Materials Chemistry
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Module - 4
Lecture - 2
Magnetic Materials – I

In this particular module and lecture, I am going to talk to you mostly about magnetic materials.

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And being the first lecture in this series on magnetic materials, I am going to consciously confine myself only to discussing the basic principles involved in magnetism, I am not going to draw any particular example, as we have done in other cases. So, in the next few lectures, we will go into some of the special cases and find out how the magnetic properties evolve in materials, both in bulk and thin films and in nanostructures.

So, in today's talk, mostly I would like to confine with some basic definitions and some understanding that is needed to view different class of magnetic materials. So, I just want you to confine only to some of the basic definitions of magnetism and let us see in the few lectures, how we can go about defining a various class of magnetic materials. So, in this talk, I will try to tell you the importance of the magnetic structure in a material.

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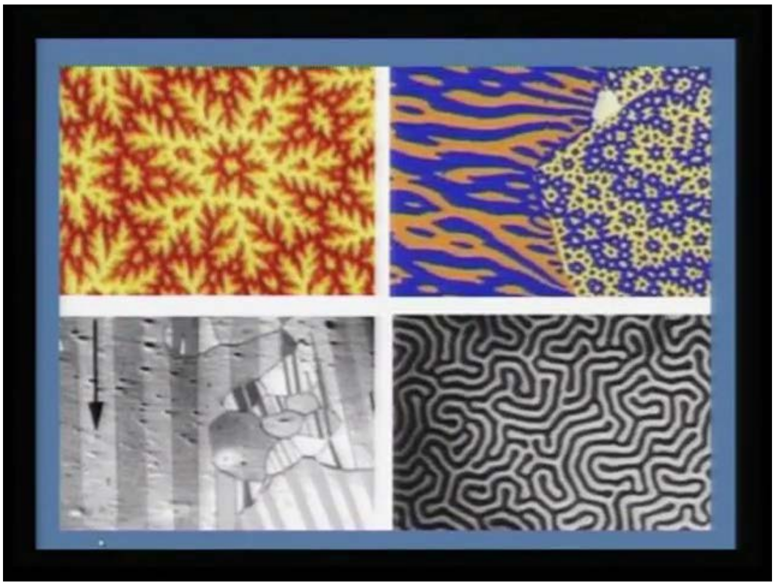

As you would see here, these are all very good cartoons of different materials, how they respond and give phase contrast, when it is under the influence of a magnetic field. As you can see here, the cartoon here on the right hand bottom, is actually a classic example of bubble memory material, where you can see all the stripes of these magnetic bubbles or magnetic stripes very clearly defined and they present a domain picture. Similarly, on the right hand side top, you can see the different range of magnetic stripes that are present.

Those in blue denotes a different magnetic environment, those in orange they show a different magnetic environment. Similarly, in thin films, you can see the phase contrast between a ferromagnetic and a antiferromagnetic stripe and because of this phase contrast, we can try to understand, what is the level of interaction or how the nanomagnetic domains evolve in different structures. And here again, you can see how the magnetic ferromagnetic domains are distributed in a given magnetic material.

So, before we understand, how this intrinsic property develops in a material, we will look at some basic definitions. I should also say that, it is very difficult to singularly isolate magnetism and discuss only magnetic property without discussing a correlated property. As a result, magnetism and electricity is one which goes hand in hand, when you think about electrical property, you also look into the magnetic property, because it is basically the charge and the spin of electron, that we are look at. Therefore, when you look at magnetic property, sometimes the importance of that study may have to do with the electrical property of those materials.

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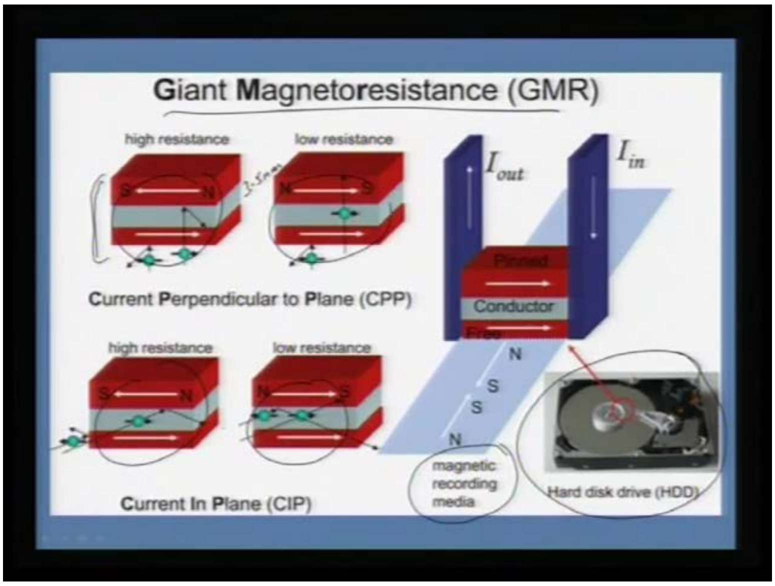

Therefore, when we think about the importance of magnetic material, again the example of giant magneto resistance comes vividly to our memory. And here is the classical example of, how magnetic information can help us order the electrical property in nanostructures. And this is a topic, which I will be dealing in detail in module 5 under electrical properties of materials. And this is one of the most fascinating magnetic nanostructure, which has affected today our hard drive and whatever we handle, our gadgets in terms of pen drive or i pod.

All this has to do with the discovery of giant magneto resistance where, you are talking about simple arrangement of three layers only, nano layers and these are all of the order of 3 to 5 nanometer in thickness. And how these ferromagnetic, antiferromagnetic or nonmagnetic layers are arranged and depending on the arrangement, either in a parallel fashion or in a antiparallel fashion, the whole idea of a hard disk drive or in other words, the read head can be engineered.

So, in today's life, as of now in 20th century, we are handling this spin wall nanostructures, which has nothing but, to do with alignment of this magnetic nanostructures, either in a ferromagnetic fashion or in a non-antiferromagnetic fashion.

So, when we study this magnetic property, we should understand this globally affects almost every spectrum of application in today's life.

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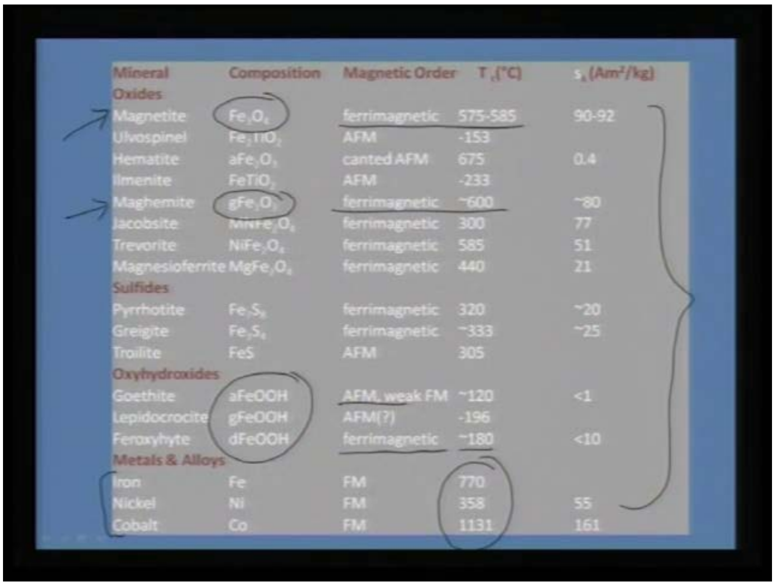

Mother nature has also gifted us with a lot of magnetic materials which are available, but some of this materials, as such have proven to be a great help in practical applications. For example, we have just come out of the age of using audio tapes, we are now more into other recording medias like i pod and other things where, digitally we record, we no more record using tapes. But, till 1990, audio tapes were very famous and the gamma ferrite, which is one form of iron oxide has been used as the tape material, which is a ferromagnetic material.

And again in today's nano biological applications, we have magnetite that is, Fe 3 O 4, which is being used. It is a ferromagnetic material having T c force 75 to 485. Then, we can also look at other examples of different phases of iron hydroxide, which are also showing interesting properties. For example, alpha FeOOH actually is AFM, AntiFerromagnetic M material, but the other phase is ferrimagnetic compound with a Tt c of 180.

So, you can see a range of oxides and apart from these oxides, we also have our traditional ferromagnetic elements like iron, cobalt and nickel showing strong ferromagnetism and ferromagnetism is above room temperature. So, these are all some of the classic examples of naturally occurring mineral oxides and metals and alloys, which are intrinsically magnetic and having this as the base, thousands of materials have been prepared with similar stoichiometry.

