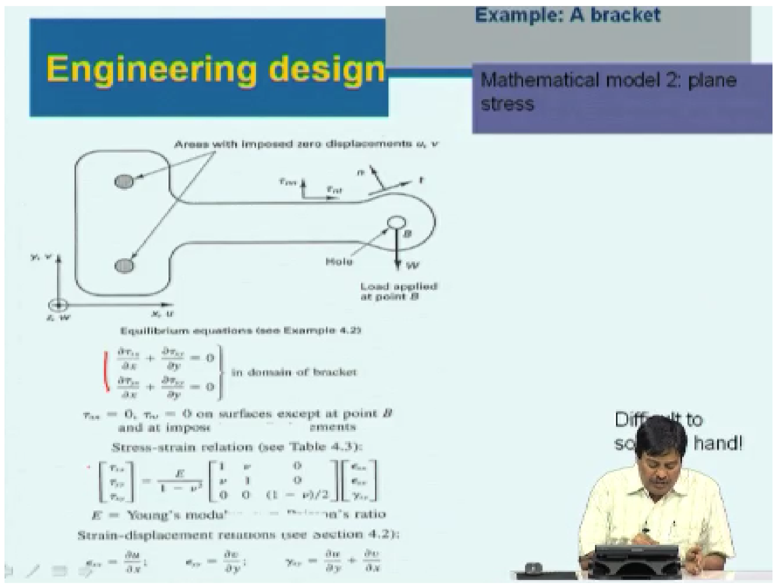

So we introduce the theory of elasticity which is a complex system of differential equation given by the equations of equilibrium and they constitute a model and this joint displacement relation if we use this and solve if at all we solve that we can get a better approximation than to the crude beam model, but solving this equation is not trivial exercise in fact it is not possible to solve many such equations exactly.

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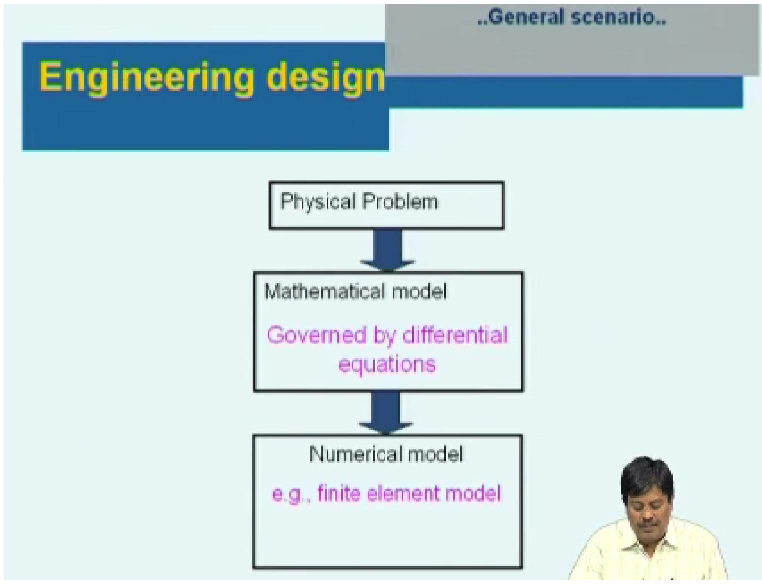

So now the question is once we develop a mathematical model in terms of a great differential equation we need to solve, so we need numerical method and finite element method is one such method that we are going to solve.

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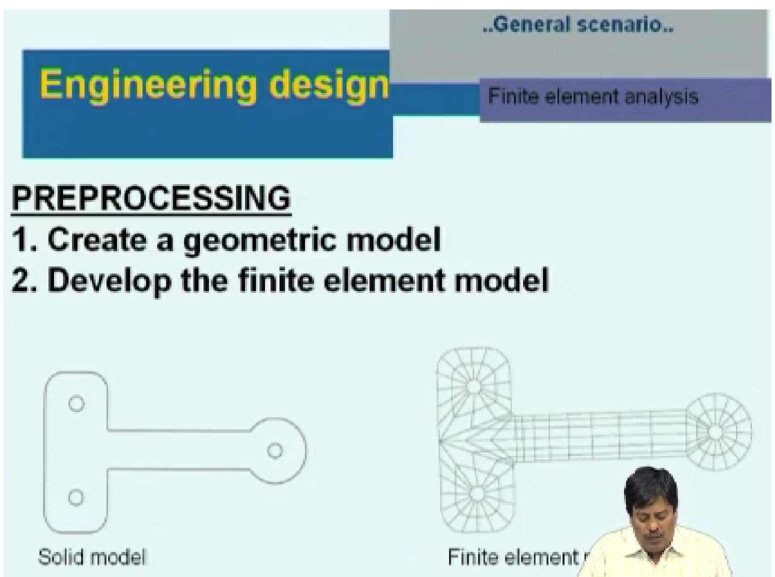

So what does the finite element do? It creates a geometric model and this is a solid model of a bracket and this is a finite element model. So it decomposes the entire domain into many subdomains which are connected together.

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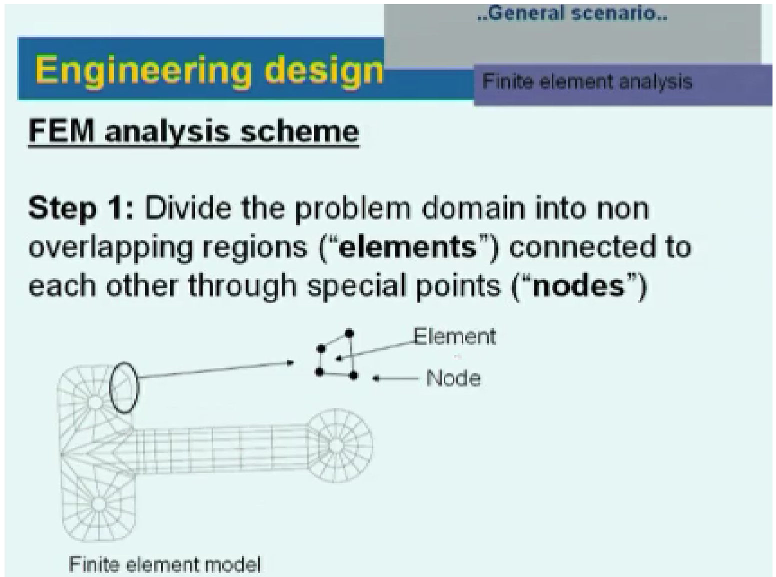

And these are connected together by an entity called element and entity called the node, so their entire structure is divided into many such elements and each element has nodes which are connected to other elements to make a structure.

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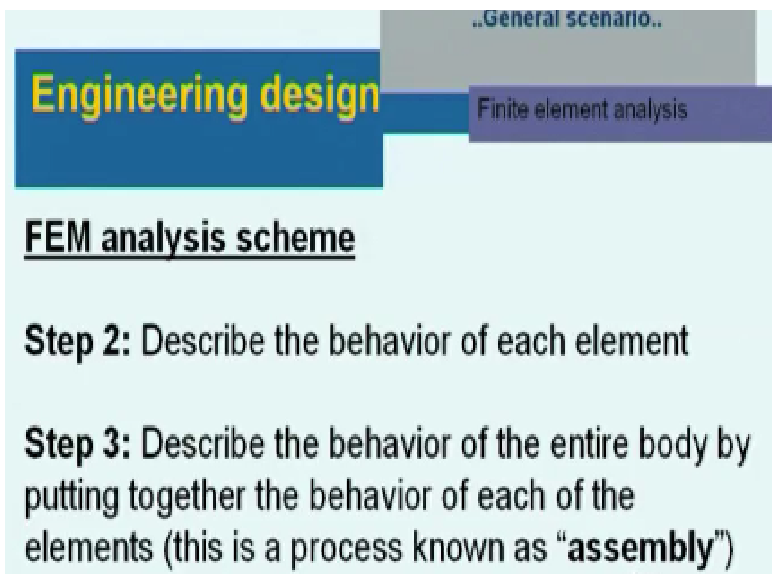

Then we described a behavior of each such element and synthesize the behavior of the whole element t to make the assembly of element and get the overall behavior of the structure in short this is what the finite element is all about.

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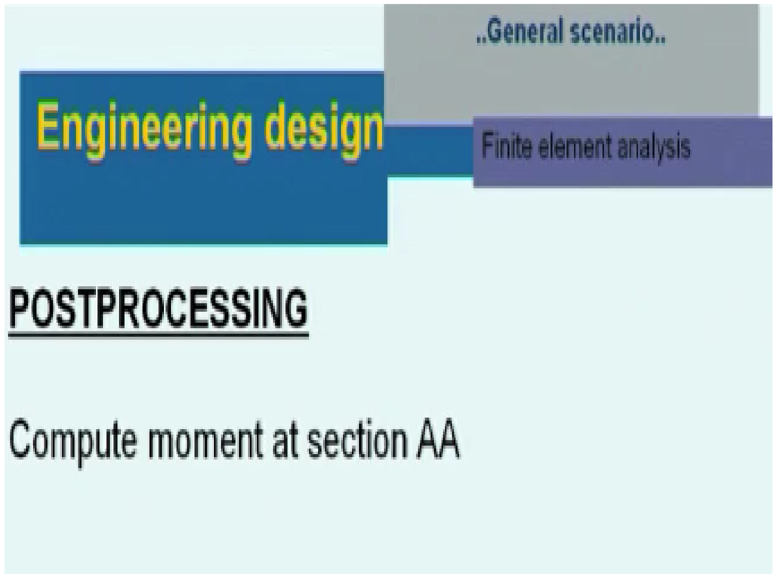

Once we get this we get the primary parameter which is in the case of a bracket is a deformation and once we get the defamation we post process the deformation to get the subsequent quantities like the stresses, the moments, the shear forces etc.

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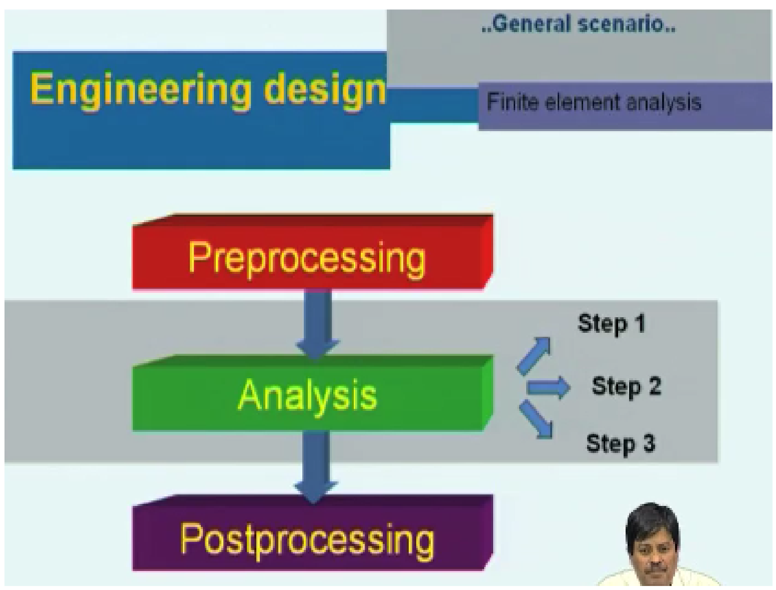

So we have 3 process first is preprocessing we create the mesh we call the mesh by taking the small elements and nodes, we do the analysis we post process the results, so it is involved in 3 steps.

