Micro and Nanoscale Energy Transport
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Lecture – 01
Overview to Micro/Nanoscale Energy Transport Part 1

Very good morning to all of you and welcome back to a new semester, so this particular course is titled Micro/Nanoscale Energy Transport and my name is Doctor, Arvind Pattamatta and I am Associated Professor in the Department of Mechanical Engineering working in the area of Micro and Nanoscale Heat Transfer. So, let me briefly introduce the course content that we will be talking about before we move on to the introduction part of this course.

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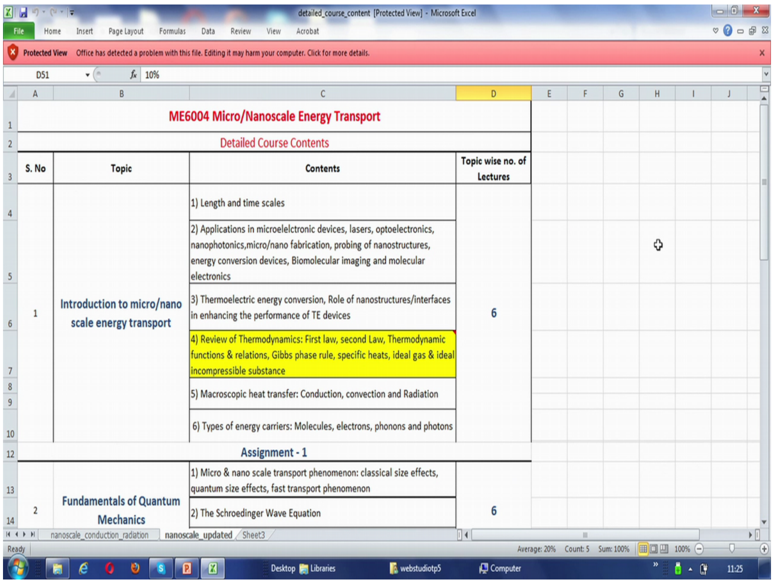

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ME6004 Micro/Nanoscale Energy Transport

Detailed Course Contents

S. No	Topic	Contents	Topic wise no. of Lectures
1	Introduction to micro/nano scale energy transport	1) Length and time scales	6
		2) Applications in microelelctronic devices, lasers, optoelectronics, nanophotonics,micro/nano fabrication, probing of nanostructures, energy conversion devices, Biomolecular imaging and molecular electronics	
		3) Thermoelectric energy conversion, Role of nanostructures/interfaces in enhancing the performance of TE devices	
		4) Review of Thermodynamics: First law, second Law, Thermodynamic functions & relations, Gibbs phase rule, specific heats, ideal gas & ideal incompressible substance	
		5) Macroscopic heat transfer: Conduction, convection and Radiation	
		6) Types of energy carriers: Molecules, electrons, phonons and photons	
Assignment - 1			
2	Fundamentals of Quantum Mechanics	1) Micro & nano scale transport phenomenon: classical size effects, quantum size effects, fast transport phenomenon	6
		2) The Schroedinger Wave Equation	

Let me show you the overall important topics that we will be covering here, I have also made a plan a time plane of how many lectures that I will be talking with each topic. So, we will have first two weeks; will be spending time on the introduction part. So, why do we take two weeks here because the introduction is not just power point introduction that I will be showing in the next 2 or 3 classes it will also involve some fundamentals which probably you need to some fundamental terminology and fundamental understanding of some basics which we need to know before we go into the subject wise topics such as the quantum mechanics.

For example that is the next topic that we will be looking at. So, the introduction will be a little bit more elaborate here. So, we will be for example, In fact, the introduction will be starting with something that we know already in the continuum scale. So, we will be looking at the aspects of Macroscale heat transfer which you many of you might know or many of you are knew a conduction convection and radiation, and we will also look at what are responsible for the modes of heat transfer, fundamental scale their characteristics. So, all these will be covered in the introduction part.

