Particle Characterization

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Summary

Welcome to the fortieth and final lecture in this course on particle characterization. I thought we would use this last lecture to essentially review, what we have covered in this course, and point out aspects which have been included in the curriculum, and aspects which have not, and which really merit further study on your own.

Now, you know particles are very complex objects, and in a sense, it is like the story of the elephant and blind man. People that work with particles have very specific focus areas and that what they tend to concentrate. And so, depending on the application that the particle is used for the investigators focus is very different. For example, if you are a researcher, and you are really trying to understand some fundamental characteristics of particles, the way you approach a subject will be very, very different; you will want to concentrate on individual particles and their characteristics, you would want to manipulate individual particles, and really look at how they behave under various types of applied forces, various environmental conditions and so on.

On the other hand, if I am running a factory, and I am dealing with particles of various sizes, various properties, then my interest is not going to be so much on characterizing particles from an analytical view point, but rather characterizing them in a functional manner, in terms of how the particles behave in the specific process that I am trying to run. So, conventionally when people talk about particle characteristics or particle characterization, what they really talk about is the analytical part. So, most of this discussions start with doing microscopic analysis of the particles or doing addax analysis for doing composition analysis or doing x r d for crystal structure analysis, or doing a f m for 3-D morphology characterization, but that is only a very limited aspect of particle characterization, because all that that tells you is some specific properties of the particles, but they may or may not be relevant for the application that your trying to run.

So, your definition of particle characteristics and particle characterization has to be broader than the very narrow scope, that many people mistakenly use when describing particle characteristics. So, the beginning and the end point of your study of particle characteristics should not be based on analytical techniques. Analytical methods and instruments are useful tools, but they are not an end tool themselves. You use these equipments in order to obtain certain basic understanding, whether qualitative or quantitative about the particulate system that you have at hand, but that is only a necessary step it is not a sufficient step that is where it begins but that is not where it ends.

So, for example, let us say that you are running a cement factory, right, you need to understand particles, you do because cement is essentially particulate media and by the way, that is you know fundamental challenge with particle technology; solid material cannot be used in bulk form in many industries. So, you have to break it down and use it in particulate form. So, virtually every manufacturing process industry that deals with hard products uses particles in its processing they may not realize it, but that is what they are doing and unless they have a good understanding and insight regarding, how these particles are going to behave in their system. They are not going to run a very efficient process and a lot of these factories that make products that involve particles or essentially designed based on very empirical considerations, you know there is a process that is been handed down from generation to generation; they keep running it forever. Without properly understanding the mechanisms involved the fundamentals of the materials that are being used in the process and so on. You know but when somebody puts in appropriate thought and consideration into what is happening to these particles in their process and how their handling and their processing can be improved, there is a lot to be gained. So, the basic message is particle characterization is something that should really we thought of in a very systematic and very comprehensive way and that is essentially the sequence that we have try to adopt in this course. If you recall, we started out by essentially classifying particle characteristics and we said that there are morphological characteristics, there are structural characteristics, there are interfacial characteristics, there are chemical characteristics, there are transport characteristics and finally functional characteristics of particles.

This is kind of the broad classification of particle characteristics, a subset of this is the analytical characterization of particles and in particular, we did spend I think 2 to 3 lectures talking about microscopic techniques x r d and a f m, because these are very powerful instruments that are used very very widely in particle characterization. But again, I do not want to give over or undue importance to the use and description of these analytical tools, again in terms of additional reading, additional understanding .There are text books written on each of these techniques, there are text books on s e m text books on t e m text books on x r d text books on a f m.

So, you should certainly browse those materials in order to broaden as well as deepen your understanding of how to do analytical characterization of particles, but in this course what we have try to emphasize is the fact that again that is only component of your overall understanding of how particles exist and how they behave. So, if you look at the first module that we covered in this course, we spend a lot of time talking about shape analysis and you know the reason for that of course is that when you look at a particle, the first thing that jumps out that use the shape. So, you cannot really do particle characterization unless, you take the time and effort to first characterize the shape.