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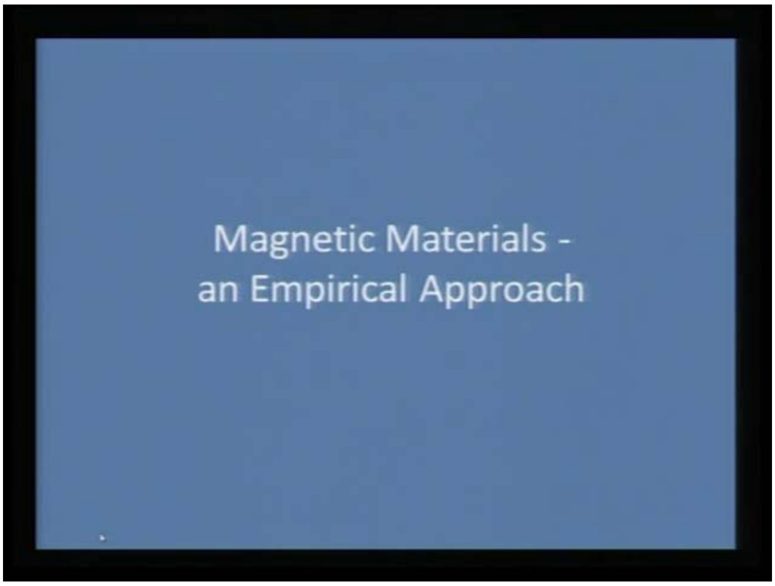

Now, let us look at magnetic materials as an empirical approach and try to see, how we can distinguish one from the other. Then, we can categorize, what sort of a magnetic material we can talk about and depending on the nature of magnetism, we can also group them for different applications.

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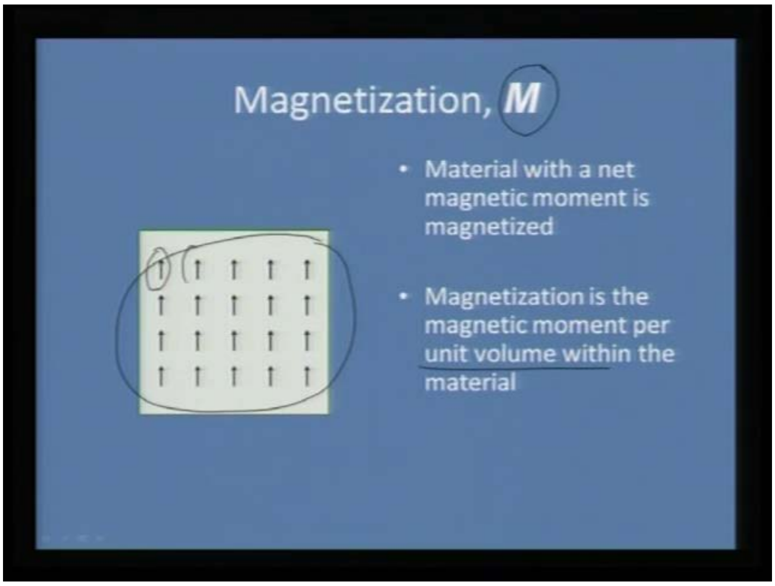

First of all, some of the terminologies that we use very frequently in magnetic materials is magnetization M. Material with a net magnetic moment is magnetized and the magnetization is the magnetic moment per unit volume within the material. So, that gives the strength of your magnetization M and that depends on the net magnetic moment in a given area and also it depends individually on the size of magnetization and the number of such dipoles.

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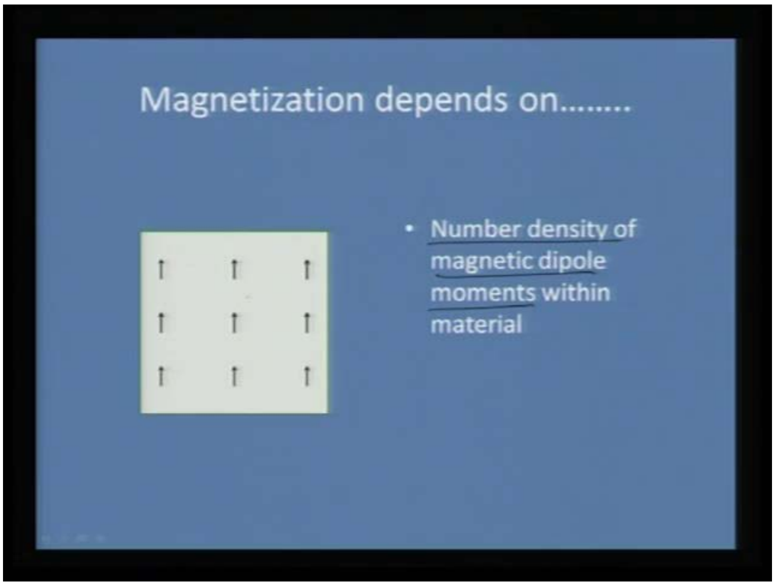

So, magnetization that way depends on the number density of the magnetic dipole moments within the material. So, if it is more crowded then, we are talking about more density, therefore more magnetization.

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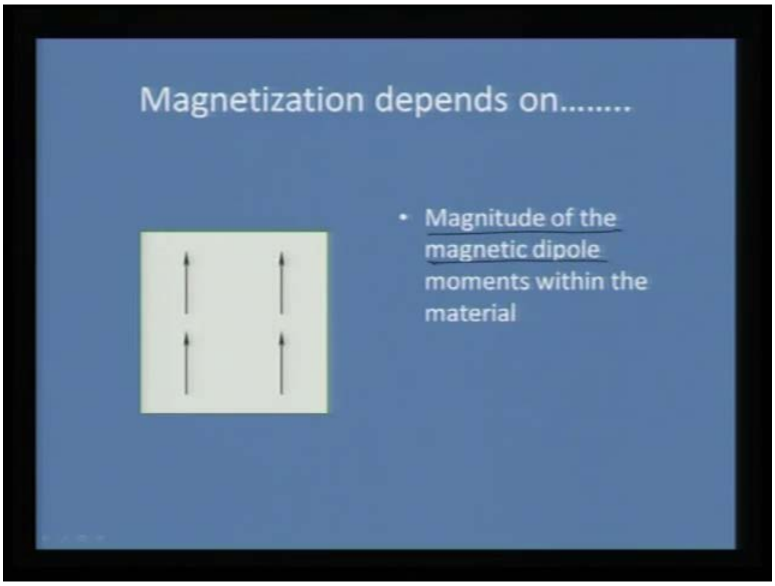

So, we also talk about the magnitude of the magnetic dipole, not just on the density as we saw, but also on the magnitude of the magnetic dipole. Because, sometimes they can as we would see in the next few slides, sometimes they may be reverse and in one case, the magnitude of the dipole may be smaller, but it will still result in a net magnetization.

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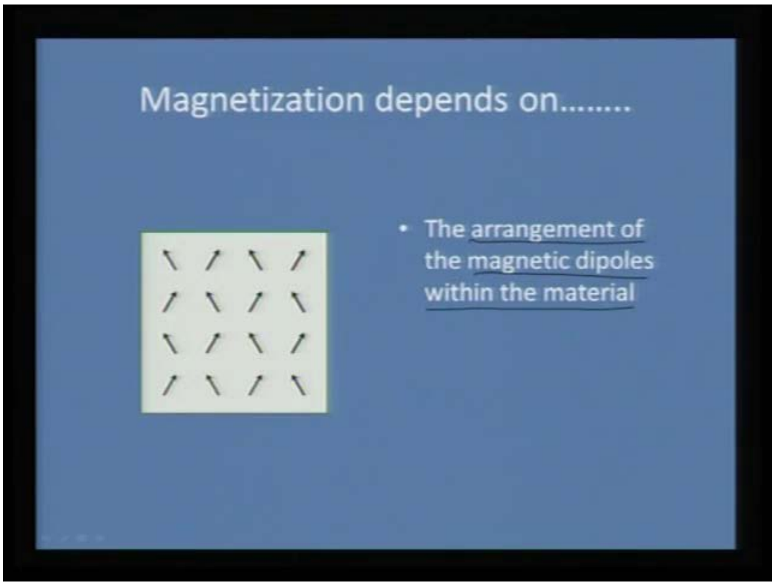

And then, the alignment of this magnetic dipoles will also cause the net magnetization, therefore we talk about arrangement, apart from the magnitude and the density, so the arrangement of the magnetic dipoles will tell, whether there will be a net resultant magnetization or not.