And then this will be followed by some understanding of quantum mechanics, because if you are looking at Nanoscale energy transport essentially you have to look at the duality of matter. So, either it could be wave nature or it could be a particle nature. So, to understand the wave nature, you have to deal with the theory of wave equation Schrödinger's wave equation, solving the Schrödinger's wave equation for some simple systems. So, these will be dealt with in fundamentals of quantum mechanics. So, I am going into a great detail, but nevertheless we will be a spending considerable time to because the aspects of quantum mechanics are quite different, from the classical mechanics that we understand. So, in order to introduce you to the basics of that and apply these to a few fundamental systems will itself take about two weeks.

So, following that now from quantum mechanics, we have to gradually move towards the statistical thermodynamics. Now to do that we need to understand the system to which we apply the quantum mechanics. So, quantum mechanics can be applied to as simple as in infinite potential well this is like the text books problem that we will do to something like understanding you know, solid state physics. Now why I am going to talk a little bit about solid state physics is; if you are talking about Nanoscale conduction one of the simpler system is to consider solids; and therefore, conduction heat conduction in solids and therefore, you have to know have some background about the distribution of atoms in lattices and therefore, what is it corresponding quantum mechanical principles that can be applied to study the solid state structures.

So, there are several sub topics which I have listed here. So, I am not go into all the details now, but we will see this cover this one after the other many of you have some understanding what conductor’s insulators semi conductors are and so on. But we will give some perspectives from quantum mechanics to show you why they are classified the way that they are show this way and also some important things before we move to statistical thermodynamics, the statistical thermodynamics is basically the bridge or the interlink between the phenomena nanoscale and the properties at the macroscale. So, properties such as heat capacity and internal energy have actually a nanoscale basis and we can understand that through the quantum mechanics and looking at the energy states at the molecular level, but how do we directly link that to a macroscale property like; temperature and heat capacity is done through the statistical thermodynamics.

So, we are not interested now in looking at each and every energy state possessed by a molecule or whatever energy carrier, but finally, you are looking at a statistical ensemble of these and this is what is going to affect the properties of this system at the macroscale. Therefore, we are looking at statistical thermodynamics; again, statistical thermodynamics itself is a separate subject being offered in some departments, but we do not have that much of time to go into all the aspects of it we will just cover, I do not think I will have even time to cover the ha the probability and distribution functions and so on.

I think we should be able to revise it yourself, but we will talk about the derivation of some of the important distribution functions, equilibrium distribution functions. So, which you are heard about this, so there are Fermi Dirac Distribution Function, The Maxwell Distribution Function, The Boltzmann Distribution, Bose Einstein Distribution Function. So, these distribution functions are the most important fundamental distribution function covering all the energy carriers, and from there we will go on to define macroscale properties; such as the internal energy specific heat and so on and also we can deviate a little bit, although this is not rigorous statistical thermodynamics use can also use kinetic theory. See there are two ways one is a rigorous derivation of all these classical constitutive relations from the nanoscale transport process and that is what we will do, but they can also a bypass and do a less rigorous way from what is called as kinetic theory. Kinetic theory of gasses for example, from that we can actually derive again this constitutive relation, but they are little bit hand waving and they are little bit less rigorous, but we can also do that. So, ultimately once the equilibrium distribution functions are understood from statistical thermodynamics within deviate and goes to the non equilibrium transport processes.

So, what nanoscales know unlike the continuum scale even the local transport process at non-equilibrium? So, everything is at non equilibrium. So therefore, how we understand the transport phenomena happening with the local non-equilibrium, what we will study and the particular equation to describe this is called the Boltzmann transport equation.