And so, he first few lectures were devoted to shape analysis and the key points are I want you to take away from that are shape is a qualitative characteristic, unlike size which is quantitative. However, it is interesting that size is not an absolute parameter size is always relative to something, whereas shape even though it is a qualitative characteristic in a sense can be quantified more precisely. It is not as dependent on the measurement method as sizes it is a kind of an interesting contradiction that you have there, but in terms of shape analysis then given the fact that it is not an absolute measurement. You basically get out of it, what you put into it? So, more the effort that you put into shape characterization, the more detailed an understanding of shape will evolve. But as we discussed during the lectures, there is a breakeven point, you know what is the threshold - that you want reach how much, how detailed an understanding of shape do you do you want have and usually you have to reach an optimum setting based on the cost of doing analysis verses a cost of not doing the analysis. So, depending on how sophisticated your analysis needs to be and how precise and detailed your quantification or qualification of shape characteristics needs to be? You decide, how much is enough? Right.

You may decide that you only want to do a simple visual inspection or you may want to you to do optical microscopy or you may want to do e d x or t e m, s e m type of analysis or even a f m analysis. So, depending on the time you put in to it and the cost of the equipment. You can certainly get more and more detailed understanding of particle shape, but finally you have to make the decision as a process owner, as to how much is too much. Now, when we discussed shape, we also said that there are categories of methods that are used for doing shape analysis.

In the old days, when sophisticated instrumentation was not as widely and freely available, as it is today; people tended to represent particles by a single dimension. The diameter being the most you know convenient way of representing shape. So, virtually every particle was classified as a spherical equivalent and given a diameter. Now, the next logical step was to represent shape in 2-dimensions essentially, one long dimension and one shorter dimension. So, the l by d ratio basically came into play as a shape indicator as or methods of analysis improved, we started obtaining 3-dimensional images and metrics were particles. So, the l d w type of approach where you define 3 orthogonal directions and 3 characteristic sizes in each dimension, were then adapted as a way of characterizing shape.

So, again in these methods, shape is actually being obtained by first doing size analysis. You are actually measuring dimensions in various planes and by considering certain ratios, you assigned shape but there are other methods that we discussed, which have more recently evolved that essentially digitized the profile of the particle and then use very complex algorithms to extract the main features of the profile and essentially by doing spectroscopic analysis and comparing it to a library of shapes in a data base you can assign very precise shapes to the particle. So, you know on the one hand, we have the very simple 1-d or 2-d representation of shape. On the other hand, you have the very detailed mathematical description of the particle profile and where you want to be again depends on what your process is what your application is and what you are trying to achieve with your shape analysis.

Now, when we talked about size characterization, the considerations are very different because in size analysis, the basic decision you need to make is or you going to try and analyze at single particle level or at powder level, because that really drive something else, if you decide that you do not need to do size characterization at single particle level, but you just want to an average or mean size of a population of particles then your job is much easier. And typically in that case, what you do is dynamic testing, you set this particle powder in motion and look at its dynamics under various applied fields, whether it is a sieving process or whether it is a gravitational sedimentation process or a centrifugal process or a diffusional process.

We discussed various methods of setting the particle population in motion and based on the transport characteristics, extracting information regarding their size, so that is an approach that works very well in essentially in bulk processing industries. Where what will they care about is how you know entire quantum of material moves through the process rather than how each individual particle moves, but supposing you do need single particle information on size, then essentially the challenge is really getting it captured in such a way that the single particle is stationary long enough for you to be able to analyze it.

Because particles are constantly in motion, you cannot hold it in place unless you apply a certain force to it and especially as particles gets smaller and smaller and start approaching nano dimensions their tendency to move is much greater. So, the huge challenge and single particle analysis is actually the collection. Once you have immobilized it on a surface for analysis, then the problem actually becomes much simpler. So, we talk quite a bit about how particles can be captured for analysis, we talked about filtration equipment, cascade impactors, impingement settlers, diffusion screens again all of these make use of the fact, that particles move in a predictable manner. And therefore, they can be collected and classified on the basis of size and then once you have immobilized them on a surface. You can then do your microscopic analysis or other types of surface inspection. In order to do size characterization, simultaneously with shape characterization, but many of these techniques are what I would call qualitative techniques, because a microscopic analysis is very laborious, very time consuming and there is quite a bit of uncertainty involved, because when you are doing manual inspection, especially you can only look at a very small percent of the sample and you are essentially extrapolating your conclusions from this very small sample size.