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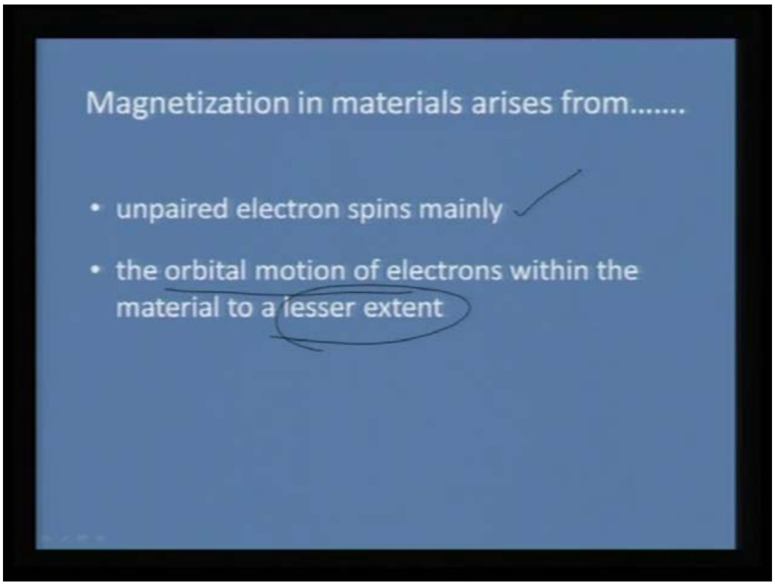

Magnetization in materials generally can be categorized to two things, one is unpaired electron spins or it could be due to orbital motion of electrons within the material to a lesser extent. So, what is predominant is the number of unpaired electrons, but we should also understand, there is a spin orbital contribution, spin orbit coupling. And because of the orbital motion of electrons also, there is a intrinsic moment that is induced, but this is of a lesser extent, so two contributions from the material itself, apart from the dipoles.

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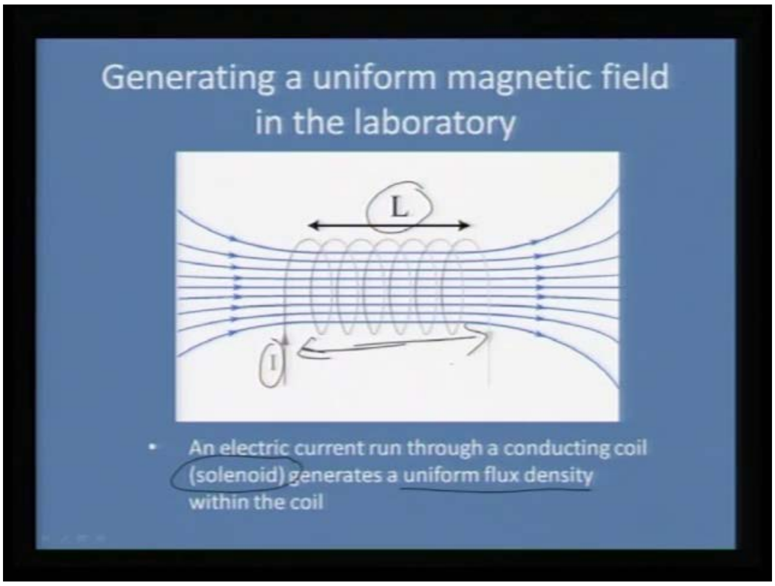

So, how do we measure the strength of a material, now we need to have a external force by which we can judge, whether the material is good or not. So, in general, we can generate a magnetic field and this magnetic field actually is generated by a solenoid. And solenoid is nothing but, you wrap up any material say, glass or even a ceramic tube, you can just wind it with the conducting coil. And then, that electric current passing through this conducting coil will give you a flux or a magnetic field and that is how, you can generate a uniform flux density within the coil.

So, the number of turns that you make with this conducting coil, will determine what sort of strength that you employ. So, you pass current and this is the length and the number of turns of this conducting wire will give you the strength of the magnetic field. Therefore, you can generally create electromagnet based on the number of coils, so this is not impossible for you to generate in a lab scale.

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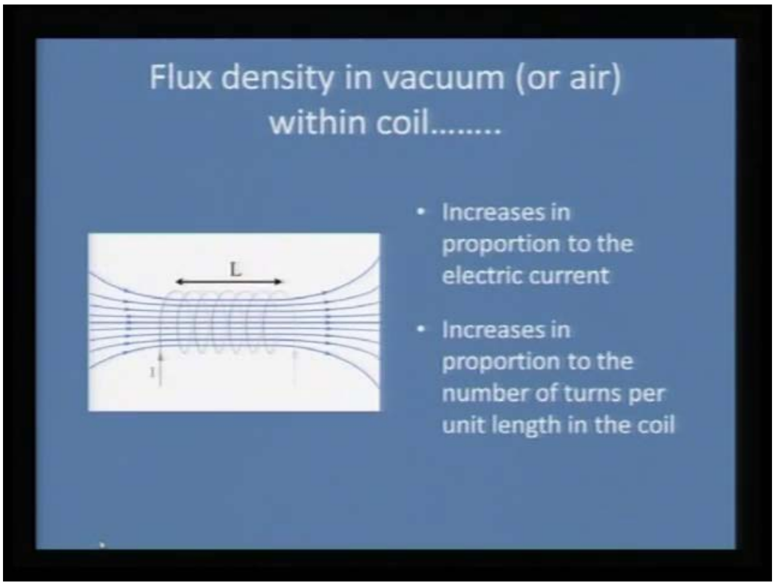

So, flux density actually can be in vacuum within the coil, so it increases in proportion to the electric current as we saw and also it increases in proportion to the number of turns per unit length in the coil. So, that would give you the strength of your electromagnet.

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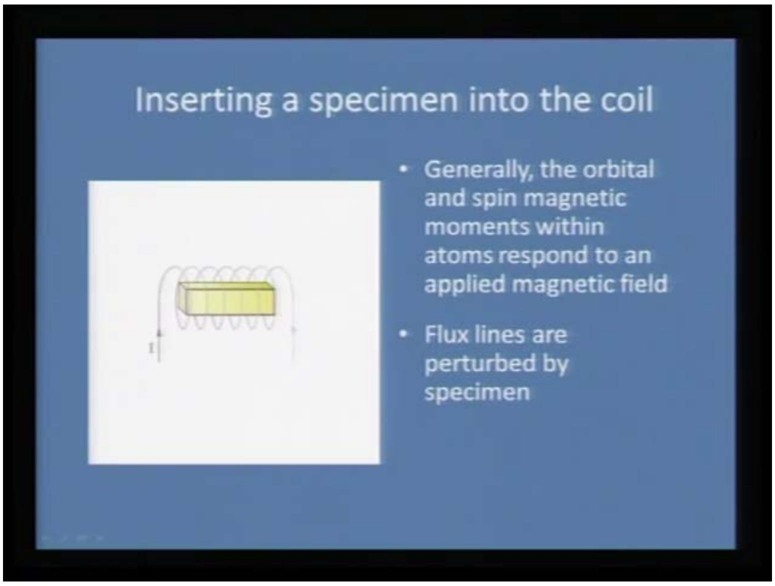

Now, once you keep a specimen inside the solenoid then, the response of this material to the solenoid will actually determine the magnetization. So, generally the orbital and spin magnetic moments within the atoms respond to the applied magnetic field and the flux lines are actually perturbed by the specimen. So, how the flux is either let to pass through the material or it repeals the flux, determines what sort of materials you have.

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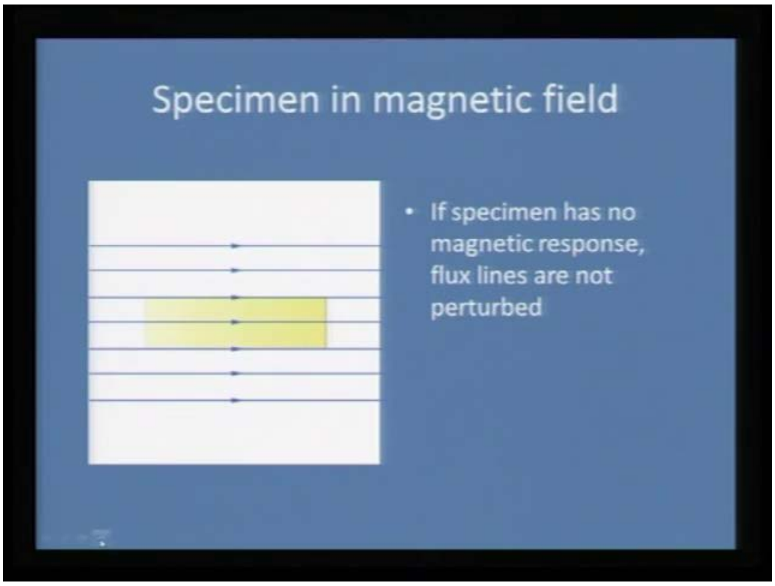

For example, if you have a material, which does not have any magnetic response then, you simply see the flux passing through the material and therefore, the flux lines are not perturbed.