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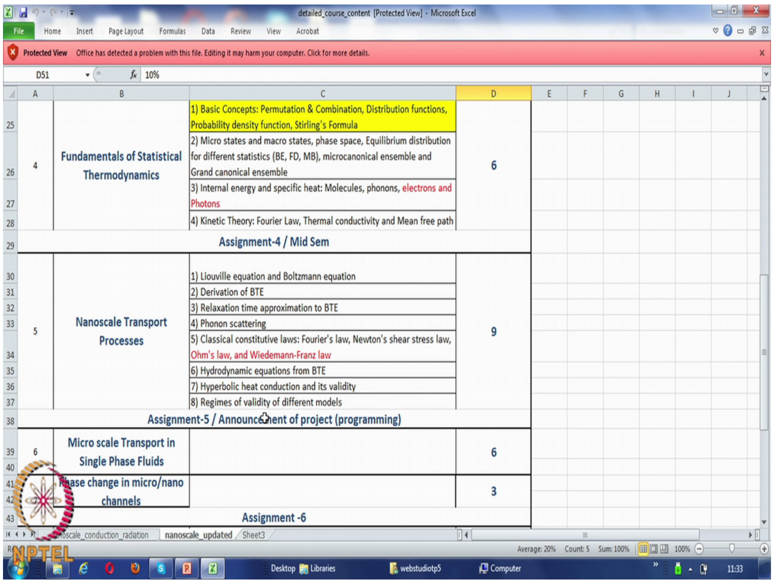

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A	B	C	D
4	Fundamentals of Statistical Thermodynamics	1) Basic Concepts: Permutation & Combination, Distribution functions, Probability density function, Stirling's Formula	6
		2) Micro states and macro states, phase space, Equilibrium distribution for different statistics (BE, FD, MB), microcanonical ensemble and Grand canonical ensemble	
		3) Internal energy and specific heat: Molecules, phonons, electrons and Photons	
		4) Kinetic Theory: Fourier Law, Thermal conductivity and Mean free path	
Assignment-4 / Mid Sem			
5	Nanoscale Transport Processes	1) Liouville equation and Boltzmann equation	9
		2) Derivation of BTE	
		3) Relaxation time approximation to BTE	
		4) Phonon scattering	
		5) Classical constitutive laws: Fourier's law, Newton's shear stress law, Ohm's law, and Wiedemann-Franz law	
		6) Hydrodynamic equations from BTE	
		7) Hyperbolic heat conduction and its validity	
		8) Regimes of validity of different models	
Assignment-5 / Announcement of project (programming)			
6	Micro scale Transport in Single Phase Fluids		6
	Phase change in micro/nano channels		3
Assignment -6			

So, I call this as BTE here, BTE is the acronym for Boltzmann Transport Equation and this is the most fundamental equation for describing the transport process at non equilibrium scale for any energy carrier. It could be electrons it could be pronons, protons I will come to these definitions one after the other a yeah and it could be molecules and we will talk about again. Now the rigorous derivation of the classical constitutive laws again from the Boltzmann transport equation such as the Fourier's law Newton law and here you will see that we can also do that for the electrical engineering like ohms law Wiedemann Franz law.

So, at fundamental scales their governing transport equation is the same. So, it only depends on what kind of macroscale system you are looking if you are looking at the fluid mechanical system you look at Newton's law or if you are looking at a heat transfer system Fourier's law you are looking at electron transport you can derive the Ohm's law then for metals we have the Wiedemann Franz law and so on.

So, also not only the constitutive relation, but also the macroscale transport equations the conservation equations what we call because, we derive this for a control volume in the conservation form can then, you can either do it in a differential form or you can do an integral form of this conservation equations. But nevertheless what we call as these macroscale transport equations can also be derived from the Boltzmann Transport equation and this is what we will do and will particularly focus on heat transfer and then, show that what we understand by the continuum heat transfer need not be valid at small length and time scales. So, and if either of these conditions also does not meet then the assumption of continuum will fail. So, it is not just small lengths scales, but also time scales.

So, we will look at deviation from your Fourier's heat conduction equation and what can be possibly done to compensate for this non equilibrium heat transfer process. So, these topics 1 to 5 are particularly focused on the nanoscale processors. So, you are looking at nearly sub continuum level here now. Then we will move on to continuum level, but something at the scales of the microns to 1 millimeter or 2 millimeters; where you have some certain interesting phenomena happening, but they are all happening still at the continuum level. So, to study that again we have to start with convection. So, when you talk about nanoscales there is nothing like convection nanoscales, all pure conduction because you are talking about each and every energy carrier and there is no bulk transport the level scale of the energy carrier itself, it is just collisions and transport of energy. So, it is primarily diffusion and therefore, when we talk about conduction inside the nanoscales. But when we talk about convection it is at the microscales. So, you have a bulk velocity and there is a motion of the fluid and so on. But there are certain interesting things associated with the surface forces that we will look at. So, that we classify this again whether we are looking at a single phase system or a multi phase system.