So, huge error involved in doing any kind of manual inspection for size characterization. And therefore, in if you want to do reasonably accurate quantification of size, then other techniques have to be looked at where you can sample much larger fractions of the sample volume. So, we talked about two methods, in particular that are very widely used -one based on light scattering and one based on the interaction of an acoustic field with suspended particles in a fluid. And you know laser light scattering is a very good technique to use for dilute suspensions and it can enable us to characterize particle size, all the way from nanometers to millimeter size. The problem is that a need do a very dilute suspension and b the scattering intensity drops as particle size to the power 6. So, as the size starts approaching the sub-micron and the nano dimension, the scattered intensity becomes very week and therefore, the laser scattering method loses its usefulness. So, we talked about a couple of methods for addressing that essentially the condensation nuclei counter approach, where we actually get fluids to condense on the outer surfaces of these particles to grow them to a size, where they are large enough to be detected using a laser scattering or light scattering instrument.

The alternative approach particularly useful for more concentrated slurries and suspensions is a use of acoustic attenuation spectroscopy, where you essentially irradiate the suspension with acoustic fields of varying frequencies, and by studying the characteristics of how these waves are absorbed and transmitted, you can actually get a very good description of the particle sizes that are present in the solution, again ranging from nanometers to millimeters in size. So, shape and size characterization we spent quite a bit of time over, because at least to me they are the two most fundamental or basic characteristics of particles and everything else is somewhat secondary.

Now of course, the third thing that you want to understand about the particle is its structure what does surface look like, what is the subsurface looking like and what is the core of the particle looking like, because the core is what represents the particle material at its purest, the surface has incorporate in an it influence of the manufacturing environment that the particle has encountered.

So, there is a large gradation in the properties of the particles as you approach the core of the particle from the surface and the so called sub surface region represents the regime, where the transition from surface properties to core properties takes place. So, in this context we talked a little bit about the structure of the surface, the structure of the sub surface and the structure of the core, but more importantly we focused on the interaction of the outer surface with its surroundings, because the particle never exists in isolation.

It is always constantly trying to interact with its immediate neighbors. Now, when you have a particle and it is suspended in a gas, the well initially the formation of the particle itself requires a certain energy transfer to happen because your essentially taking a either molecules and building them to make particle or you are taking a large surface or object and breaking it down to make particles, in either case, you have to supply energy to make it happen so the excess energy that is left is then retained by the particle as its surface energy.

And the magnitude of this surface energy really determines the extent of its interaction with its nearest neighbors. So, we talked a little bit about the definition of the surface energy parameters. Parameter which is a thermodynamic quantity and we also talked about how the surface energy parameter influences the interaction of the particle with its surroundings, for example, if the particle is interacting with the another particle the surface energy determines how aggressively the two particles are attracted to each other and also repelled by each other.

So, the surface energy parameter plays directly into the inter molecular or inter particle van der Waal forces of adhesion, which are characterized by the Hamaker constant and as the surface energy increases. So, does the Hamaker constant and therefore the force of interaction between the particles also increases. Now, before we got in to particle to particle interactions and particle to surface interactions, we also talked little bit about adsorption. Obviously in terms of particles that are suspended in a gas. The adsorption of the gas on to the particle is a very crucial mechanisms for us train to understand.

So, we talked about the Langmuir isotherm and also we talked about the models that allow for the existence of more than one layer of adsorption. So, the tendency of a surface to adsorb a gas molecule is a very crucial link that determines, how a gas interacts with the particle, even in the absence of any chemical effect, you know the physisorption effects are important to understand even before we start talking about chemical reactions and so on. And now, so in terms of particle to surface interactions, we talked about adhesion and adhesion again the van der Waals forces are the most basic forces of attraction between two solid surfaces, but we also talked about various other forces of attraction and repulsion.

Electro static forces, we talked about surface tension based forces, viscous forces and so on the net effect of all these forces on adhesion is essentially that adhesion force scales as particle size.

So, as a linear dependence between adhesion force and particle size, so as the particle size increases the force of adhesion will also increase proportionally. And then we talked about particle removal from surfaces, which for the most part can be characterized as having a square dependence that is removal force scales as square of the particle size and that is the reason why if you look the reason, why finer particles are harder to remove from surfaces it is because the particle removal forces drop much faster than particle adhesion forces. So, it becomes progressively more difficult to remove particles from a surface as they become finer. So, in that context we talked about certain methods of particle removal which are less size dependent.

In particular ultrasonic removal and mega sonic removal, which essentially create fields that remove particles by a mechanism that is very different from the normal shearing mechanism that is used in conventional methods of removing particles from surfaces, like sprain for example.