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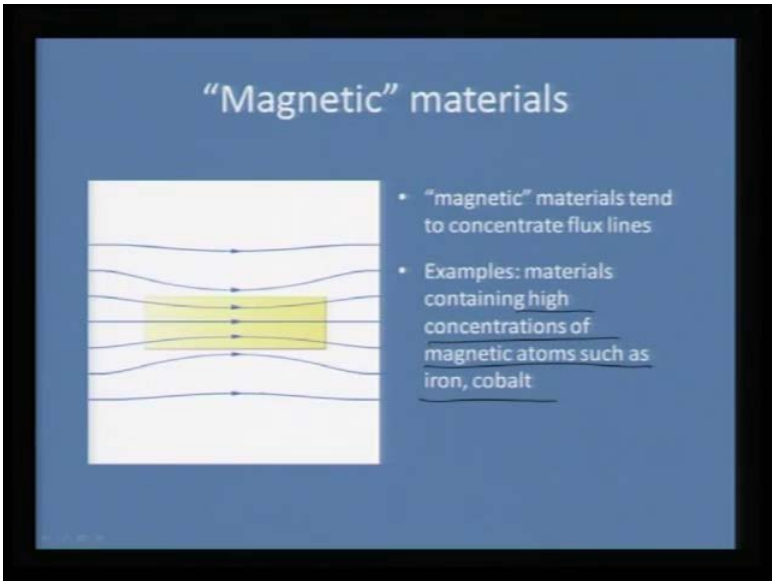

But, if the material has a considerable magnetic moment then, it tends to concentrate the flux lines. For example, materials containing high concentration of magnetic atoms like iron and cobalt then, you would see, that it is actually putting force on the flux lines.

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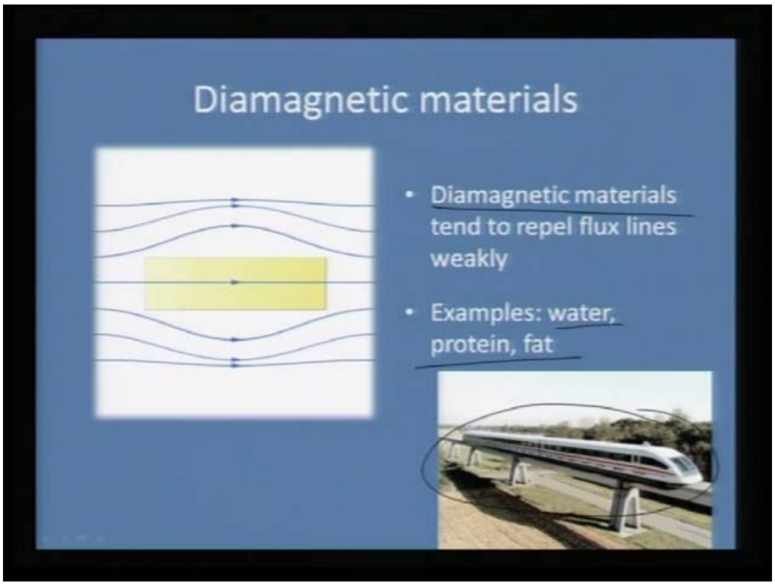

Now, there are some materials, which totally repel the flux line and this is your flux axis, this is the direction in which you apply the flux. But, you would see, totally the flux is repelled and in that case, you actually categorize that material as diamagnetic material, which will tend to repel the flux lines. Example water, protein, fat, these are all molecules which will not allow magnetic field to easily penetrate through, although higher fields can do damage these molecules.

And a classic example of a situation where, the material is actually not a diamagnet, but in a super conducting state, it behaves like a diamagnet, is the high temperature super conductivity. And one of the possible application that, we would see in detail in the next module is the magnetically levitated train where, the issue of diamagnetism actually brings about a total repel of this flux lines.

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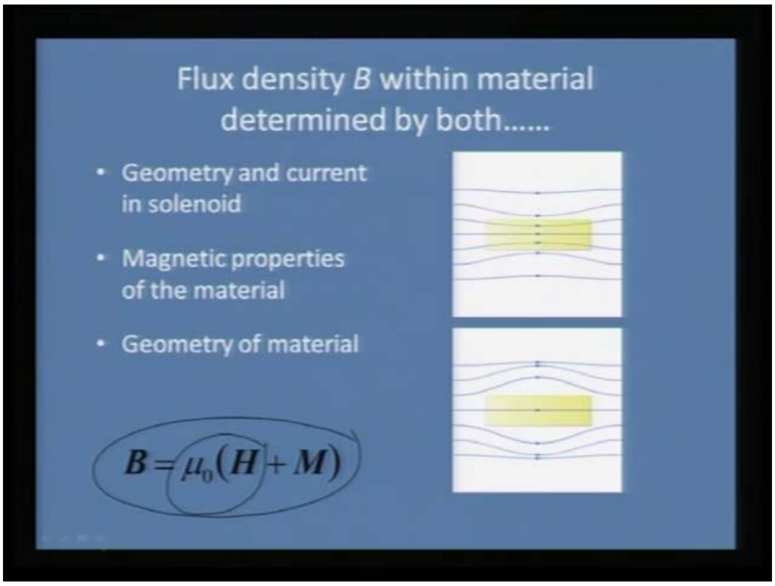

Flux density B within material can be determined by both the geometry and current in solenoid, magnetic properties of the material and the geometry of the material. So, two three things are interdependent, one the solenoid itself will determine what sort of flux density you have then, the magnetic property of the material and then, the geometry of the material. So, B, if it is your flux density then, you talk about mu U H, which is due to your magnetic field and then, mu 0 M, which is due to the magnetic material itself, so two things are interconnected.

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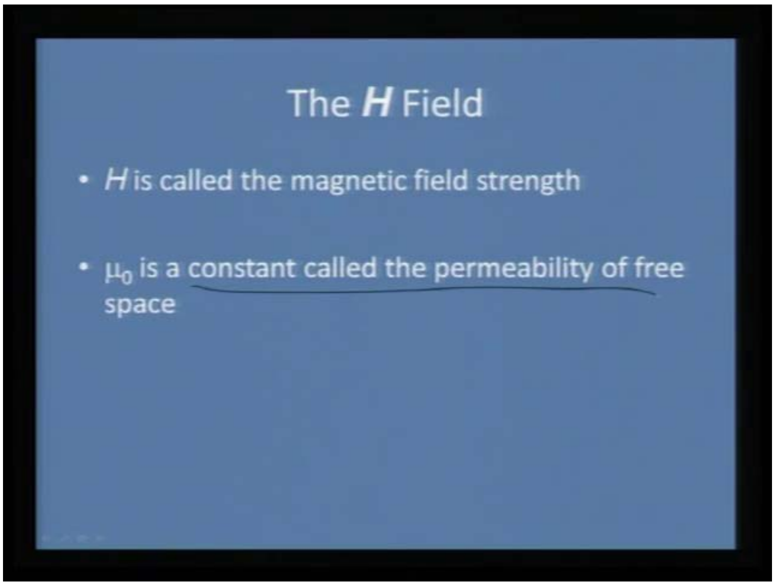

And your mu 0 is nothing but, the permeability of free space.

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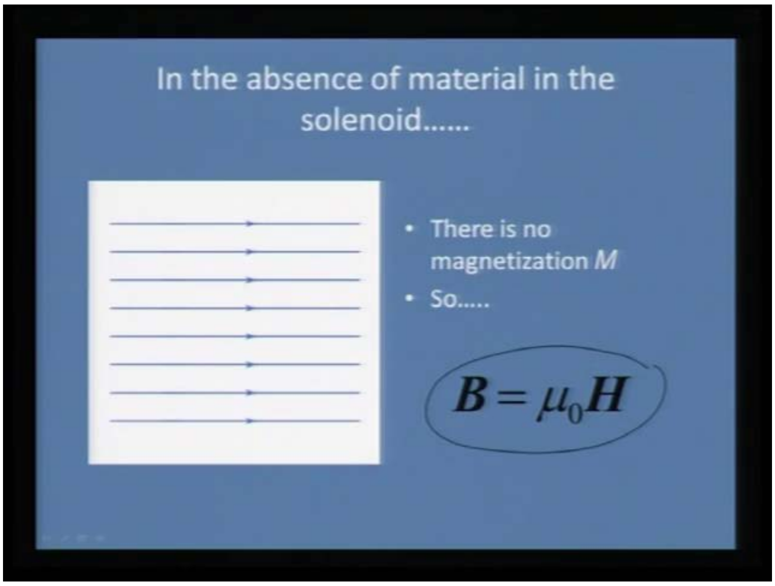

So, in case there is no magnetization, if the material is not magnetic then, your flux density is equal to mu 0 H. But, if the martial is magnetic then, the other parameter also will come into picture.