So, the single phase system again you have to understand what happens when, there is a fluid flow in a capillary tube or micro channel compare to a classical duct flow or a macro channel you know. So, what is the difference between these 2 and what kind of phenomena do you observe here. So, all this is in still single phase, but nevertheless this is different from your macroscale phenomena for one influence of gravity is now, reduced to a great extent that you see several of phenomena. That is, associated with know gravity effected by gravity in the macroscale.

Now disappears at the microscale. So, following this will also look at phase change. So, not only the single phase changes here. Now when I say phase change it is also phase change due to evaporation or condensation or 2 phase flows. So, 2 phase flows could be a simple mixer of air and water and then, you have different 2 phase patterns and the pressure drop and these kind of thing pressure drop parameters are affected by the different flow regimes arising out of simply mixing air and water in a classical t junction and then you just look at all the flow patterns an d study that. So, that is a simple two phase flow, but there can also be a state where you have purely evaporation and condensation. So, this is classical phase change problem.

So, how the phase change problem in micro nanoscale looks and how it is different from your macroscale phase change. So, this also we will spend at least a week understanding that and we will also briefly look at nano fluids because, on I mean although they are nano fluid. So, you do not have any sub continuum transport process happening there they are still in the continuum scale, but there are some important mechanisms such as know slip between the nano particles and the base fluid which could be at the micro nanoscales and also certain phenomena which is different from the conventional fluids. So, what is causing the anomalous change on the thermo physical properties of nano fluids and therefore, how they are utilized for efficient heat transport.

For example, they are now increasingly becoming efficient fluids for better heat transfer both in the conduction and in the convection sense. So, we will also pay some attention to nano fluid for some for a week or. So, and finally, we will look at the applications. So, I am not going to cover applications while describing the fundamentals, but towards the end because I know many of you have some idea about the applications of micro nanoscale transport. So, I will talk about some applications may be mostly in micro fluidics and nano fluidics and. So, therefore, we have about material for 15 weeks.

So, I think this is basically the theme of this is how the course content has been resigned. So, we see that we are covering quite of bet you are not just focus sing only on connection or conduction, but we are covering as much as possible the breadth of the subject is quite large and therefore, we have to see how much at attention to detail we pay under each topic and this is where the diversity of the audience come to play. If man y of you have a good understanding of say quantum mechanics or the statistical thermodynamics then we could have been much faster.

But what I understand is there are some of you from the b tech background some of you are fresh from your bachelors and you are come into the MS or PHD program. So, I do not think I can assume that all these to start with. So, therefore, wherever possible I will just spend enough time, but at the same time I cannot spend a lot of time teaching only quantum mechanics in this course. So, we have to also cover other topics as well. So, we will give some attention, but not too much and then I also ask you to put your effort into going to the references and reading them.

Now, do not just depend on only my classroom lectures for understanding the fundamentals. So, I will also point you towards some of the important text books. So, let me come back to the presentation here.

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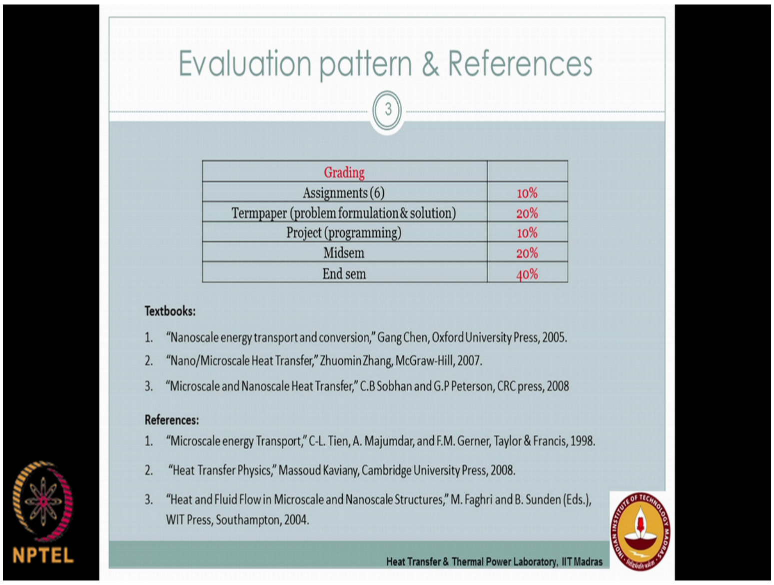