And then later, we discussed cohesion, now cohesion is different from adhesion in the sense that we talk about cohesion between adjacent particles, whereas adhesion essentially refers to the attachment between a particle and a surface that it comes in contact. Now, cohesion is a phenomenon that essentially involves two particles coming together and essentially forcing the fluid molecules in that out of the way in order for them to find each other.

So, here again, we talked about various types of interactions. The hydrophobic, hydrophilic interactions, the effects of an electronic double layer around the surfaces of these particles and what that can do in terms of either keep it the particles separate are getting them to find each other. In particular, we talked about forces that coming to play in cohesion that are not seen in particle to surface adhesion phenomena, in particular the fact that two particles in suspension behave like they are attached by a spring.

So, there is a compressive force that is involved in a normal direction and there is a tangential or shearing force that is involved as a particles, try to move away from each other and also there are viscous forces involved in terms of the change in the nature of how particles are attached in suspension. So, essentially you can go from very simple liquid bridging of two particles to larger macroscopic formulations where multiple particles can be brought together essentially, forming a cluster or a droplet in the end. And the forces of cohesion essentially increase as the surface area of interaction increases and for a nano particle or a very fine particle the tendency for cohesion is much higher primarily, because they are more active when they are moving around with higher velocities. So, it is easier for them to find the nearest neighbor.

So, if you look at the ratio of inter particle separation distance to the size of the particle that is a very important parameter, as the inter particle separation distance starts to approach the size of the particle itself the probability that a particle will actually find another particle, rather than finding a molecule of the surrounding fluid becomes higher and so as a concentration of the suspension increases.

As the mobility of the particles that are suspended, increases it becomes increasingly possible that particles will attach to each other. In cohesion becomes something that we need to be aware of and we need to deal with. Now, in many industries cohesion is to be avoided. So, there are techniques that have been developed over the years to keep particles, apart during the time that they are suspended and similarly, surface to particle to surface adhesion is also to be avoided in many cases. Because you know particles are usually processed in such a way that they will encounter solid surfaces, during the process but you do not want to lose particles due to attachment to the surface. So, whether you have particles that are flowing in suspensions across the surface or whether it is something as simple as powdery material that is kept in a valve. You do not want the powder particles to stick to the walls or the bottom of these valves, you know when you shake the test tube or valve, and you want all the solid material to discharge. So, even simple things like that or in the larger scale you know you are keeping grains in a silo. And you want to discharge the grains, you want the grains to flow in a uniform and constant velocity manner and you do not want to see clumping, you do not want to see channeling? There are so many behaviors that can happen, if layers of the solid material or particles start to move in a coordinated manner rather than in a completely uncoordinated manner.

So, from the view point of flow ability, from the view point of storage and dispensing you want to minimize cohesion. So, that is a reason that these phenomena are important to understand and characterize. Now, particle transport in general is another aspect that we dealt with quite a bit, because transport characteristics are very important for us to understand, if we want to be able to use particles effectively in our process. So, based on size, we said that diffusion can be an important mechanism phoretic phenomena are very important to characterize and understand convection is obviously plays a major role, whether it is force convection or natural convection.

If the flew, if the particle is of a size that it can follow the stream lines of fluid flow. Then convection becomes a predominant mode by which particles are transported from one place to another and then we talked about interception, which happens when a particle comes in contact with a surface and preferentially attaches to the surface rather than staying in the fluid, and when we talked about inertial impaction, you know as you keep going up the size scale, once you exceed a certain critical stokes number inertial impaction, becomes a dominant mode of transport of particles and of course that the larger sizes body forces become important.

So, gravitational sedimentation and so on, become key mechanisms for how particles are transported in a system. So, if you look at this entire range of particles sizes and the associated transport rates you will see that it is very important for us to understand the size distribution first. So, that we can relate that to the transport behavior that we see for the suspension, of course related to transport is deposition transport leads the particles to land somewhere, right I mean there is usually a sink in a process just like there is a source for particle, there will be a sink for particles.

And it is a transport phenomenon that determine, the rate at which they sink. And so deposition is a different, consideration from transport because a surface across which a large transport flux is happening may be characterized by a low deposition flux, because the two, although they are related it is not a 1 to 1 relationship and the critical parameter, there is the sticking coefficient. So, this sticking coefficient for the surface is low then even though, the transport flux may be very large, the deposition flux may be very small.