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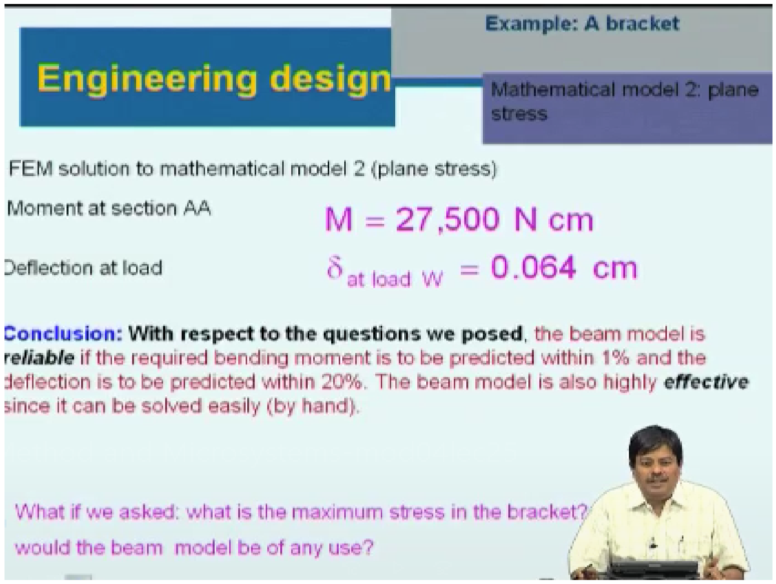

And now if we put this sophisticated model and find out what is the moment we will come to that how we can do that little later of the theory of analysis we get the moment is exact as what was predicted by the beam but the deflection is at the higher end. So we can conclude that with respect to the question we pose the beam model is reliable if the required bending moment has to be predicted within 1% and the deflection to be predicted within 20%.

But the good thing about the beam model is it is highly effective since it can be solved easily by hand very fast whereas the other method required a computation tool to like a computer to solve now the next question we ask what is the maximum stress in a bracket is it possible to predict with a beam model the answer is no because we do not know we beam is a approximate crude model where the entire analysis is along the axis of the beam.

Whereas the stresses can occur anywhere within the bracket which is not possible to capture, so we indeed need a sophisticated model we indeed need a numerical method and finite element method is one such method that can be used to achieve our goal.

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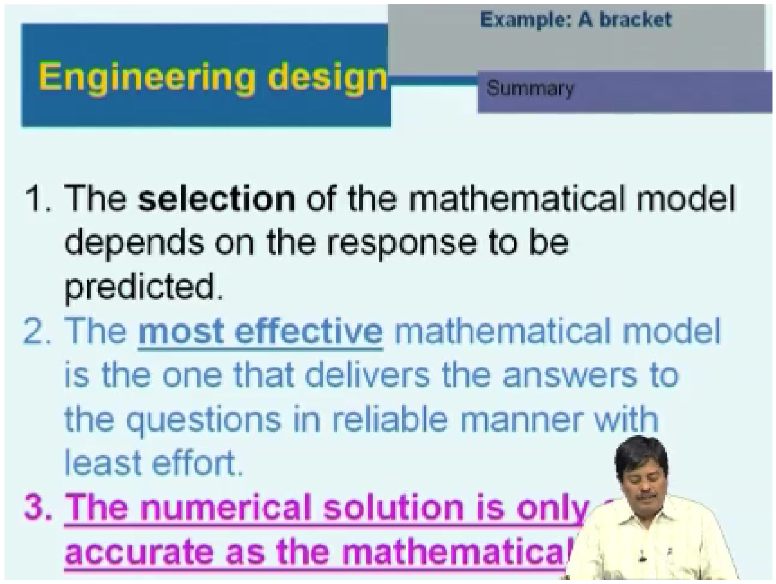

So the selection of a mathematical model depends upon the response to be predicted especially with respect to this beam analysis what we have done and the most effective mathematical model is the one that gives us answer in a reliable manner with the least effort hence in conclusion we can say that the numerical solution is the only accurate tool to model the mathematical aspects of a physical problem.

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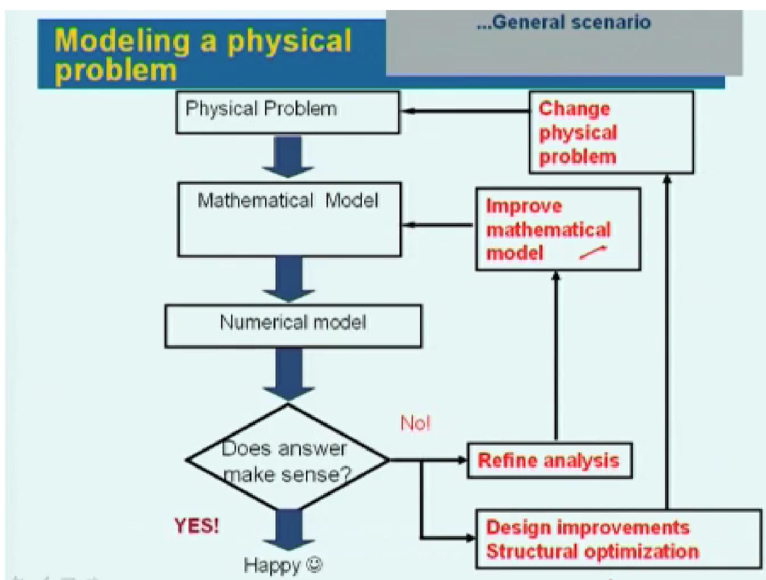

Hence we can summarize whatever we talk now in the form of a flow chart we construct a physical problem based on certain analysis for certain requirements we can set the mathematical model for this physical problem we use a numerical tool to solve this and we find whether the answer is okay or not is it does not make sense then we leave at it otherwise we have to redefine the analysis.

We need to change our assumption come up with an improved mathematical model and do the same analysis and if even that is not okay now we need to question our own physical system so we need to do some design optimization go back change the physical system and do perform the analysis till we get the required confidence in the answers that we got from the numerical tool.

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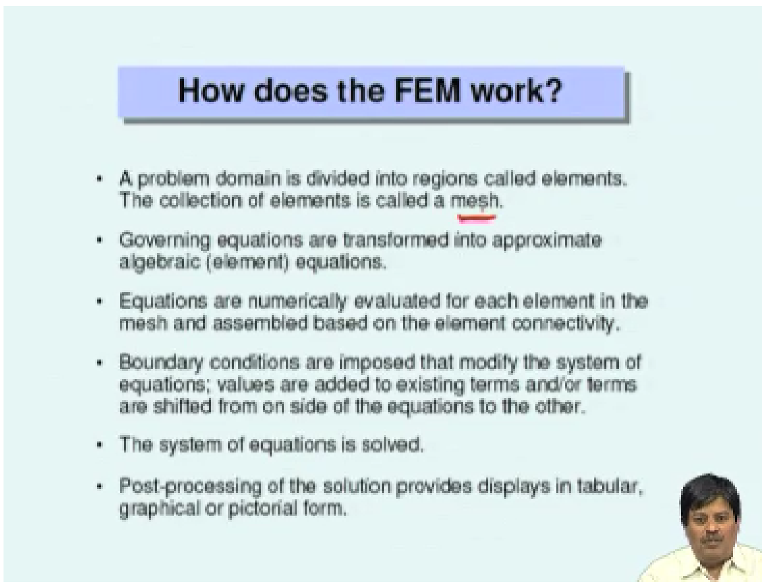

So in summary we can say how does the finite element work, so the entire domain is divided into small sub regions called elements? And the collection of elements been called what is called the mesh so the mesh is an important component in FEM governing equations that is the equations which we constructed from the physical system to the mathematical equation are transform into approximate algebraic equation.

That are amenable for numerical solution and the equations a numerically evaluated over each element of the mesh and assembled based on the element connectivity will come to these details a little later then we put every problem has some boundary conditions and the boundary conditions has to be imposed on to the system and then the result thong sub smaller systems are solved to get the required responses then once the systems are solved.

We post process the results to get the subsequent quantities like the stresses, displacement, current, voltage etc. as the case may be which depends upon the problems we are solving.

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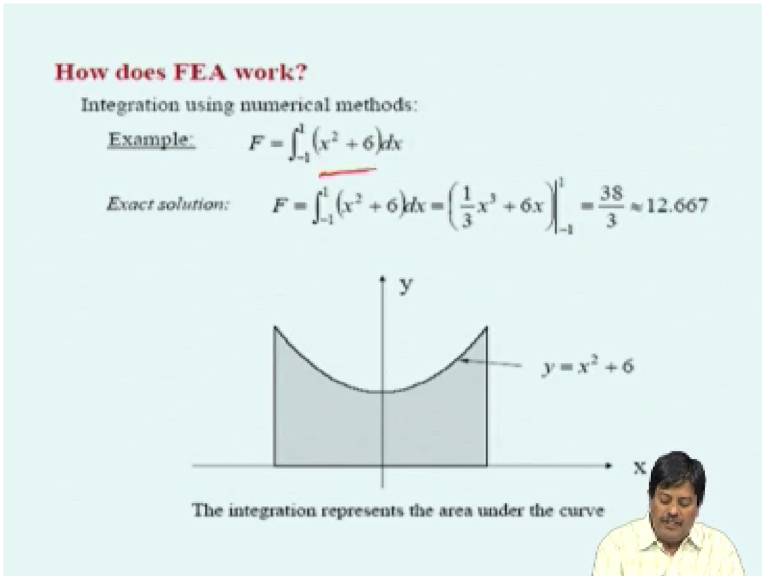

Let us see how FEM works, so basically if you take a small integral given by here which can be exactly integral and the exact solution is given here and the domain is between -1 to +1 and if you take the function X square+6 the variation looks somewhat given in this figure and now if we plan to use this in a numerical sense, how do we do this?

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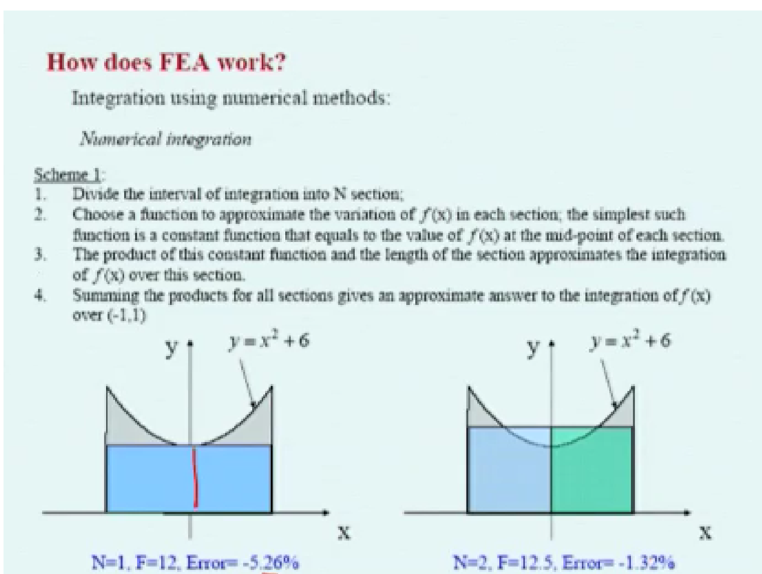

There are 2 ways that we can do in the first a scheme we divide this whole region into sub regions many many so in the first case we have divided into one in the second case we have divided into 2 segment within each segment we choose a function f(x) which approximate the section and once we approximate this section we assume certain value of f(x) the most easiest way to do it is the constant value taken exactly at the midpoint of this section.

For this say for example divide into one element we take this as the value of f(x) the product of this constant function and the length of the segment will give you an approximate area under the curve which becomes the value of the integral and summing up all these quantities from all of each of these subsection will give me the overall value of the integral for example let us take a single.

If we divide this region by one in one segment and compute it, we get that the average error is about -5.26% and if we increase this to 2 segment the error decreases from 5.26 to 1.32.