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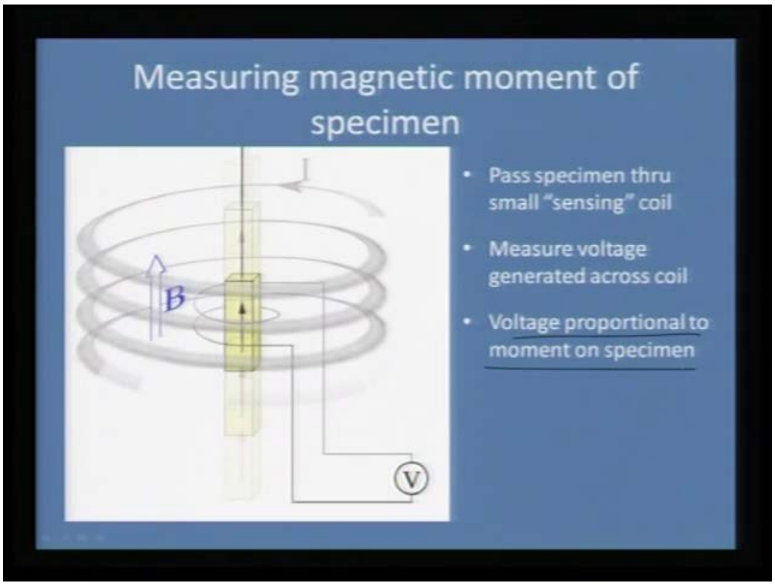

So, measuring the magnetic moment of the specimen, we can actually pass the material through the solenoid and measure the voltage generated cross the coil. And voltage is actually proportional to the moment on specimen, so that is the way we measure the strength of the magnetic moment.

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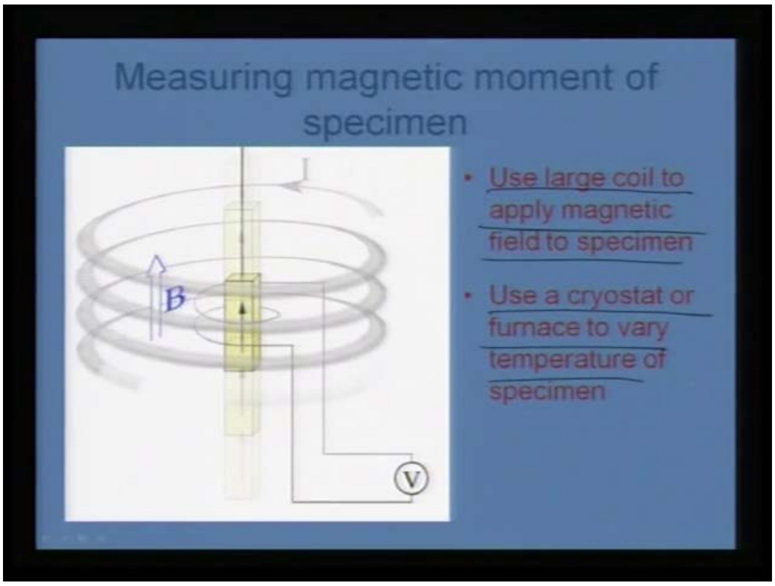

And we can also use large coil to apply magnetic field to the specimen, we can also try to do this same measurement using either furnace for high temperature applications or a cryostat for low temperature applications and today, using this principle, many equipments have come into picture.

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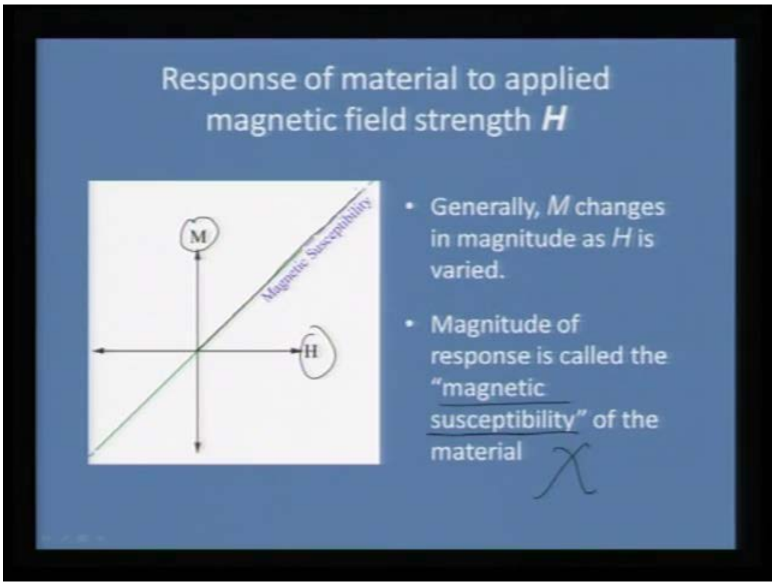

Now, the way the material respond is actually linked to the susceptibility, a value which is actually dependent on both magnetization as well as H. So, we will come to the definition of susceptibility, which is usually denoted as chi. Generally, magnetization changes in magnitude, as H is varied, so this is what you call as a linear response. So, as you increase the field then, the magnetization also keeps increasing and the magnitude of the response is measured by chi.

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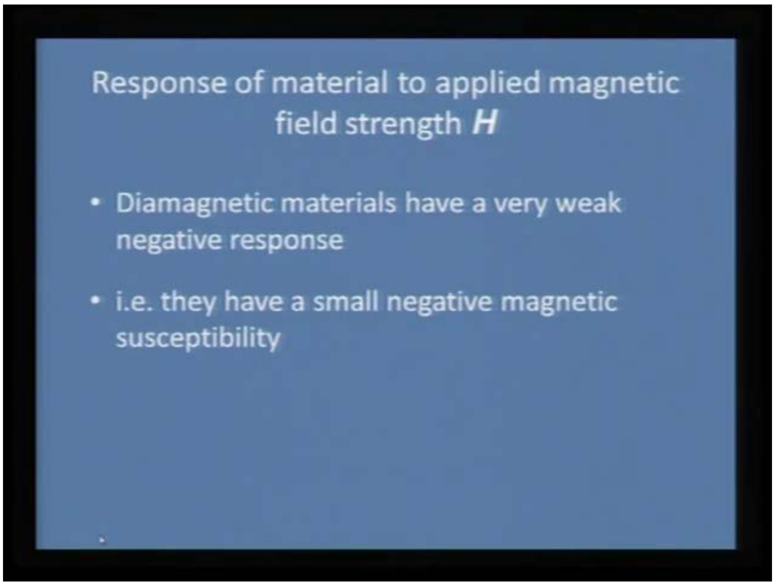

And therefore, diamagnetic materials will have a very weak negative response, because there is no net moment and they have a small negative magnetic susceptibility.

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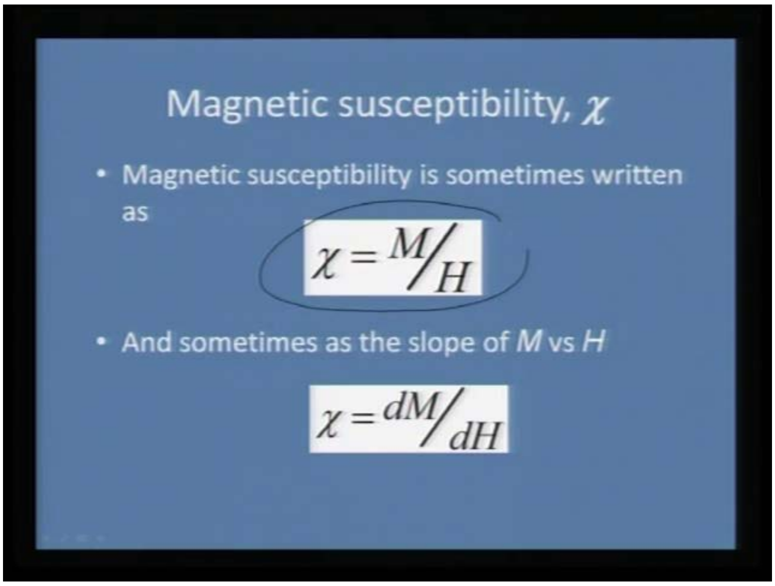

So, susceptibility per se can be defined as chi is equal to M by H or sometimes, it is defined as difference in magnetization over difference in H. So, this would actually give you chi or sometimes it is also taken from the slope, as we see from this expression. So, chi can be derived from a simple M versus H curve.