Evaluation pattern & References

Grading	
Assignments (6)	10%
Termpaper (problem formulation & solution)	20%
Project (programming)	10%
Midsem	20%
End sem	40%

Textbooks:

1. "Nanoscale energy transport and conversion," Gang Chen, Oxford University Press, 2005.
2. "Nano/Microscale Heat Transfer," Zhuomin Zhang, McGraw-Hill, 2007.
3. "Microscale and Nanoscale Heat Transfer," C.B Sobhan and G.P Peterson, CRC press, 2008

References:

1. "Microscale energy Transport," C-L. Tien, A. Majumdar, and F.M. Gerner, Taylor & Francis, 1998.
2. "Heat Transfer Physics," Massoud Kaviany, Cambridge University Press, 2008.
3. "Heat and Fluid Flow in Microscale and Nanoscale Structures," M. Faghri and B. Sunden (Eds.), WIT Press, Southampton, 2004.

So, let me discuss the grading pattern first. So, I would say the grading pattern has been distributed fairly between the different aspects that are required for you in order to understand an elective course. So, you have to understand that an elective course is fundamentally different of course, we also teach in class we use the board or we use the power point the same way, as core course is start that what is the difference elective course is suppose to be where you people have to do a lot more work then; their faculty member this is what we have to understand. So, this is this is the basic theosophy of offering electives the reason is that you gain some fundamental understanding from the core courses which are thought in classic texts books sense line by line you understand certain definitions principles and so on.

But then when you apply this to a more complex system you know. So, these are not very, very well structured and well defined. So, we have to do it by different ways it is not just writing an exam that will make you understand. So, you have to do lot of assignments you have to do some reading on your own you have to work on projects. So, this is where your involvement and interaction becomes more important in elective courses. So, typically we will have about six assignments 6 to 7. I would say we will see how many things we can club together that carries that will carry about ten percent of the overall Weightage and then what I want to give will be a project that will be towards the end, but mean while I think you should also work on a term paper. So, it could be I just put in bracket here does not mean these are hard coded could be something like you define; some problems in each topic you come out with the problem formulation and you solve them yourself and that is the way of challenging yourself into understanding that particular topic and these problem should not be from any of these text books.

So, this is the condition it could be similar do not just change the numbers and define the same problem that is not acceptable, but could be on a similar structure. But it is a different problem it could be a numerical problem it could be a conceptual problem and you come out with the solution. So, like this for each topic you have to each per student should take up one problem formulate a problem under solution, so we have for example, defined about nine topics here right, under each topic. So, each student should take up one particular problem formulate come out with the formulation and also the solution. So, it could be a numerical problem or it could be a theoretical problem also.

You understand what I am saying. So, the thing is it will also encourage you to come out with a problem which is different from what I usually give as an assignment. So, it will also make you more confident into applying what you learnt. So, this is the idea behind this particular term paper and this will therefore, be done though out the semester this is not only at the end of the semester. But you have to continuously do that and as and when we cover the topics and I give you the assignment the particular term paper conserving that assignment. If the assignments spans a quantum mechanics and statistical thermodynamics, you are suppose to also complete problem formulation and solution for these 2 and then hand it over to me a after the assignment of that particular topic is over.

So, this is the continuous process and apart from that we have will have a project it will be basically programming because we cannot ask you to do experiments at this particular scale. So, it could be solution of certain questions and studying certain energy transport in certain systems, we will try to do it as simple as possible for you to understand what is start here and we will also have exams the I mean will have only one mid semester which will be twenty percent it looks a little bit on the lower side, but we are giving a lot of a emphasis. So, forty percent emphasis on the application parts and the end semester will be forty percent right.