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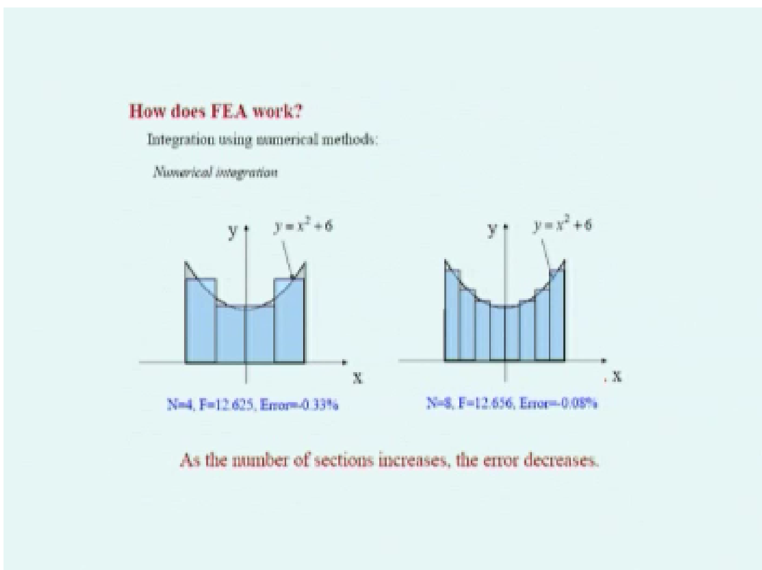

If you decrease it further to 4 segments drastically reduces to.3% and if we increase further the number of segments it to almost negligible 0 to 8% FEM works exactly in this principle the more the number of elements you choose within the domain more accurate would be your basic the accuracy of the answers it improves a lot, so this is in the principle that FEM works.

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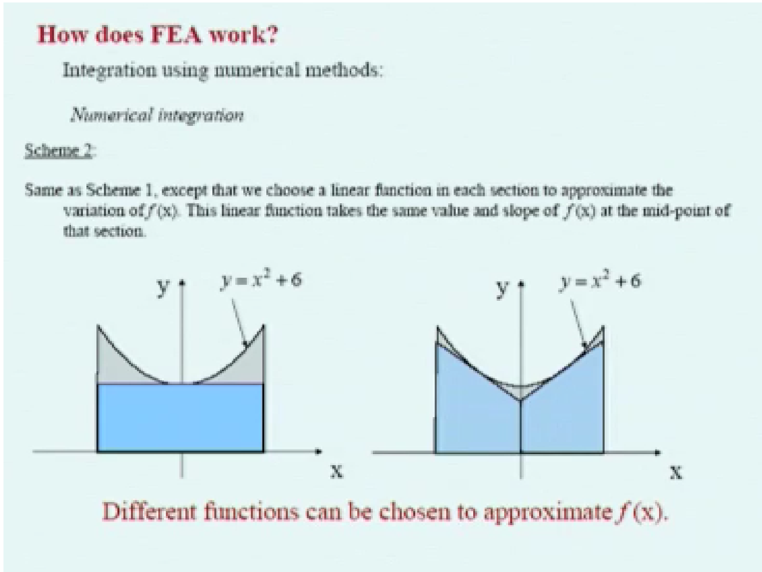

The second method by which we can integrate is instead of choosing a constant value we can choose a linear function f(x) when we take this the function behaves as shown in the manner and which is vast improved to the constant value we have taken and even with 2 segments we are able to get very accurate results only a small portion is not represented. So as we increase the order of the approximation within this element we can get better solutions.

This is the very principle in which the finite element works and this is the principle that we will adopt in future for analysis of many of the systems that will follow in this particular course on smart and microsystems.

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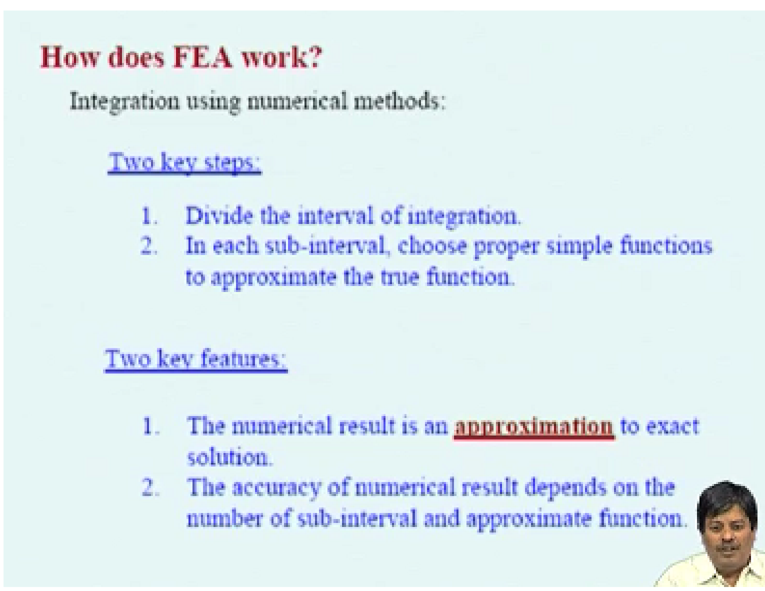

So what we have done here is 2 key steps one is divide the integral interval of integral to improve the accuracy and each integral you choose a proper function so the numerical result what we have seen here is an approximation to the exact solution it is not exact it is only an approximation and more number of intervals we use the approach the exact solution and the accuracy of the numerical results depend on the in number of sub intervals and approximations that we choose.

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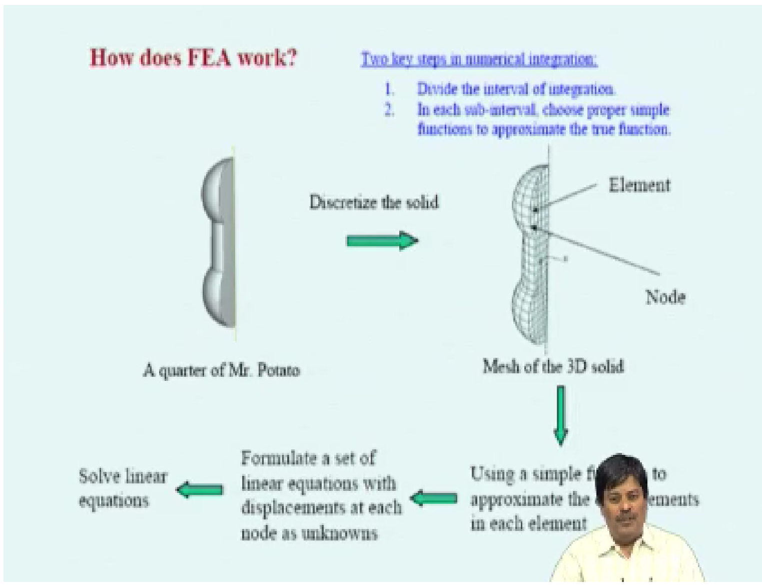

So very directly translate this to FEM if you have a section here which is given here if you want to increase the accuracy of this model by FEM we divide into sub elements more of the elements much better is the result okay and the 2 key steps which are identified is that and detain each element we can use in our approximation function which is of higher order So the more the higher the order better would be the approximations to the exact solutions you get to the problem.

So once there is a one to one comparison with what we did for the integration with the finite elements.

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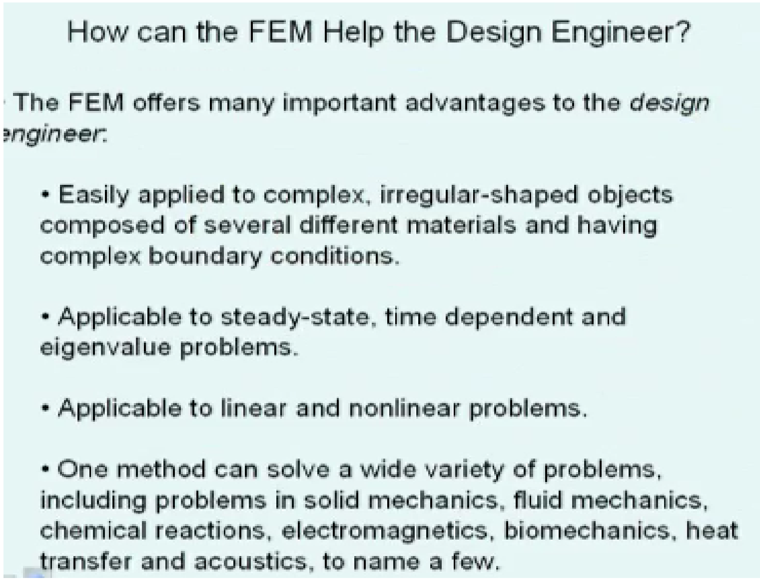

Now we will come why do we have to study finite elements how does it help the designers FEM offers many important advantage in design it can be easily applied to your complex geometries, irregular shape geometries composed of several material models different material construction having complex boundary conditions a variety of analysis can be done with FEM it can be steady state or it can be a steady state or transient or Eigen value problems.

We can solve both linear and nonlinear problems wide very idea of problems including cutting across all kinds of disciplines such as solid mechanics, fluid mechanics, electro magnetics, bio mechanics, MEMS, acoustics etc.

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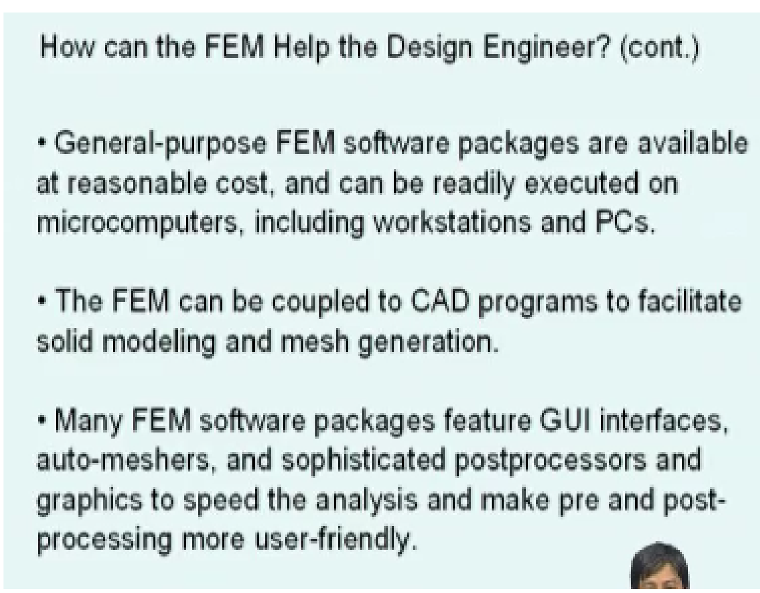

There are many general purpose FEM packages that has that are industry standards are available at a reasonable cost and can be readily executed and microcomputers including workstations and pcs FEM can be coupled to CAD models to direct modeling and machine is a major problem so you can actually have CAD program we can actually translate that CAD programs and automatically mesh to the system.

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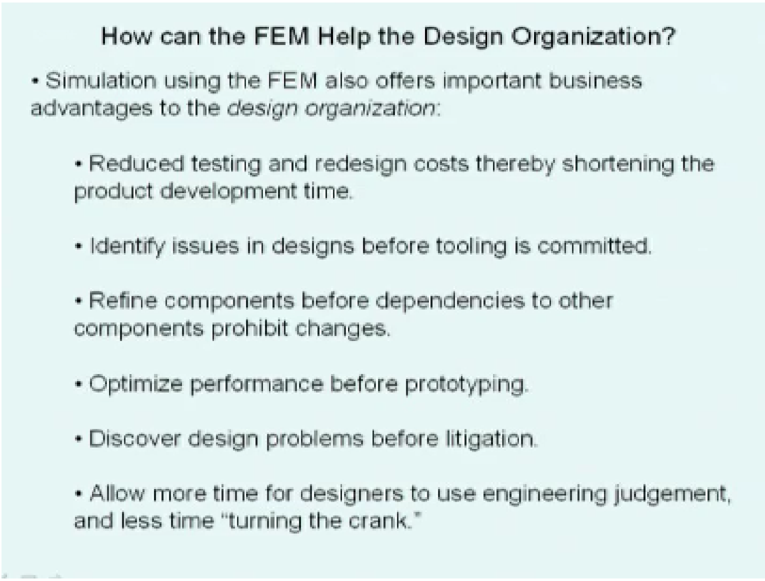

And there are many other how does it help the design organization basically it to gives us the reduced time redesign cause identify issues in designs component before dependency and other components probably changes optimize performance before prototyping and allow more time for designer to use engineering judgement so there are many advantage that the FEM can offer in design organization.

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Now let us talk about the need FEM in microsystems and MEMS is it required.