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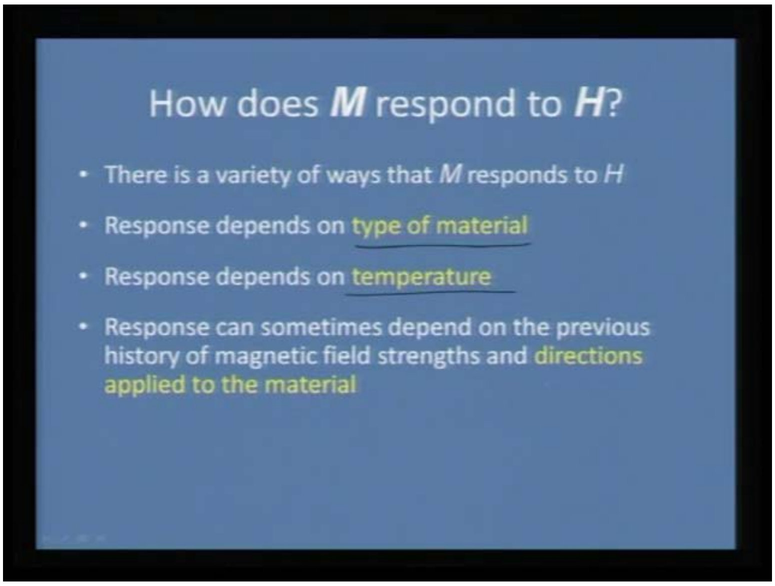

There is a variety of ways that M response to this H, so the response can be based on the type of material that you have or the chi can actually vary or magnetization can vary with temperature. Response can sometimes depend on the previous history of the magnetic field strength and the directions applied to the material. In case of thin films, it is heavily direction dependent, perpendicular to the film, it will show a very different behavior. In the access of the film, it will show a very different behavior, therefore this angle dependent magnetization is much more exemplified in single crystals and in thin films. But, in bulk, usually this dependency is not highlighted much, so in general, magnetic materials show a non linear response if they are really magnetic.

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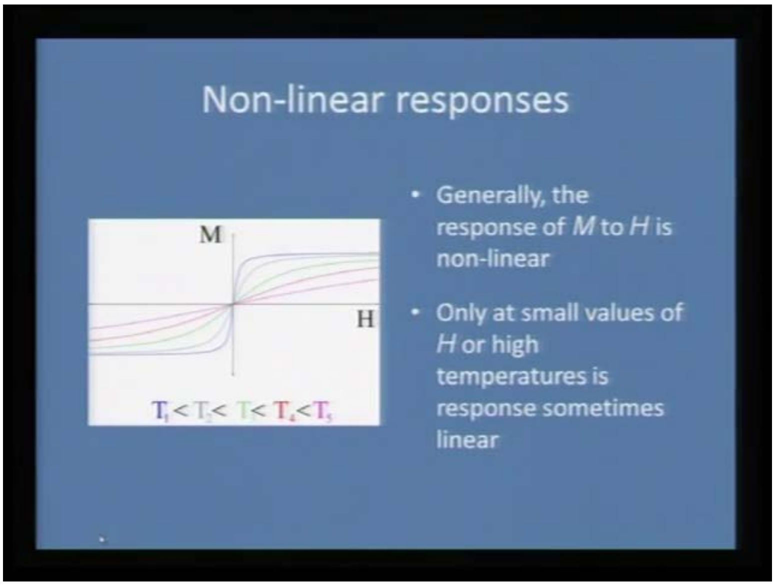

And suppose, your temperature T 1 is less than T 2 less than T 3 and T 5 for example, so at high temperatures, significantly you would see a response like this, whereas at low temperatures, you would see a very clear magnetic behavior, and therefore they are always non linear with respect to temperature. So, we can say that, M versus H behavior is usually a non linear behavior.

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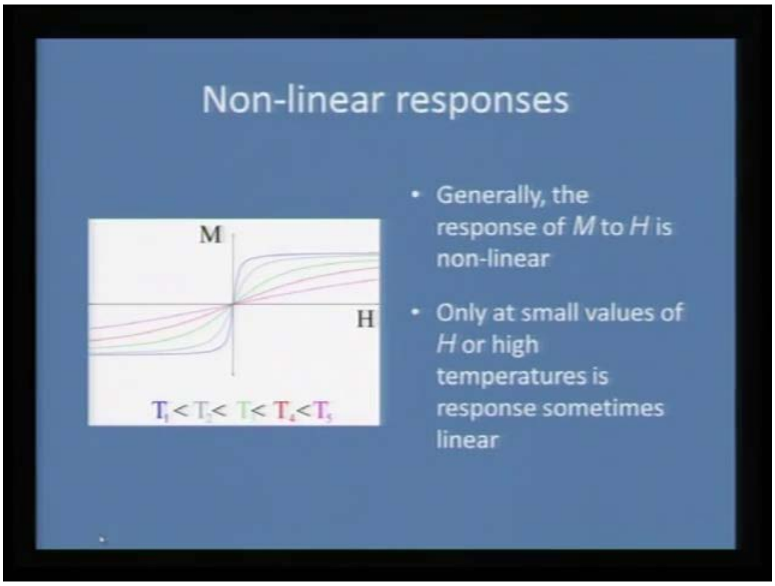

And only at small values of H, they are usually linear where, you can see at a any point, at low values of H they are linear, otherwise they are mostly non linear.

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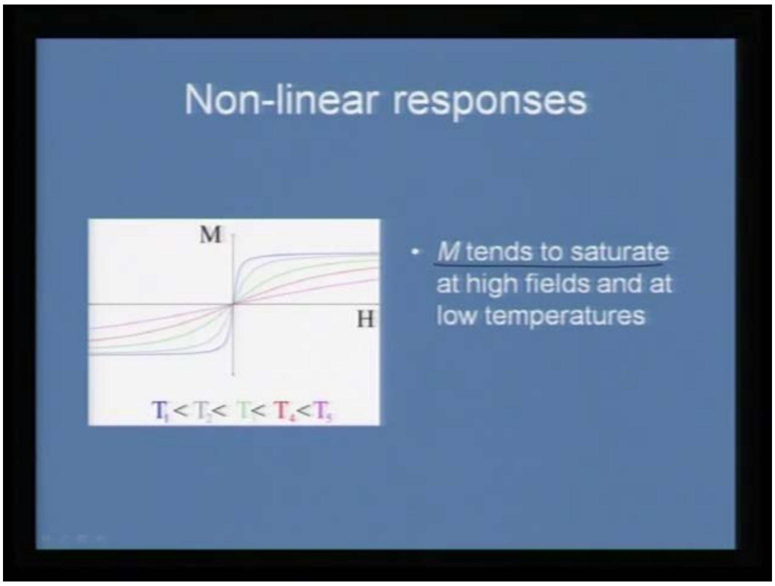

And M also intrinsically tends to saturate at high fields and at low temperature, as you would see here, at low temperature that is, T 1 the saturation is at much lower H. Whereas, in the case of high temperatures, saturation takes a very large field, so this is one of the manifestation of a non linear response.

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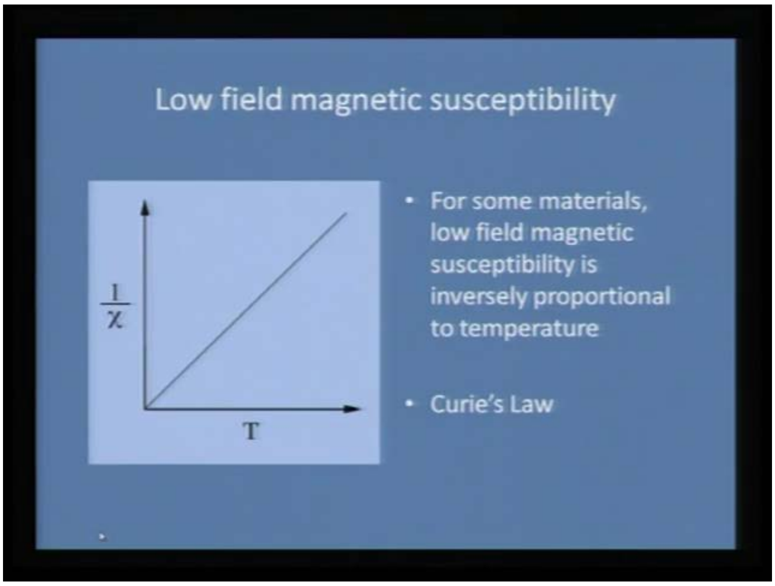

And therefore, if you actually make a curve of a plot of 1 over chi, as a function of temperature for a low field magnetic susceptibility, you would actually see a linear dependence, as you would see from this. And this is nothing but, the Curie Weiss law and if it is a ferromagnetic material then, this nature of this linearity will change. If it is antiferromagnetic material or diamagnetic material, the nature of this 1 over chi versus temperature plot actually vary. So, from this, we can easily verify, what sort of a contribution that we are getting.