And this sticking coefficient again is very much dependent on parameters on the stokes number, then in general the higher the stokes number the greater the sticking coefficient. Although when you look at very fine particles, the sticking coefficient can again increase because of again the inter molecular forces of attraction and so on but in general as particle size increases the sticking coefficient will increase and therefore the rate at which deposition happens will increase as well.

So, in many process industries particle transport and particle deposition are very important considerations that we need to understand and characterize. Certainly, with a background in fluid mechanics with the background in mass transfer with the background in heat transfer you know that should not be difficult to do but one thing we need to remember is particles are very inter disciplinary in nature.

They are exist at the interface between solids, gases and liquids. So, in order to get an understanding of how particles behave, you need to have an understanding of all 3. you need to know, how solids behave, you need to know how gases behave and you need to know how liquids behave, because a particles is essentially a combination all three; most of the time the other important consideration in our transport analysis is whether we can treat it is as a single phase flow or you have to treat it as a multi-phase flow.

So, essentially in single phase flow, the assumption is that the particles are small enough that they can be treated essentially as heavy molecules in the flow in which case you can use the single phase flow assumption, but if the again the stokes number is larger enough the particles have sufficient inertia, you cannot treat them as a simple heavy constituent of the fluid, instead you have to treat it completely, separately as the second phase.

So, the multi-phase so, the multi-phase flow verses single flow decision it is a very crucial one in our modeling of how particles are transported and of course you have to treat the fluid flow as a multi-phase flow frequently, you have to use a Lagrangian type of analysis, where you try to follow the dynamics of each particle individually; which certainly leads to increasing complexity in analysis, but at same time better precision in your model.

So, after we discuss transport phenomena and deposition phenomena, the next aspect that we consider was the chemical and compositional characterization of particles and here is where we went through the laundry list of all the analytical equipments that is available and from a from that view point, you know the analytical physics, analytical chemistry that is applied for particle characterization there is a huge amount of material that is available, which you can access and read, based on your particular needs of course one of the key aspects that is when you talk about chemical characterization of particles, it is not only the composition, but also how the particle chemically reacts with its environment. So, the chemical reactivity of a particle is very important to understand and we talked about specific example, such as dissolution, sublimation, burning of a fuel droplet as examples of where the chemical reactivity of the particle, plays a huge role in how it behaves in a system, you know when you look at for example chemisorption verses physisorption – right – chemisorptions: is much stronger, because when we have two material can interact at a molecular level and react chemically their bonding is much stronger. So, in general, if a particle is able to react chemically with its environment, then we extent to which the environment influences a particle is much greater.

If the only reaction is physical in nature, then the interaction is much slower and also much easier to study and to quantify. So, when we talk about chemical reactions, we have to start talking about applications, you know what are and so the last about one quarter of the course. We spent talking about particular applications, where particles are involved and trying to understand the role that particle characteristics flow play in each of these cases. So, we spend few lectures talking about nano technology.

If you talk about particulate science, particulate technology much of the scientific work that is being done. Today is in the nano regime, the kind of think that we have understood everything, we need to about particles in the micron and super micron sizes. But as a sizes shrink, we know that very interesting things happen. The properties of a particle change in a very non-linear fashion as you start approaching nano dimension, for example - the chemical reactivates much greater.

So, if you want to use particles for catalysis there is a huge advantage to be gained by using nano catalyst verses micron size catalyst and so, nano technology is one area, where it is fertile ground it is essentially hard technology now and for a particle scientist it is a very exciting field to be end. So, during our discussion of nano technology, we talked about nano synthesis of nano materials from the top-down approach and from the bottom-up approach.

We talked about dispersion of nano particles it turns out that it is actually much easier to make nano particles than to keep them apart as nano particles. So, the dispersion whether in on a surface or in a fluid is very important to quantify. So, that we can try and control it and optimize it and so on. So, we talked about synthesis and dispersion in some detail and in the context of nano particles, we also talked about characterization, many of the techniques that we use for nano particle characterization are quite different from the techniques that we normally employ for larger size particles. So, you spend a bit of time understanding what are the sums of unique aspects of nano particle characterization? Later, we discussed applications, particularly in high technology manufacturing and when we look at for example, semiconductor manufacturing, which is a 100 billion dollar industry.

Particle behavior is of extreme concern to them, I mean these industries higher literally hundreds of particle scientist, just so that they can understand both the beneficial aspects as well as harmful aspects of particles, because all these industries use particles, because they are one of the building blocks of the product that you make whether it is a magnetic recording disk or whether it is a silicon wafer they all utilize particular technology for the for their benefit. But at the same time they also at the mercy of particular contamination, which is essentially undesired particulate material that winds upon the product and results in performance degradation or reliability losses or yield losses and so on.