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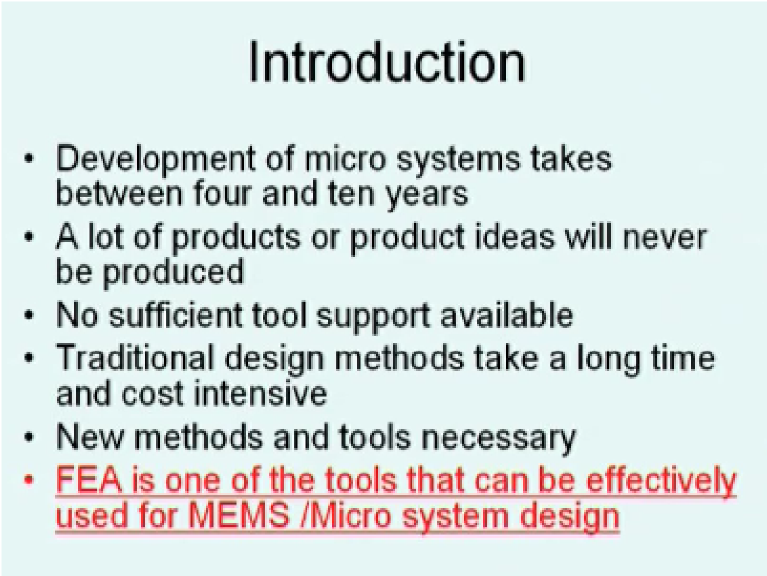

So if you take a micro system it takes anywhere between 4 to 10 years for its development a lot of products or product ideas that are designed can never be produced because of various issues like manufacturing. The process that are available the availability of the FABS many such many such constraints are there are no sufficient tools to support currently available for efficient design.

And manufacturing that traditional design method takes a long time and are cost ineffective so the new methods and tools are necessary and finite element is one such tool that can be effectively used for MEMS or micro system.

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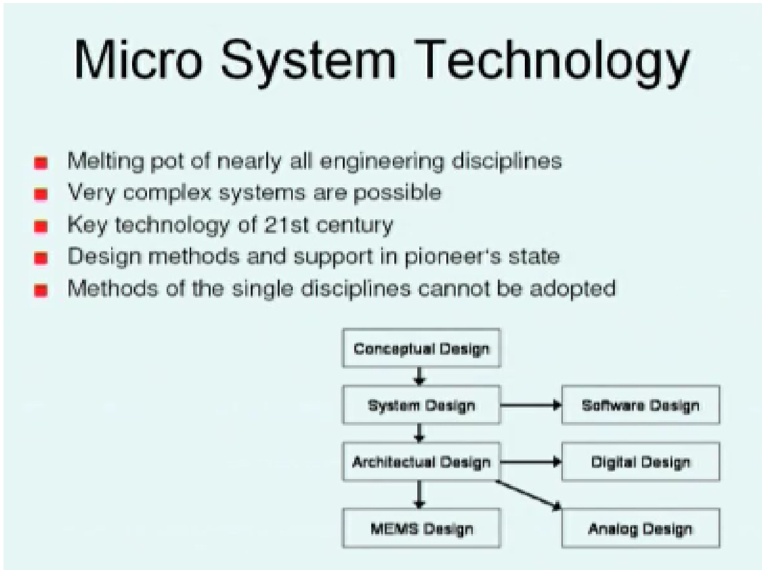

So microsystems technology if you take it is a melting pot of nearly all engineering disciplines you need it is a multi-disciplinary entity very complex systems are possible and we all know that it is a key technology for the 21st century. And the methods of single disciplines cannot be adopted straight away if you look at the overall micro system technology there are 4 components of designs.

One is the conceptual design where you say that I want this this kind of a system and that has to be translated into a system design where we need a software design competent to be there then that is converted into an architectural design where there is a digital design component and analog design competent and finally the MEMS design. So before the MEMS design can preclude all these other 3 design has to be in place before the MEMS design can be taken up.

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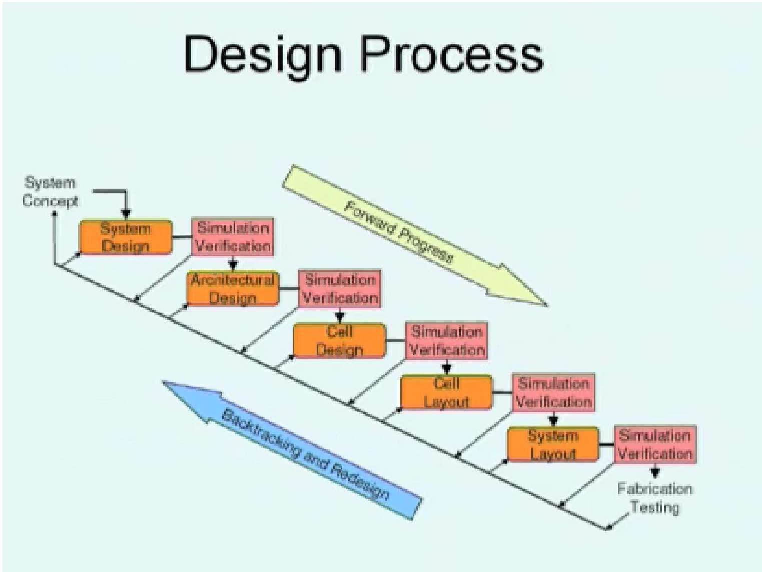

So if you look at the design process and the system concept the system concept design starts here then there is an initial concept that is developed which has to be simulated and verified and there is a architectural design as I said before which also requires some amount of simulation and verification because it has 2 components at the software design component then we make a cell design and a cell lay out and a system lay out.

This system before we can go in for fabrication at each process simulation and verification is an important aspect if to make sure that they designed the concept the conceptual design is indeed achievable indeed manufactural and this is one of the things without simulation and verification it is not possible and finite element tool is one such tools where we can actually do this simulation and verification to see whether the feasibility of the design.

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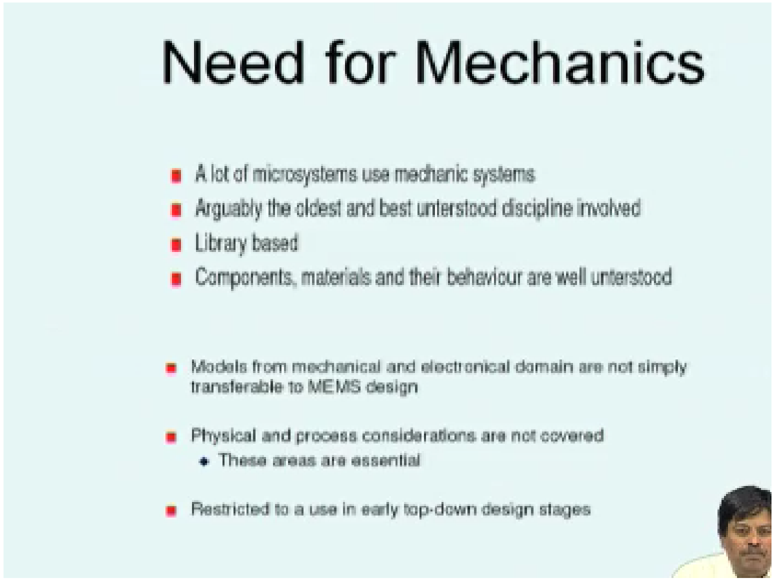

Other question we need to have, do we need mechanics? Mechanics is an important part of the MEMS design process a lot of mechanisms used mechanical systems we all know and it is arguably oldest and the best understood discipline in world and many of these mechanics based designs are library based okay suppose you need a beam connector we have a beam element available.

Though we call from the library of beams and there are many such beams out there they isotropic beams are the anisotropic beams are the composite beams etc. and the components, materials and their behavior are most well understood but there are some issues, what are the issues? The models from the mechanical and electrical domains are not simply transferrable, so you need to do a mechanical design separate and you need to do the electrical design separate.

And this needs to be coupled together for MEMS design and the physical and process considerations are many times are not covered so well understanding the design we also should say what kind of MEMS process that you are going to make it is it going to be a legal process or a DRI process or a bulk micromachining process and these process have to be embedded in the design and the simulation aspect of it. In order to make sure that the conceived design is indeed feasible.

So most of this current analysis is what we call the top down design approach which is basically takes does not take care of the manufacturing into consideration so that is something that we would look at it here.

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So the MEMS design requirement so as I said there is a multi-tasking analysis is required in the MEMS design process one is confronted with many more design and simulation tools than generally required for conventional IC design and this can be categorized into 4 categories that is the multiple physics, multiple disciplines, multiple players and multiple tasks and each of these has subtask which are.

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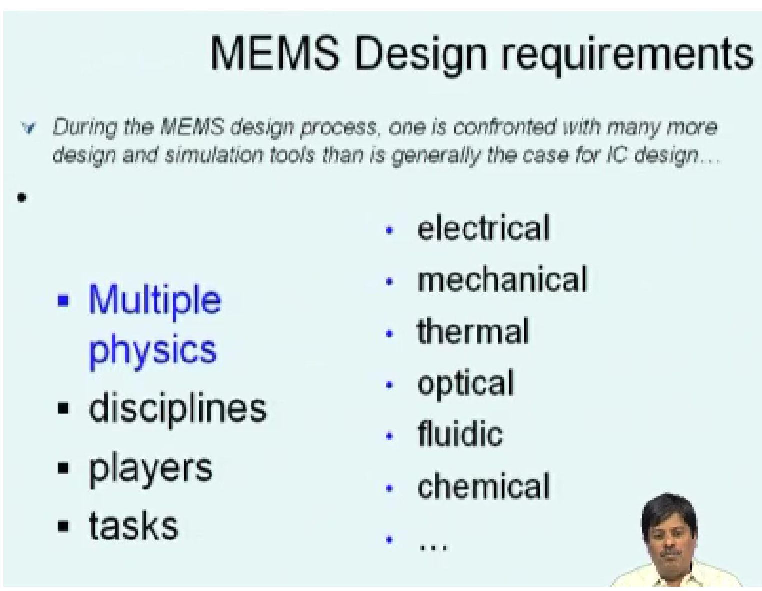

So if you talk about multiple physics very quiet they coupling of the electrical domain, mechanical domain, thermal domain, optical domain, fluidic domain etc., So all these domains have needs to be coupled so the understanding of these acquired from MEMS design.

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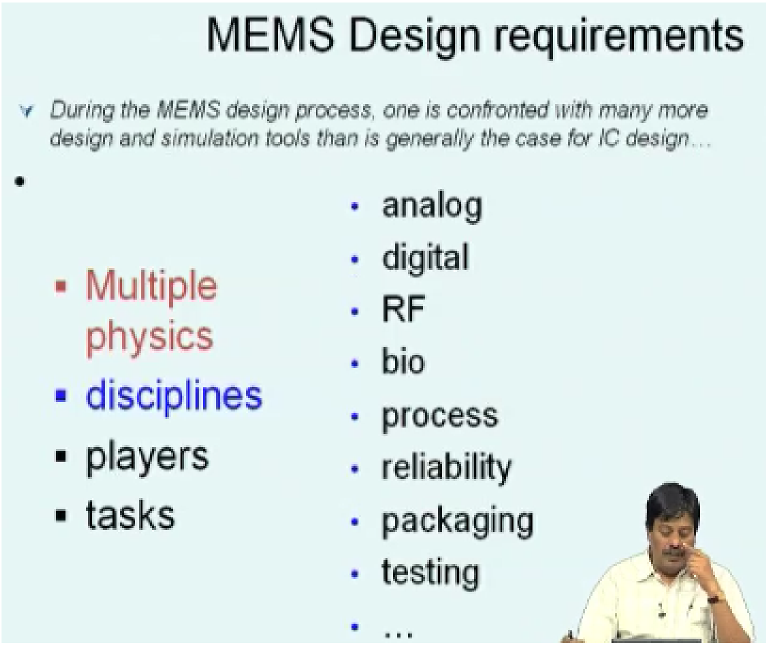

If you talk about disciplines there are multiple disciplines involved that is analog, digital, RF, bio, processes reliability, packaging testing etc.