So, the following are the text books that I will be closely following. So, one is the book by Professor Gang Chen from MIT. So, this is nanoscale energy transport and conversion. So, this came out sometime in the year 2005 to 2006. So, that was the first text book to basically address the aspects of sub continuum heat transport this is the first text book. So, there was one text book before that that is the one I have put in know references number one. So, that is by Professor Arun Majumdar, A U C Berkeley and his Professor C L Tien, who passed away he was a chancellor of U C Berkeley.

Before, one of the pioneers who started work on microscale heat transfer process C L Tien, he was the mentor of; so, many illustrates people in the areas of heat transfer in the US. So, and he passed away and then Professor Arun Majumdar is a he was working and now I think he is also more political frame work, he has taken some significant positions in the US. So, he is not for say I think doing fundamental work much now a day’s yeah, but Professor Gang Chen is still quite active and his students are also quite active in this area. So, therefore, this was a first text book as far as I know 1998 this came out, but this had everything starting from nano micro.

So, at the time there was no clear delineation of where we should stop the nanoscale transport and then continue micros everything was club together. So, many people were still trying to understand how only nanoscale heat transport should be start and that is when Professor Gang Chen in 2005, wrote a text book only on nanoscale energy transport. So, there is absolutely no microscale in that. So, completely fundamental it is a very, very well written book and still one of the best textbooks for this subject and following that I think Professor Juamin Gang from Georgia Tech he also brought out another text book on nano microscale heat transfer.

But it is more or less similar in substance to the Professor Gang Chens text book and still it is the very useful as a supplement there is a lot of examples and also solid examples and as well as exercise problems and there is a another book which is by Professor C B Sobhan, he is from NIT Calicut and he is spent considerable amount of time working with Professor Peterson at also in the u s. So, so they have written a book called micro nanoscale heat transfer which does not have much emphasis unfortunately on the nanoscale heat transfer part it is mostly microscale micro microscale heat transfer like flow into channels micro channels and so on.

But the fundamentals are not that extensively covered in this text book like the text book number one. So, also the references, if you look at microscale energy transport by Professor T N Majumdar and, this is also very good one although there are many aspects of micro scale heat transfer overlapping the nanoscale in that there is another book by Professor Massoud Kaviany from University of Michigan. So, this is called heat transfer physics. So, you see the title heat transfer physics. So, all it is not written for heat transfer engineers. So, the physics part here means that there is a lot of quantum; Mecha quantum mechanics is not that much.

But there is a lot of statistical thermodynamics at least. So, he has dealt with heat transfer the way it is suppose to be understood by a person with a physics background and this also has some very interesting content and there is another book for the micro flow part the convective heat transfer in micro channels and so on. So, that is by Professor Pagry and Sunddon the heat and fluid flow in Microscale/Nanoscale structures this is also a good book 2004 and there is another book also that I follow which is on a Microscale flows by Professor Brian Kirby KIR by Brian Kirby. So, this is also a recent text book related to micro flows and this particular text book also as lot of applications in medical field, in biotechnology and so on.

So, it is starts with very good fundamental introduction and then slowly towards the end the end of the book it looks at also applications in micro fluidic applications in medical field biotechnology and so on. So, Brian Kirby is also another good text book and. In fact, Professor Brian Kirbys, website Karnal as also some portions of this text book posted online and there are also lectures video lectures of him talking about derivations of these equations in for micro fluidics and so on. So, well these are the text books and I am I am not very sure whether all of these are available in your library, but at least I am I am sure that Gang Chens books that should be a copy or 2 which I had put an order request some 2, 3 years back and they had couple of copies at that time.

So, you please check and if you do not have access to these books you let me know and we will say what we can do, but primarily you should have a at least 1 or 2 text books and references with you because you know. In fact, I have not given the references for quantum mechanics statistical thermodynamics and all those here, but there are many-many books for those; if you look at quantum mechanics there are. So, many books the one book that I usually follow is David Griffiths. So, that is our classical text book on fundamentals of quantum mechanics. So, David Griffiths and that is, very well written and normally any engineer should be able to follow that and there are also many books on statistical thermodynamics. So, it does not matter you take up for example, thermodynamics of materials.