So, the industries kind of try to approach particles in both ways, you know how do you handle particles that you want to have in the product, and how do you handle particles that you do not want to have in your product. So, we talked quite a bit about filtration methodologies, filtration technologies what are the mechanisms involved how do you ensure that you challenge the filter with particles of you know the right size. You know, if you want to understand how efficient a filter is you do not want to challenge it with a material that can it can easily filter, if you want to challenge it with material that it will find very difficult to handle. So, we talked about the maximum penetrating particle diameter or m p p d, which happens to be in the 0.1 to 0.5 micron size range then we talked about clean rooms in general. You know these are contamination controlled environments, where the particulate concentrations in the air are kept are below certain limits, we talked about clean room classes, we talked about surface clinginess levels all of these involves again understanding particle behavior in order for you to be able to construct and operate a clean room, you need to have a almost a complete understanding of how particles are generated, how particles are transported, how particles are deposited, how particles adhere to surfaces and how particles can be removed from surfaces? Unless you have a very good grasp of these 5 basic principles, we just cannot build an operator clean room very efficiently. And so, we talked about clean room methodologies, clean room techniques various sources of particles in a clean room, how they can be quantified, how they can be minimized and so on.

Now, moving away from high technology manufacturing, we also talked about some applications of particles in less high-tech industries for example, any industry that utilizes heat transfer equipment. We talked about heat transfer fluids their tendency to atomize and the associated exposure for explosions and so on. We also talked about solid particulate powders in the environment and how they can again be to ignition and explosion has its and how they can be quantified. We talked about particles that are present in the environment and how they can cause a health problems as well as environmental problems like acid rain and so on. Now, all of these aspects certainly involve some very key considerations, how particles behave in various environments it all goes back to particle characteristics, ultimately you can link the effect the behavior of particles in any system to their basic characteristics that we covered in the first one third of the course, you know it all goes back to size, shape, structure transport properties and so on. And so, what we have try to do in this course is essentially evolve a holistic understanding of particle characteristics and how they affect their behavior in real systems and real processors and we are try to give you a feel for what techniques and tools that are available for characterizing particles in terms of their most relevant properties. Now, where you go from here mean again, this course was essentially intended as an introductory course to give you a broad understanding of how particles are characterized.

Now, for each of you, as I was saying, you know it is the blind man and the elephant story there may be one aspect that is of particular interest or a particular importance. For example, if you are working in nano technology aspects of particle characterization that should be the most appealing to you or the ones that are specifically designed for fine particles. So, you need to have a good understanding of how to characterize nano particles, you know from a physical view point from a chemical view point. How do you measure particle size of nano particles very different challenge, you know compare to somebody who is working in an industry that involves huge boulders. The other interesting thing about particulate technology is that it encompasses a size range that is at least 10 to the power 6 orders of magnitude means some other can be working in nano technology and climb to be a particle scientist and someone can be working in coal mining they can also climb to be a particle technologies and they both have very valid arguments. So, particle technology is a field, which is so broad that you have to bring in multiple expertise and blend everything together in a very inter disciplinary manner.

You know there is a lot of emphasis, now on inter discipline, you need to search, particle science, particle characterization, particle technology has been in the fore front of this people working in this area have for several decades, essentially worked in a inter disciplinary research areas it is a very interesting and very exciting filed to get into and hopefully again this course has given you a feel for the various attributes of particles and you know what they can lead to I do erg you to not only review the lecture materials from this course but also do a lot of reading of your own on this particular aspects that again interests you in terms of whether you are working on a particular research problem or whether you are working in industry that employs particles you have to customize your learning to the problem at hand.

Again keep in mind that particle science, particle technology, particle characterization is a very wide field. Nobody can have a comprehensive understanding of everything that is involved. So, it is better to do segmentation identify, the specific regime that is relevant to you and try to deepen your understanding of that particular area. That to me is a much smarter strategy, then trying to understand everything about particles and the characteristics. So, I will stop at this point and any questions that you have feel free to ask. Now, if not I hope you had a good time with you, know the material that we have covered in this course and hopefully this has kindled your curiosity and you'll learn more about particles and their behavior and use your knowledge in a productive and beneficial way for all mankind.