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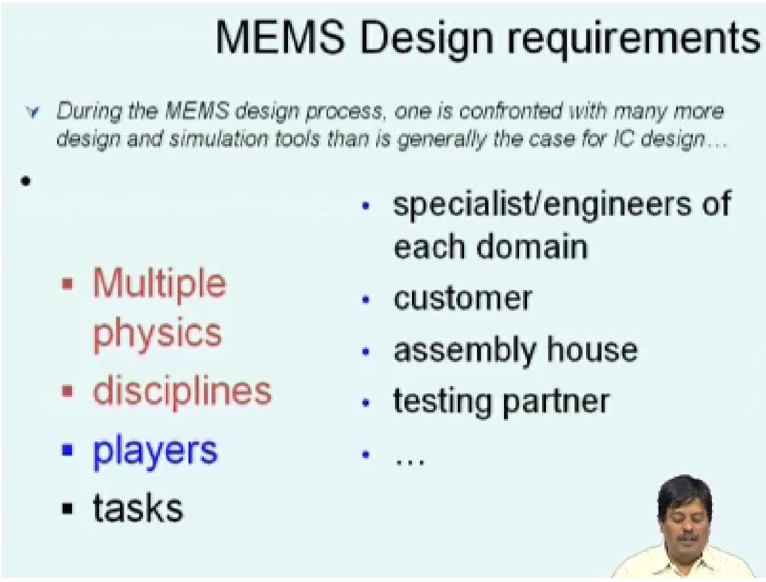

If you talk about the players involved we need specialist or engineers in each of these domains like mechanical, electrical, thermal, optical etc. We need to get the customer inputs in order to improve the design we need to see the assembly house, the FABS and those kind of entities which are very key to the success of any MEMS device that are going to be developed and also of course not to mention the testing partners.

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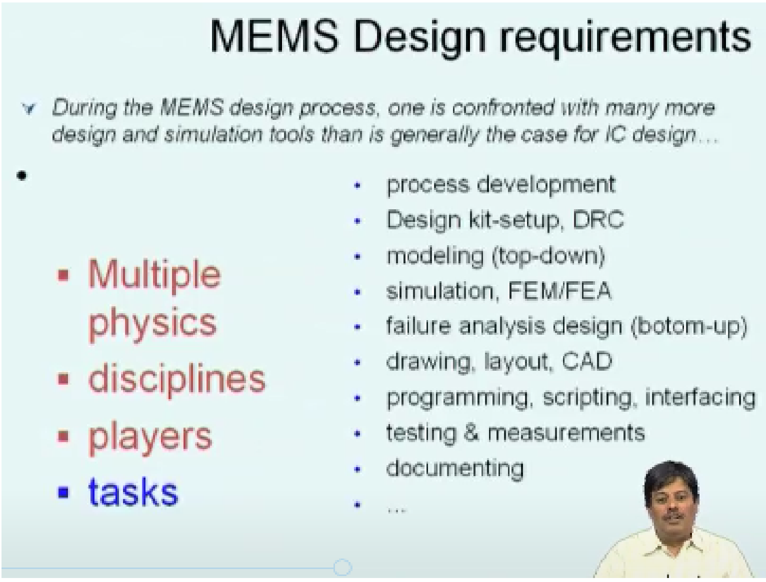

So if you talk about the tasks there are many multiple tasks are involved. FEM is one such task the others are process development, design kit set up, design rule checks modeling from top down, simulation drawing layout, CAD, process flow, programming, scripting, interfacing, testing measurements and many more, so as we see that MEMS is a very MEMS design and manufacturing is a very involved process where this is one where the manufacturing.

And the design goes hand in hand unlike the conventional mechanical or civil design we cannot separate the manufacturing from the design. So the manufacturing aspect has to be taken in the design in order to make a MEMS device.

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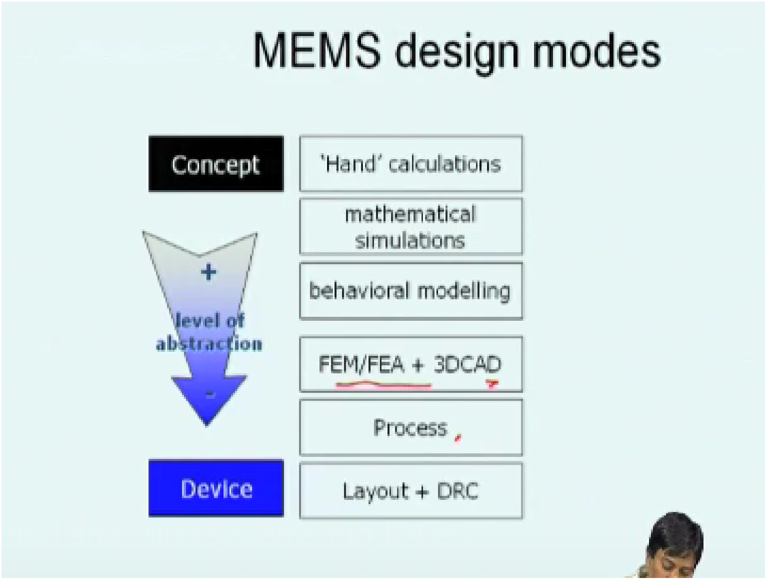

So that of what are the MEMS design modes was we have a concept and we have a design and there are a number of intermediate steps that are going to be there. So what is the level of abstraction that we are talking about so we have started can serve with the concept and calculations than we create a mathematical model and we simulate it and then there are different modeling is there.

We talk about MEMS modeling as a behavioral modeling which we need to check with finite element tools and we need to derive design the process flow in the manufacturing then make a layout to the design checks before it is going for fab for the final device manufacturing, so there is a lot of things in world in the design from the concept to device and as we see that FEM is a very key aspect here in this aspect.

So as I said FEM is very much very important for the design and manufacturing of the MEMS.

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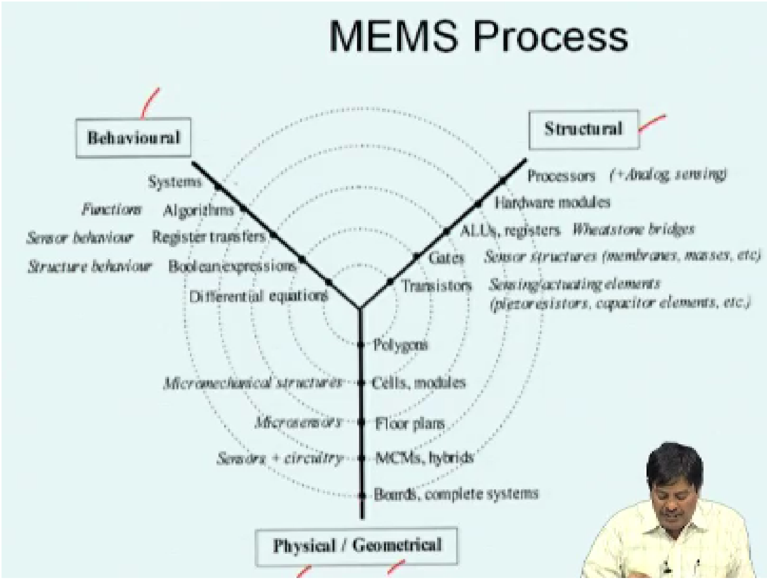

So what is a MEMS process, the entire MEMS process can be taught of as 4 step competent one is the structural, one is the behavioral, one is the physical and geometrical, we put the physical and geometrical in one axis here, the other y axis it is a y process which forms in a big circle and there is a overlapping of the activities for example if you take a cell here in the geometrical cell and modules and mechanical structure here.

Okay we need this cell is basically is over lapping with the sensor structure in the structural aspects and the behavioral aspects you have the Boolean expression and the structural expression, so there is multiple overlapping of the activities and all these activities which are following in each overlap each other for example for the complete system we need to have the processes here and the system integration with functions has to be there.

And the systems we talk it as a behavioral aspect whereas the processes or the structural aspects and the complete system is a physical and geometrical aspect and there is overlap of each other, each of these activities forms the outer and inner circles which are of importance so we start with the polygon here and end with the system here, so the MEMS process you see is a very complex process that is there for us to design.

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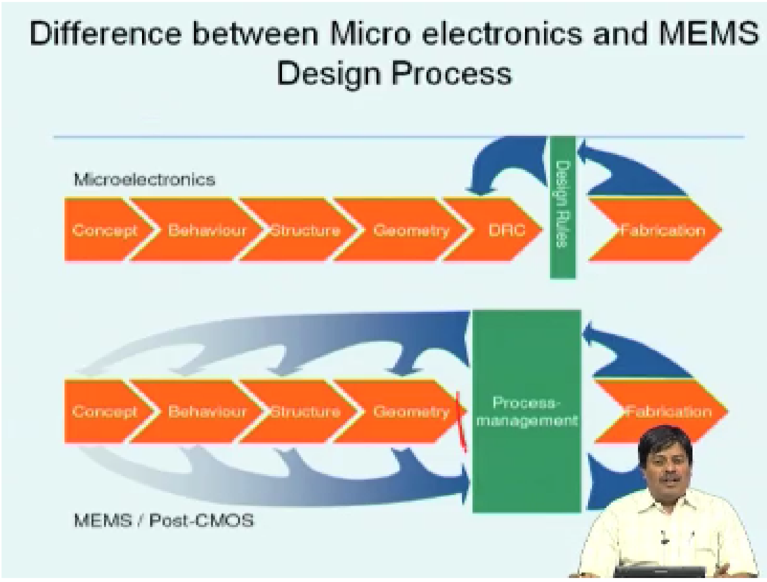

Now let us talk about the difference between microelectronics and MEMS, microelectronics is a well-established design process are there where we start with the concept we do the behavioral modeling develop the structure geometry, design rule checks and there is the fabrication . So up to the geometry part of it there is hardly any difference between the microelectronics and MEMS but what is more important is the process management.

And the success of the device that you design depends upon effective process management, what is the process management involved? Process management involved, the choice of the FAB, the choice of the fabrication flow diagram and the complete management of the entire flow process itself so the unless you have a process management in place MEMS device would not be successful.

And for all these things the finite element plays an important part in development of this process management aspect of it which is very critical and which is not that critical especially in the area of microelectronics.

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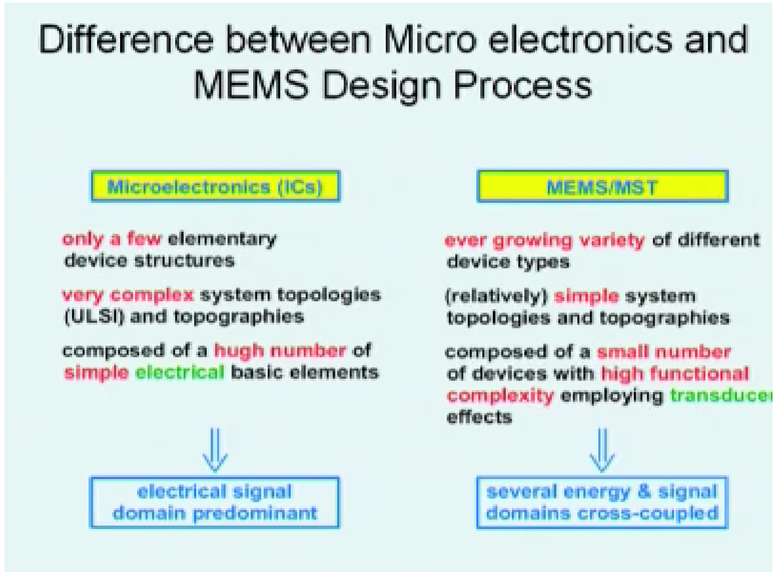

So let us take the difference between the microelectronics and MEMS design process let us talk about microelectronics there are only a few elementary device structures that are that can be developed with microelectronics as suppose in MEMS you have ever growing variety of different devices the microelectronics aspect design is very complex system topologies are very complex and topographic are very complex.