So, if you look at thermodynamics that is start to material scientist and metallurgy lot of statistical thermodynamics are covered in that. So, any text book which deals with thermodynamics of materials should have a reasonable portion of statistical thermodynamics all right. So, so these are the major text books that I have listed here, but you should supplement these with the particular text books for quantum mechanics statistical thermodynamics and so on. So, all of these books do not cover these in a great detail, but if you want to understand the basics you have to go back to the corresponding text books.

So, far any questions on the overall structures I have given you a very big picture I think on this particular course, I think what you typically need on the very first day and now you have to decide whether your expectations are being met in this particular course or not, the emphasis we will be mostly on the fundamentals. So, fundamental understanding to get a clearer picture I hope unfortunately, it is also very mathematical. So, I will try to see if I can reduce the mathematical aspects a little compress them a little bit, this time because the very first time I thought, I am myself realize the student found it very mathematical and therefore, there were sometimes lost in the equations to understand the clearer picture.

So, this time I will try to compress that and I will also try to bring out the physics as much as possible. So, if you have any questions then we can talk about that we do not have much time, but I will just stop with this quote this is the starting point of every text book on related to nanoscale energy transfer.

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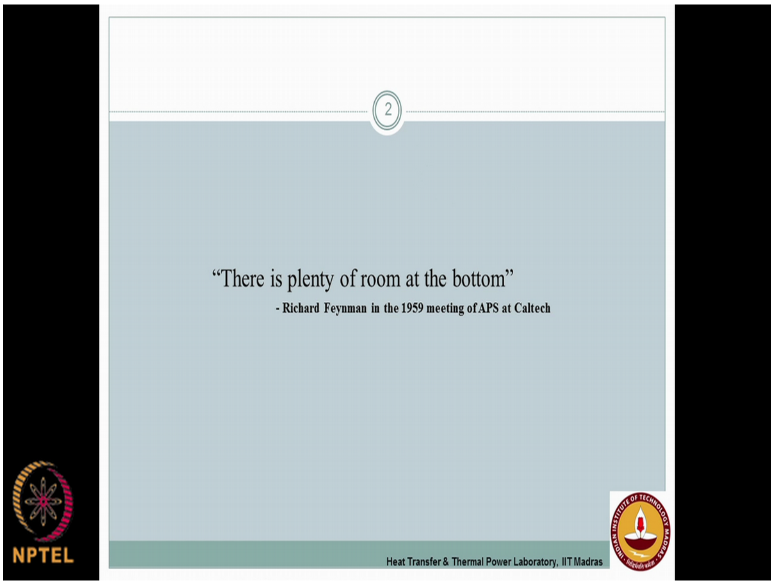

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"There is plenty of room at the bottom"

- Richard Feynman in the 1959 meeting of APS at Caltech

Heat Transfer & Thermal Power Laboratory, IIT Madras

This was the famous quotation by Professor Richard Faynman in his lecture at the American physical society held at Caltech in 1959. So, there is plenty of room at the bottom. So, yeah I mean this is quoted for everything pretty much related to micro nanoscale need not be heat transfer it could be something else. So, physicist also quote this in the now a day's engineers also starting to quote this, but nevertheless means that we are now seriously have a dealing with systems, which are much bellow the scales of what our physical senses can resolve and therefore, we have to understand even though we cannot see this kind of phenomena with our observation with our physical senses.

We should be able to see how we can capture them know in whatever possible way know we have understood this. So, far it does not mean that whatever we have understood is complete there is still a lot of room people still are struggling to understand phenomena at these scales, but nevertheless some picture as emerged and let us try to at least understand part of that in this course and our emphasis will be primarily on energy transport. So, the energy transport here means it could be say fluid flow in the convection sense or it is heat transfer in the conduction sense. So, this is our primary emphasis for people who are working in a electrical engineering the energy transport could be flow of current and things like this so, but as I know people from mechanical sciences our emphasis should be on these 2 aspects.

So, with this I will stop here and tomorrow we will get into a more detailed introduction on this subject.

Thank you.