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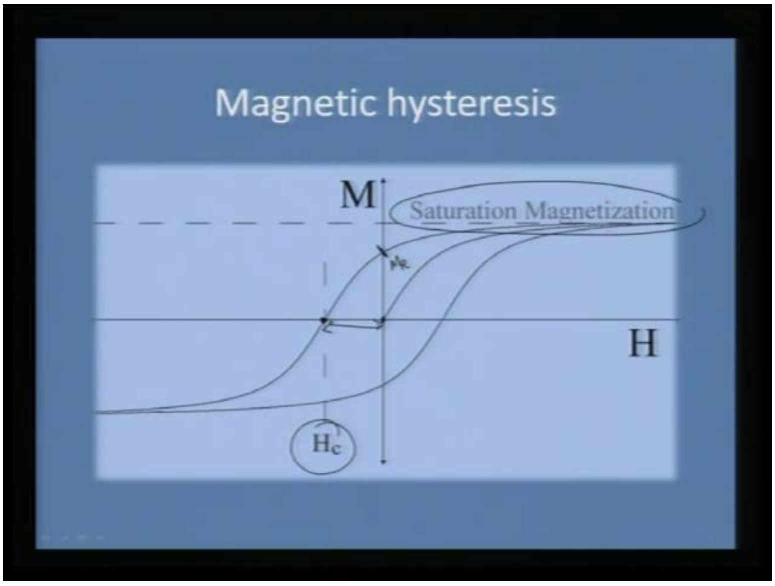

Typical magnetic material would actually give a hysteresis where, two parameters are very interesting to follow. One is saturation magnetization, it is when you take the virgin sample and then, you try to increase the field then, it gets saturated. And on removal of the field, actually it will not take the same path as that of the M s, rather it would keep going down where, this is your M r that is, remnant magnetization.

And to completely revert it to zero magnetic moment then, you need a field which is called as H c, which in other words called critical field or coercivity and that coercive field is the strength of, how much the magnetic moment is aligned. If it is quickly reversing then, you can say that, the paring of the moments are very weak. So, the strength of the magnetic interaction that is going within the sample is actually highlighted based on the nature of the loop.

So, just by looking at a magnetic hysteresis, it is possible for us to gauge, whether it is a strongly correlated spin or very weakly correlated or whether it is paramagnetic or non magnetic. All this can be verified using magnetic hysteresis for example, if a material is a strong ferromagnet, which has a very good saturation magnetization then, the disappearance of this M s against temperature will decide the curie temperature. In other words, that is the critical ordering of ferromagnetic behavior, beyond which the aligned spins will be diluted and it will go into a paramagnetic state. So, if your M s is disappearing, as a function of temperature you call that field as a critical temperature for a curie temperature.

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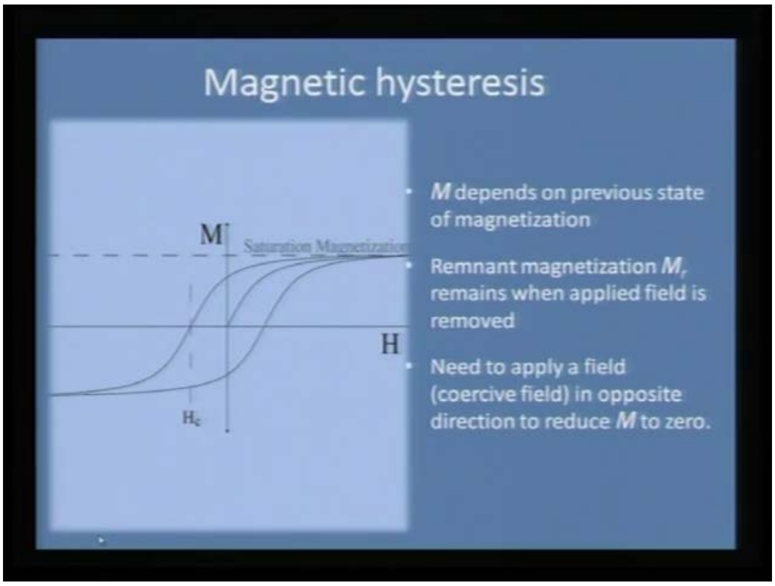

In other words, that is the critical ordering of ferromagnetic behavior, beyond which the aligned spins will be diluted and it will go into a paramagnetic state. So, if your M s is disappearing as a function of temperature, you call that field as a critical temperature for your curie temperature. So, M depends on the previous state of the magnetization and then, remnant magnetization remains when applied filed is actually removed. Therefore, we need to apply a coercive field in opposite direction to reduce M to 0, and that is what we saw from the previous slide.

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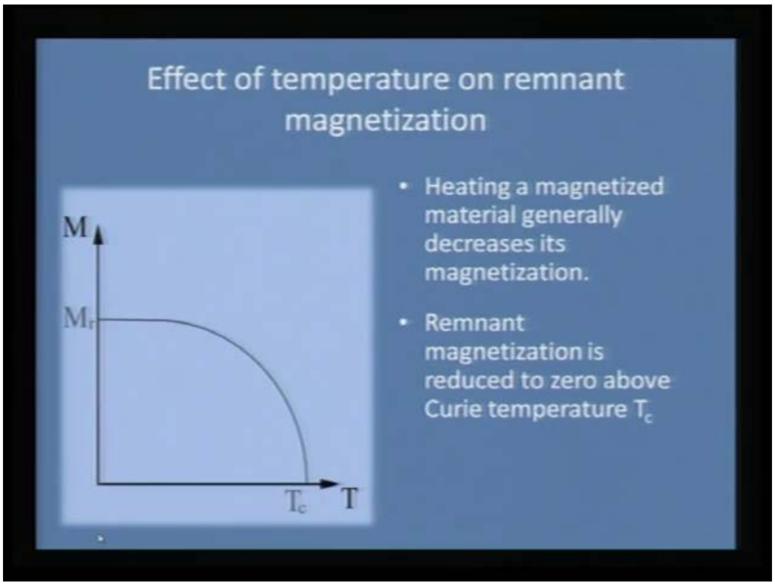

Now, magnetization also can be traced as a function of temperature and if your remnant magnetization is this at temperature 0 then, as a function of temperature, you can try to trace what is your remnant magnetization. And at the point, when your M r is actually going to 0 then, you call this as your T c. Heating a magnetized material generally decreases it is magnetization and remnant magnetization is reduced to 0 above curie temperature.

So, this is one of the way, you can determine your curie temperature by plotting M r versus T and heating a sample above it is curie temperature, is a way to demagnetize a sample. Specially for permanent magnets, if you heat it beyond the curie temperature then, it completely loose it is magnetic property. And the only way to again bring it back to a permanent magnetic behavior, is to again chill the whole sample in a external magnetic field, otherwise they remain demagnetize and that is actually called as thermal demagnetization.

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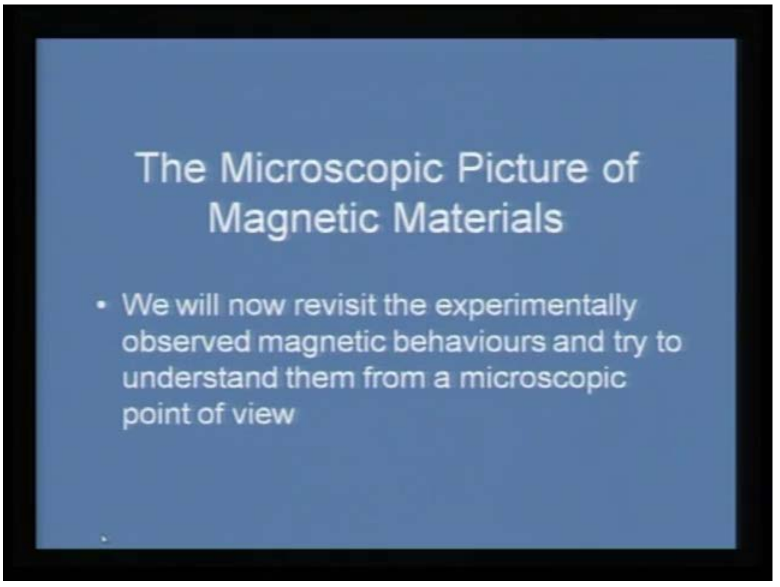

Now, let us look little bit into the microscopic picture of the magnetic materials and see, what is intrinsically happening within a material when it has a moment. So, we will look little bit into the experimental evidences and try to make some conclusion on the different types of magnetization that comes in materials.