Whereas MEMS the system topologies a very simple compared to microelectronics and again in microelectronics it is composed of a huge number of simple electrical basic element whereas in MEMS is composed of small number of devices with high functional complexity employing transducer type effects So in summary we can basically say microelectronics is only the electrical domain predominant design.

Whereas in MEMS there are several energy domains that have to be across coupled in order to make a system, So the MEMS design is an order of magnitude more complex compared to the microelectronics.

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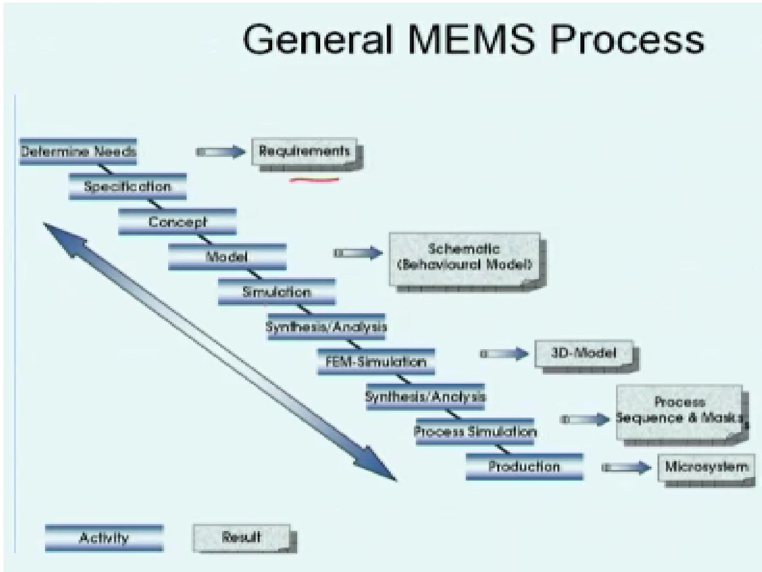

So let us see the entire design process so as I said we start with the specification based on to determine on the needs and sophistication we come up with a concept so that is what we call the requirement so we model this concept we simulate it we synthesize basically the simulation is through development of the schematics which is shown here and once we put all the all the sub elements of the schematics.

We develop the model 3D model it is shown here which is subjected to finite element analysis and their analysis is performed by synthesizing all these subcomponents and once we get this done based on the results of finite elements simulation we develop the process flow diagram that is the flow sequence what kind of mass we need to use for manufacturing, what kind of process we are going to have based on the simulation results.

And then finally it goes to the production where we develop this micro system so it is a fairly complex process and we see that how important the finite element analysis linking from the concept to the final fabrication.

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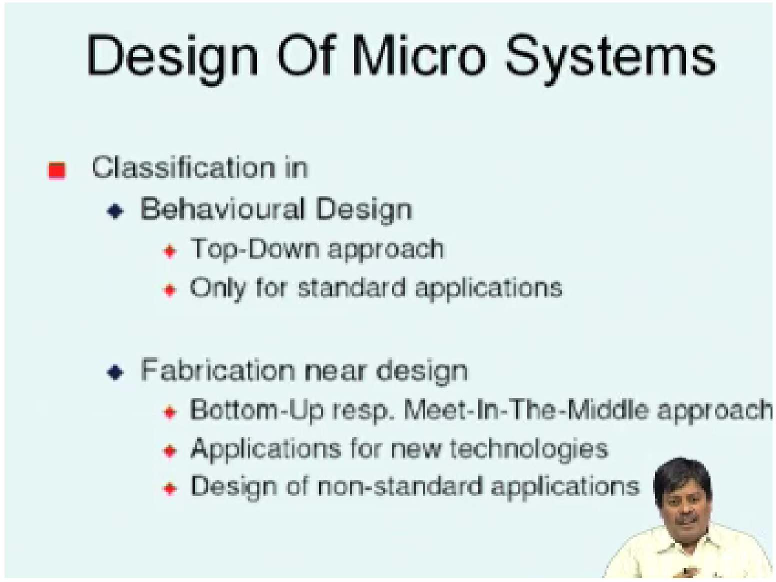

So a lot of the different classification of micro system design First we call it as a behavioral design which is what we call the top down approach we go from the concept to design and the second is the fabrication near the design where we do a bottoms up approach so both designed so we need to do both in order to get a complete system so we will go through what are the important aspects of each of this.

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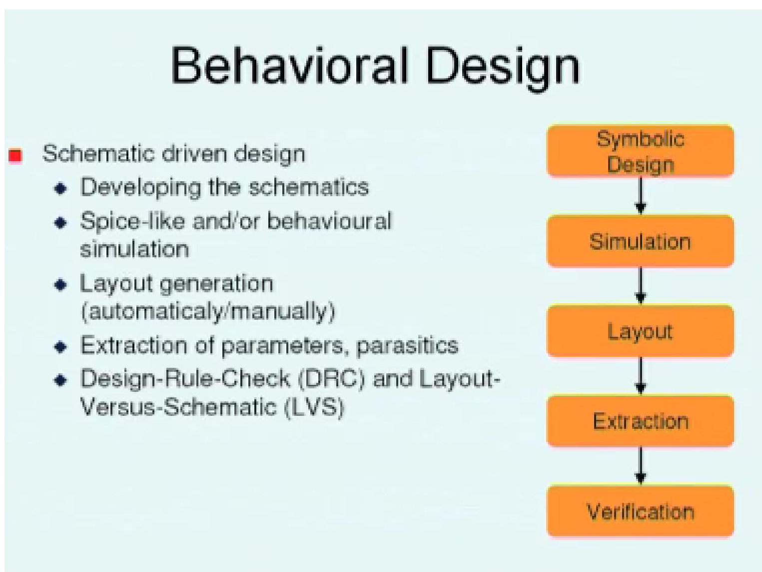

So in the behavioral design basically it is the most important are the more difficult part of it is development of the schematics so by schematics we said that okay we take a big device say on our switch or something we need to say where we need to put the circuit elements where we need to put the filters where we need to put the switches etc. and these are all library based so it basically it is what we call this place like behavioral simulation.

Then we generate the layout. The layout either automatically or manually and we extract the parameters or parasites, parasites is what are the pattern meters on which a particular factor is dependent upon we performed the design rule check and then we make the layout and this layout goes for the fabrication the process flows the lot we say what kind of process we need and it goes to the FAB for the making of this device.

So we have a symbolic design that is based on the concepts we simulate we make a layout we extract the parameters we verify and send it to the fab. So these are the process involved in the behavioral design. So what we see here is there is something lacking here that is we do not take the aspects of the fabrication aspect into our design so what is the outcome of this there is no guarantee that this design can work.

Because we have not taken care of the aspects that we have that influence the fabrication into our design process are also in the analysis process. So let us take an example of RF a switch so we have many circuit elements many resistors that are made here and this is something that our many software like coventor wear and intelli suits are available where this library of these elements are available.

If you know conceptually what you are looking at so a lot of engineering judgment is required a lot of understanding of the whole system is required so you put it at the appropriate place and generate the model so there is a library, so we take the okay we take this circuit element.

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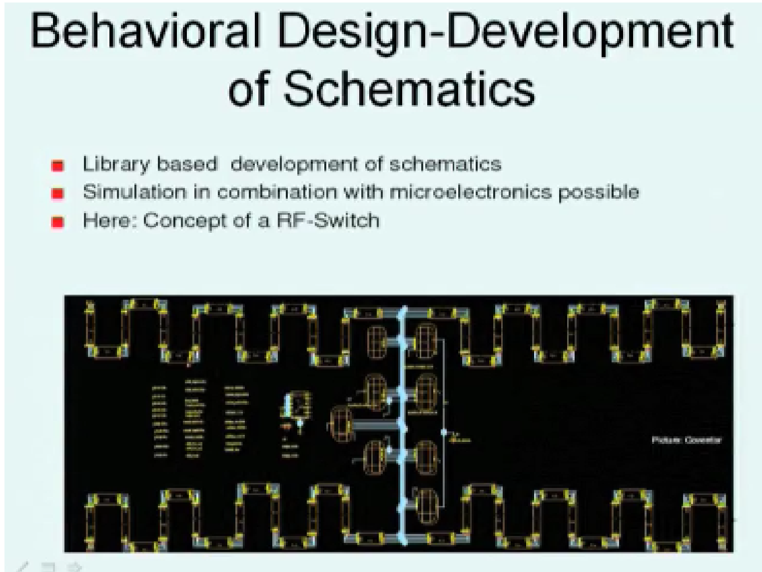

We take the resisted element we take the filtered elements all these things are put into that system into we make a layout.

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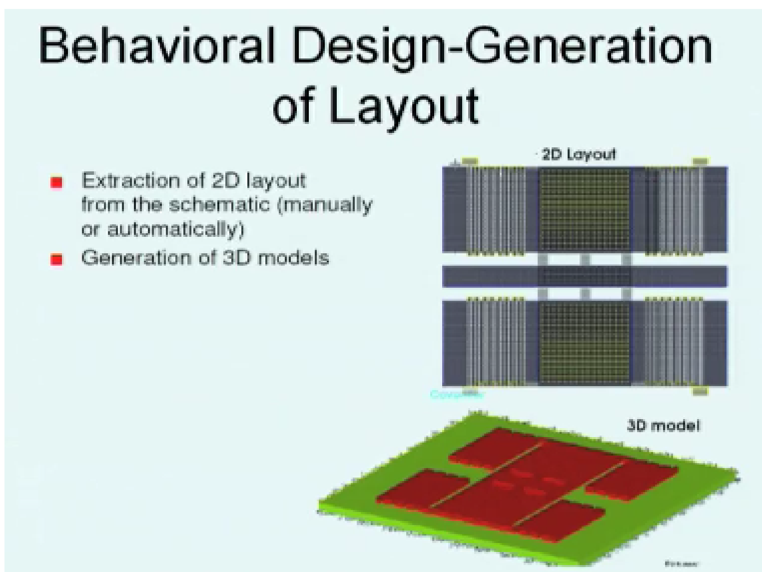

And this layout is basically converted into a 3D Model and this 3D model through many of the CAD programs and this 3Dmodel are meshed and then every perform different element analysis. So this is the layout of what we thought of a MEMS system and this layout we make the design here.

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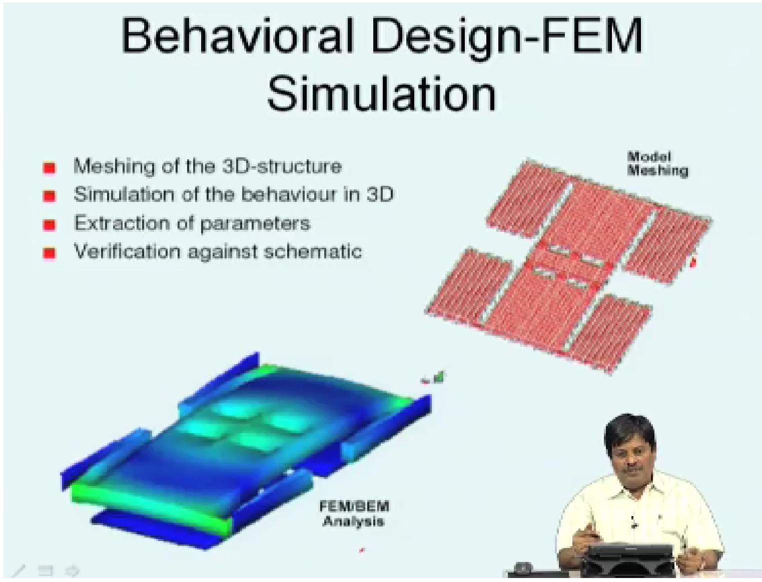

So we do a 3D simulation and here is a finite element simulation of this system of the other switch which is there this is the meshing we do from the CAD model so then once we do the analysis we extract the parameters we verify and then we decide on what kind of process we need to take so this is a behavioral design where we see that FEM also plays a greater part in actually seeing whether the concept what you thought out is what you have realized.

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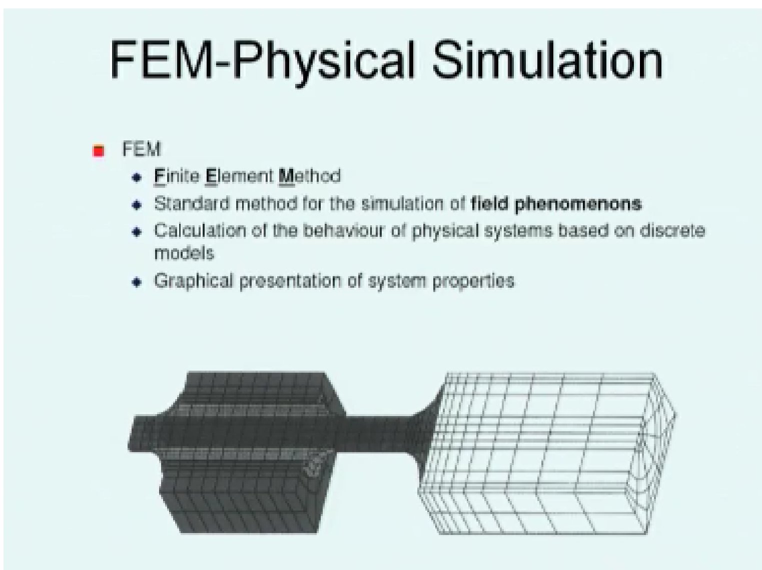

And this is a finite element model as you know that this is a standard system we have explained what is finite element how it can be used we have a graphical and we have a graphical interface which basically where we can simulate the whole aspects of the behavior of this system to various inputs that we give to the system. So that is why finite element is very useful to actually verify your behavioral design.

Whether it is a behavioral design or any design for that matter because it takes the input that you give and you basically assess this is a mathematical model for that problem and based on that the final elements to solve this.

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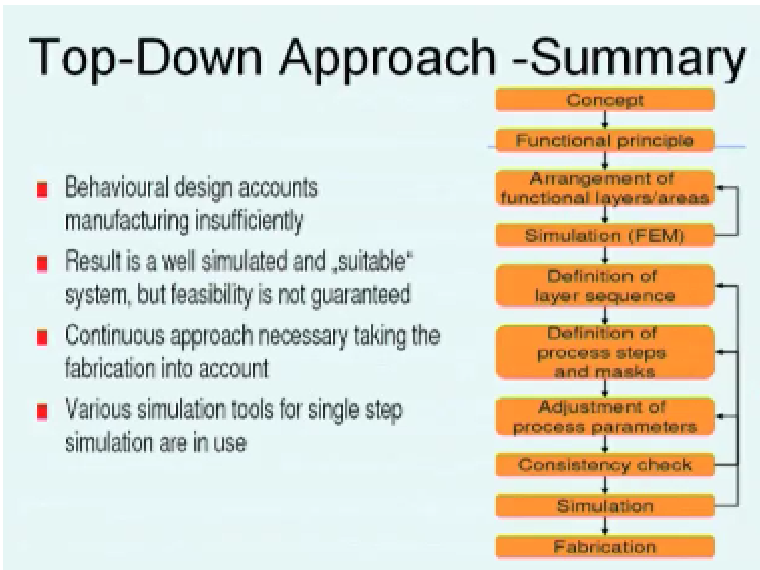

So the second approach what we are talking about is the top down approach what is this top done of which so we found that behavioral design does not account for manufacturing the result although is well simulated and suitable but feasibility is not guaranteed as I said earlier there it is necessary to have a continuous approach taking care of the fabrication into account, So the various simulation tools for single step simulation that are used can be built in here.

For example, let us see we have a concept in the top down approach as in the case of the behavioral design then we say the functional principle the arrangement of the functional layers and this can be tuned with FEM before finalizing it at, at the sub component level then we say definition of the layer sequence we need to say okay we need to have a sacrificial layer which has to be removed so what would be sum portion is removed.

So because of that some secondary effects like residual stress may creep in how do we do this so we need to do an initial analysis and this is a manufacturing aspect of it which is not taken care in the behavioral design and the definition of the process and systems and mask that adjustment of the process parameter based on the results that you get from the analysis so in every aspect of it you take care of the manufacturing asset.

So there is a greater feasibility of such a design is realizable than the behavioral design so this is a fundamental need for most of the design process and we need, we see that finite elements plays a huge part of it in the success of this top down design approach that we are talking about.

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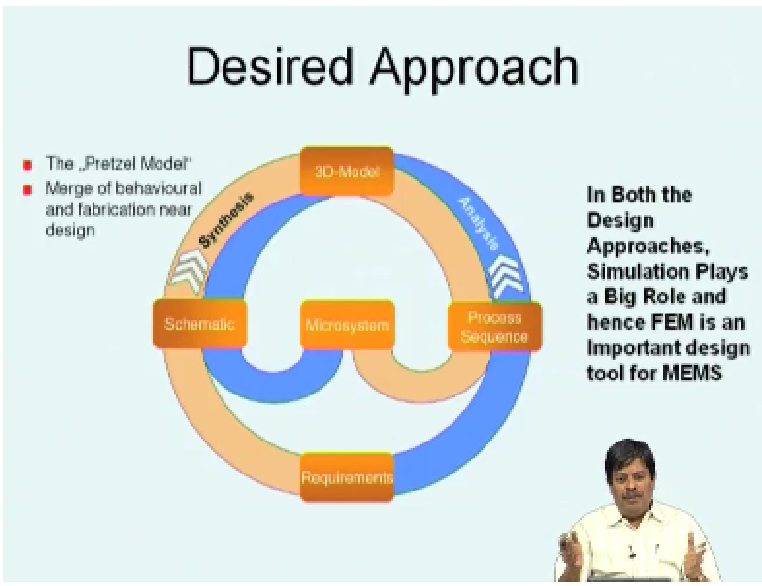

So what are we looking at right now so basically we need to have a system that is that combines the advantage of the behavioral approach and the top down approach that is you take care of the good aspects of the behavioral approach that is development of this schematics based on your judgment and take the manufacturing of it and put it together and this is called the pretzel approach.

So this is called the pretzel some kind of eatable that is very popular in America so they call this as a pretzel approach and which is very important and in both these cases both these design approaches we see that simulation plays a very big part and finite element is an important reason to and it can be said that finite element is an important design tool for MEMS.

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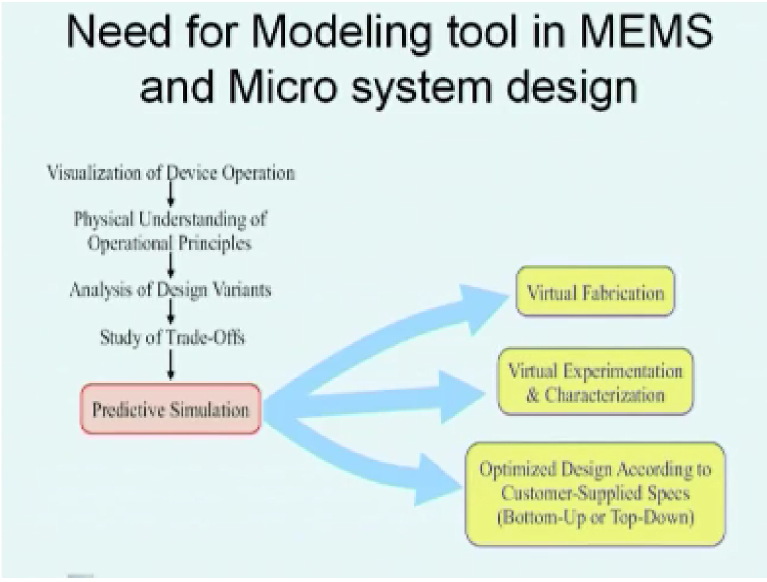

Now the question is need for such tools in MEMS. What is the need?, The need is predictive simulation by predictive simulation we can construct virtual fabrication so we can actually see once the design is released from FEM we can do build a virtual reality tool and simulate the whole fabrication process at stage by stage to see what are the problems that can be caught even before actually entering the FAB.

Virtual experimentation character agents same advantages and optimized design according to the customers supplied specifics and this is the major advantage and today because these are all costly process we cannot start with something and end up something that that is not feasible because by that time you would have spent an enormous amount of money. So tools such as this is absolutely necessary for us to do that.

So the major advantage of the predictive simulations or the simulation of the device operation physical understanding of the operating principles analysis of the design variants we have and steady of many trade-offs that are going to be part of this whole design process so their advantage of such a tool is enormous because it is going to reduce the testing time improve the design and save a lot of money especially to make sure make sure that the designed device is indeed feasible to realize.

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So the purpose of FEA we have already said make the development cycle short and cost effective to understand the behaviors limits interaction and complex processes to optimize design and we can also say when will this particular design fail for example if there is a capacity depends upon the capacity sensors depends upon the deflection of a diagram due to induced electrical voltage it can say what is the fatigue that is going to keep.

How many times how many cycles that can stand we can actually do a failure analysis so there is a major advantage in using it for the design

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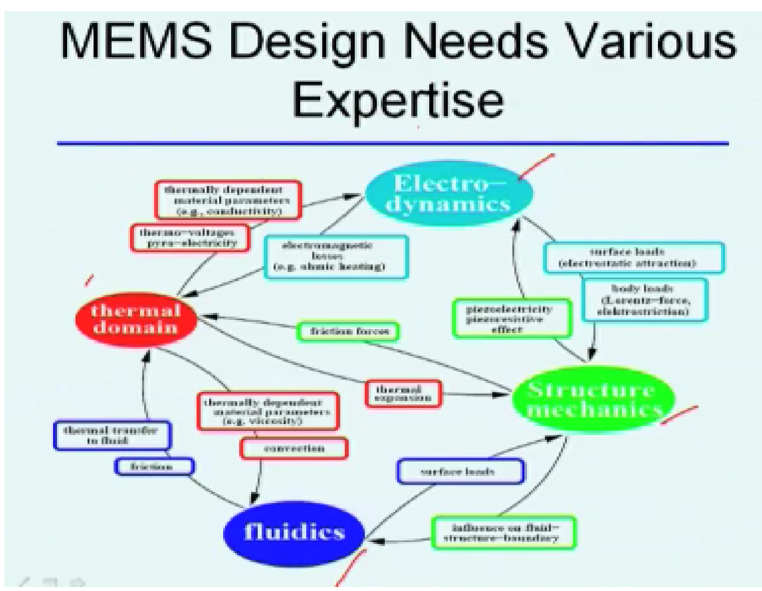

So now the question is how does this whole thing work as I said earlier it is a Multi-disciplinary entity requiring understanding of the electrodynamics the structural mechanics, fluid mechanics to develop microfluidic device thermal domain and each are coupled to each other for example if you look at the structures and electrodynamics structure is coupled you know if we want to find out what is the loads caused by the electrical input on to the structure.

Or what is the voltage that is generated due to a mechanical load, So the we are talking about pretzel electricity pyro electricity especially if it is a thermal electrical domain and the thermo mechanical domain thermo fluidic domain and you see the number of expertise that is required and each is a separate component of analysis in many of the finite element tools which has to be coupled together.

So MEMS design process requires a multi physics analysis tool and the finite element package that one is using should be in a position to do multi physics analysis and this is absolute necessity in MEMS.

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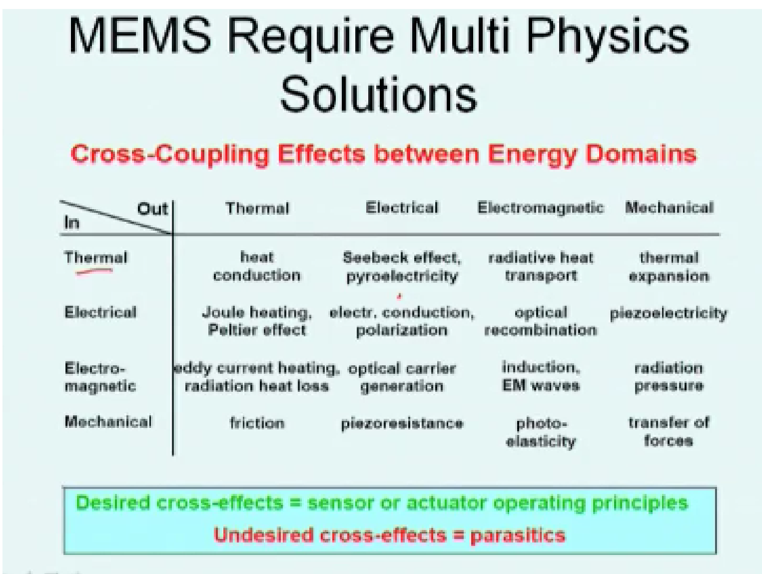

Now let us look at the cross coupling and this is where we talked about the smart material in our lecture earlier lecture. So that if you give some parameters as an output some other parameter will come out as an input and vice versa. So for example and MEMS is no different. So for example if you give a thermal as the input the output is thermal it could be heat conduction if the output is electrical it could be a Seebeck effect is very important.

Or the pyro electricity or if it is electromagnetic we are talking about relative heat transport, if it is mechanical we are talking about thermal expansion and if you are talking about electrical the electrical as an input the output if it is thermal it could be an Joule heating or a Peltier effect electronic polarization, conduction optical recombination if it is electromagnetic it is mechanical we are talking about Peltier electric.

It is jointly a change of one set of energy changed into another set of energy it is electromagnetic as input if the output is thermal we get a eddy current heating optical carrier generation induction electromagnetic waves radiation of pressure etc. So you see there is a multiple coupling of many domains here change of one type of energy into another type of energy that is what gives us the desired result and the MEMS design.

What we did generate should be able to do this that is all the more difficulty and that is the reason where the manufacturing aspect has to be built into the MEMS design process So what is the desired effects of this cross coupling the desired cost effect will be basically a sensor actuator operating principles can be checked and realized and the undesired effects are the parasitic because if for example because of the electric field.

The piezor electricity is there, it will converse into mechanical energy and in many cases we do not we may not need that so we are unnecessarily introducing certain additional complexity in terms of coupling but once we understand the behavior of the system we need not actually go by that So basically if you understand the whole thing we can eliminate the undesired effect and if you take the overall advantages of the MEMS system the advantages or wise disadvantages.

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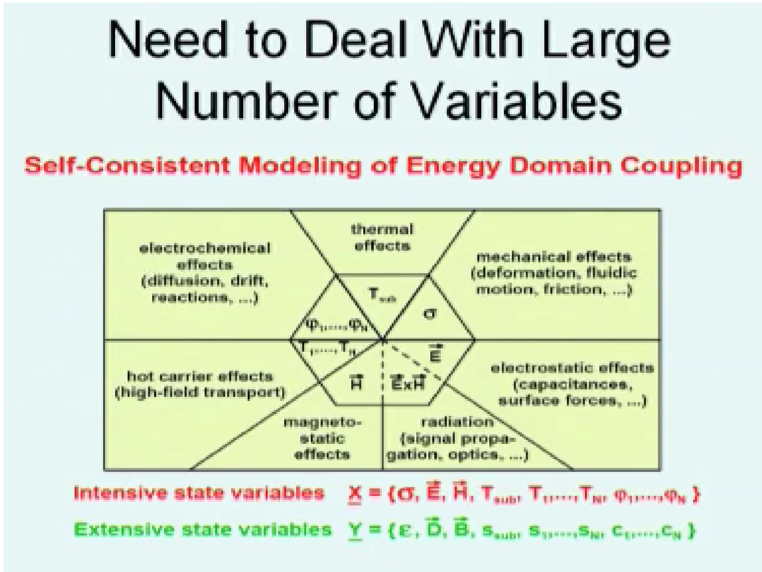

So in MEMS design process we need to deal with the large number of variables they are pertaining to different energy domains for example if it is electro chemical effects we need to talk about dependency of the design on the diffuse diffusion drift reaction if it is thermal on the temperature of the substrate if it is a mechanical effects we need to look at the deformation the fluidic motion, friction, fatigue if it is an electrostatic effect.

We are looking at what kind of capacitance we need to generate and the capacitance is very important for example in the piezor resistive pressure sensors is it has to be of the order that is measurable the surface forces that are going to generate it is going to be in the electromagnetic domains when we are looking at how we can actually radiate out the levels of radiation which depends upon signal propagation optics etc.

And in the magneto in the magnetic region we are looking at magneto static effects etc. So there are many domains since we are coupling there is a whole range of parameters that we need to look at it in order to verify the performance of a particular device that we are talking about.

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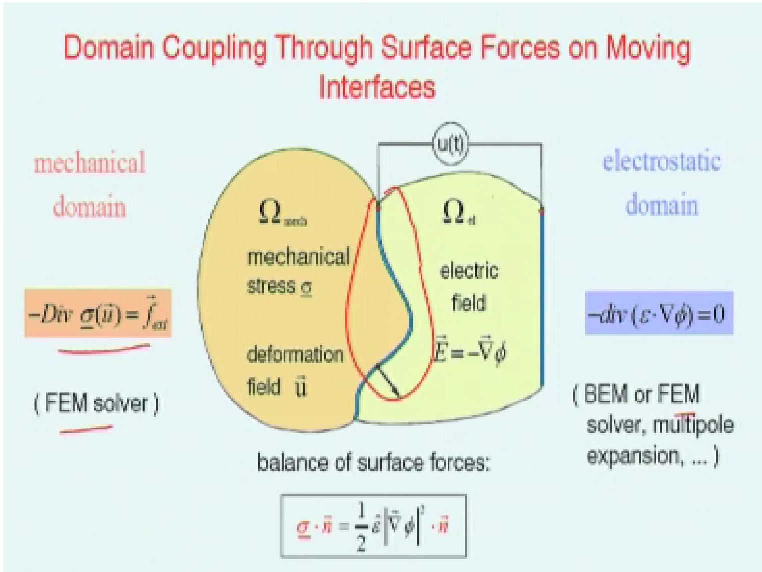

And that was important other aspect is how to be a couple the multiple domains for example let us take an example of a mechanical domain coupling with the electrical domain, the mechanical domain is characterized by a system which is given by a theory of velocity, so they divergence of the sigma = external forces okay so basically this is the mechanical equation that that needs to be satisfied on the mechanical domain in the electrical domain.

We have the equation on the electric potential that is going to be there whether it could be an electrostatic or a electrodynamics problem, We have a separate solver for Mechanical FEM solver for electrical how do we couple this coupling we need to choose one parameter that is the balance of the forces or balance of the velocities if it is a transient problem, so basically we say the forces generated due to mechanical system should be equal to the forces generated by the electrical system at this interface.

So this is going to lead us and additional matrix in whole FEM solver it is going to increase the size of the problem and this is what is needed so this coupling domain will depend on where will change if the domains are different for example if you are talking about fluid domain and the thermal domain it is the temperature at the interface so if it is going to be fluid domain and the fluid domain and the mechanical domain and the thermal domain.

So it is the electro mechanical coupling that is going to be there so I am sorry the thermos mechanical coupling that needs to be taken so every coupling will introduce an additional set of matrix and increase the problem sizes by orders of magnitude. So even though the mechanical solver is separate and the electrical solver is separate the need to couple them together and the finite element solver should have this multi physics capability if we have to use this for the analysis design and fabrication of the MEMS.

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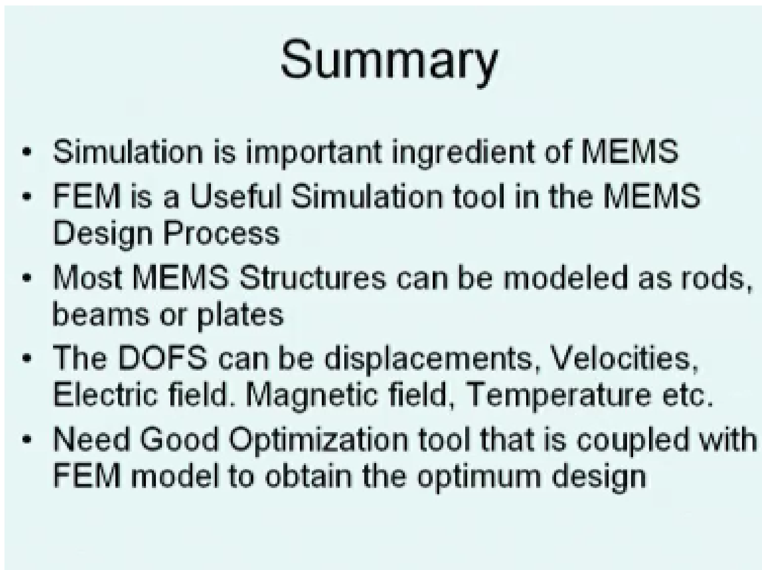

So we use different types of models in FEM the beam model, we will come to this as we go along in the later part of the lectures that I am going to give. So finally what is this we can summary. In summary we can say that simulation is an important tool in MEMS and FEM is a useful simulation tool that is required for the MEMS analysis and design and manufacturing process.

The most MEMS structures can be modeled as rods beams and plates we will talk about what are the rods beams and plates in our subsequent lectures and how do we construct the finite element models for this The DOFS stands for degree of freedom which is an important terminology in finite element can be like displacement velocities if it is a mechanical structure or if it is an electric feed or magnetic field.

If it is an electro if it is in the electrical domain or in the magnetic domain or electromagnetic domain temperature if it is a thermal domain etc. and what is required here is a very good optimization tool that is coupled with FEM optimum design so we have seen that FEM is a very important too for the analysis so in my next few lectures we are going to talk about these signs of a FEM in the science of FEM we are going to say how the process is developed.

How we can actually degenerate the variations of each of this sub element which I talked about in the initial part of the lecture and how we can actually build a system most of my lecture would be based on the mechanical systems although and the solving the mechanical equations derived from theory of velocity all the subsystems subsequent development for MEMS requires the electrical domain or the magnetic domain can be directly extended.

So it is only the mathematics aspect of it which I am going to talk about taking the mechanical system into consideration in my subsequent lecture.

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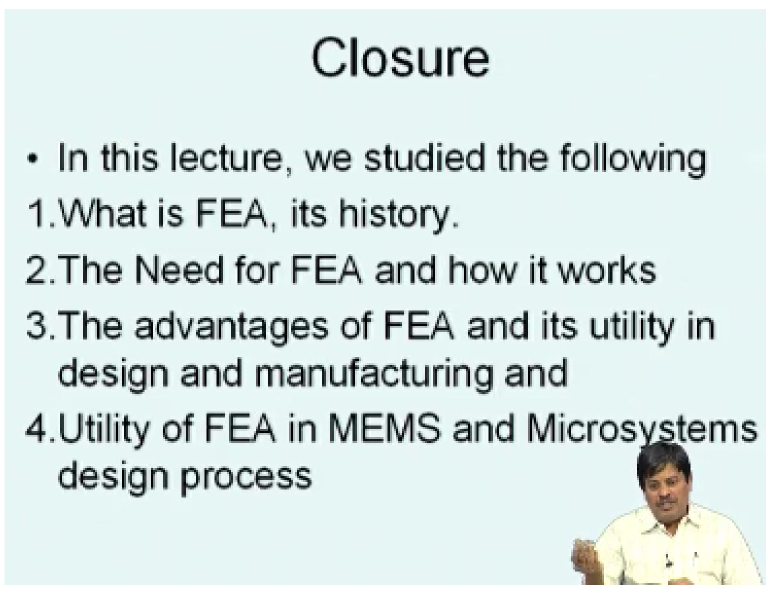

So in closure I would say in this lecture we studied what is a finite element analysis its history how it works how the number of elements increasing the number of elements is going to increase the number of elements the accuracy of the solution what are the advantages of FEA for example how it can reduce the testing time how it can reduce the manufacturing time how it can be used in the MEMS design process how it can actually help in making the rapid prototyping.

So many such advantage can be developed using FEM and we also said how important MEMS, FEM in MEMS and micro system design how we get how we can build in the FEM aspects into the manufacturing how it is going to how we can couple 2 domains even though we have a separate FEM solution here so these are some of the aspects that we have studied in this lecture. Thank you.