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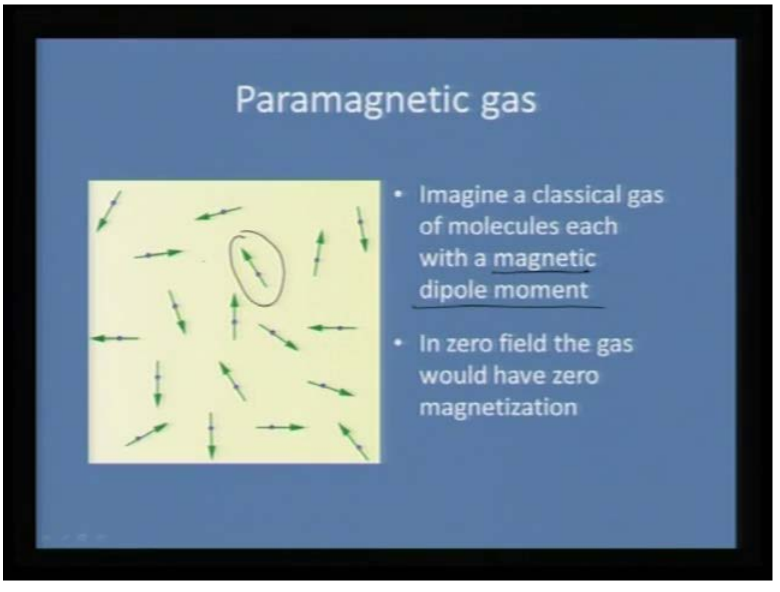

One is a paramagnetic gas and paramagnetic gas is one where, it is like a classical gas of molecules each with a magnetic dipole moment. So, in zero field, the gas would have almost zero magnetization, mainly because these magnetic dipoles are actually very randomly orientated. Therefore, there is no net resultant spin, so we can we can compare this to classical gas of molecules.

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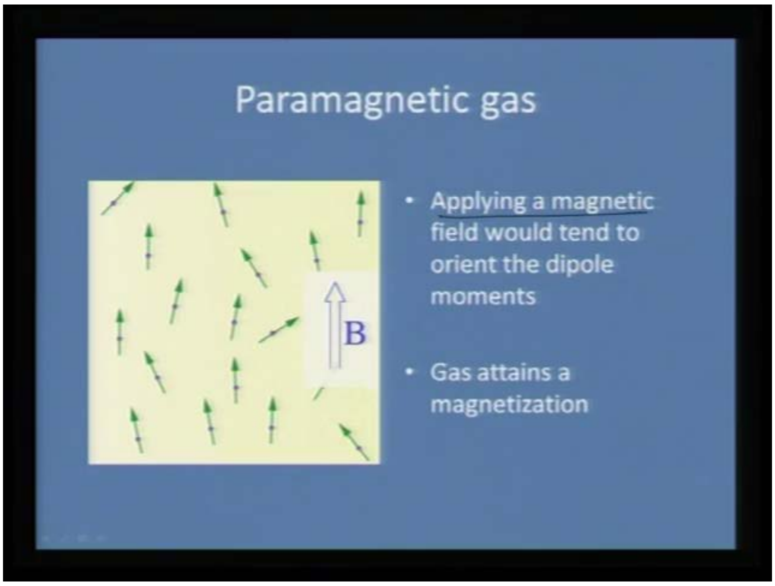

And paramagnetic gas, usually they will align when a applied field is employed and this would tend to orient the dipole moment, and therefore this paramagnetic gas would attain a magnetization. Again as you would see from this cartoon, it is not a perfectly align system, but there is a net alignment giving some amount of magnetization.

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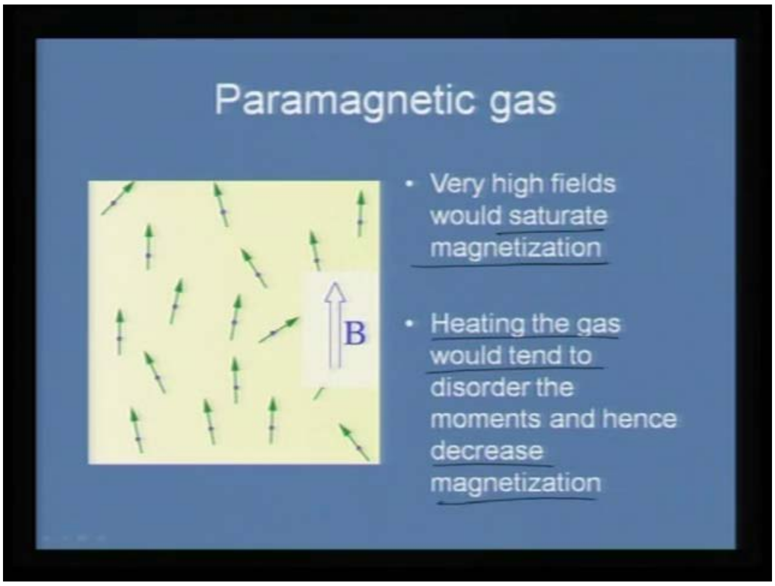

Very high fields can actually be used to saturate it, but this is not the real feature of your magnetic material, because typically if it is a magnetic material, you should actually see a coercivity. But, in paramagnetic gas, once you remove the magnetic fled, you would actually see a zero coercivity and that is the sign that, this paramagnetic samples cannot be saturated. And therefore, it would actually require a very high saturation field in order to saturate it. Heating the gas would tend to disorder the moments and hence, decrease the magnetization.

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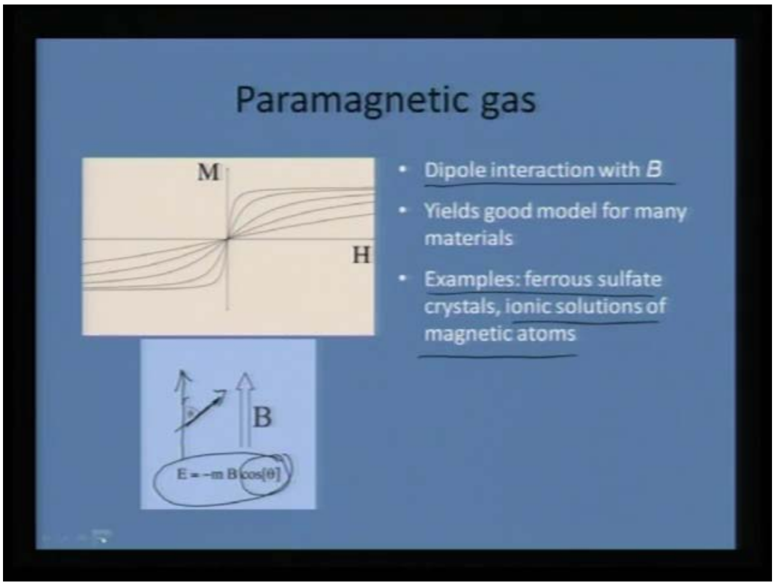

And therefore, the paramagnetic gas, the interaction energy with the applied field is actually dependent on a term E is equal to minus m B cos theta where, your theta is the angle made between the magnetization of your paramagnetic sample with the applied field axis. So, if you can really overcome this factor then, the interaction energy will be maximum. So, the dipole interaction with B actually will determine, whether you can get a net magnetic moment. And examples of such paramagnetic species are ferrous sulfate crystals, ionic solutions of magnetic moments, usually they display this paramagnetic behavior.

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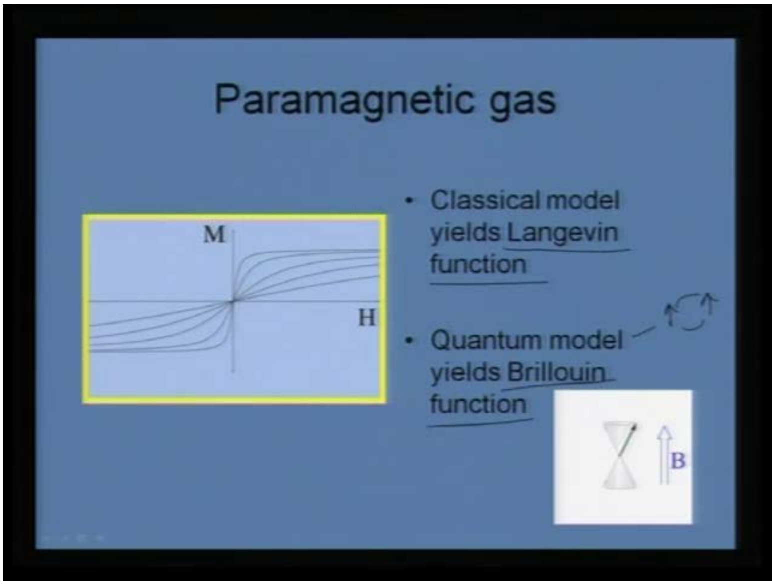

The paramagnetism per se can be interpreted based on two models, one is a classical model, where you do not really bring in spin spin interaction, where you consider each one as a independent molecule. Therefore, it is based on the field that you are applying and the cos theta dependence of the magnetic moment to the field, which will actually bring about the net magnetization. Or it is based on a Brillouin function, which is usually a quantum model where, we are considering the spin spin interaction, two spins and how they interact. The coupling between two spins in the presence of the field will give a net magnetization, therefore the study of paramagnetism itself is a quite a challenge.

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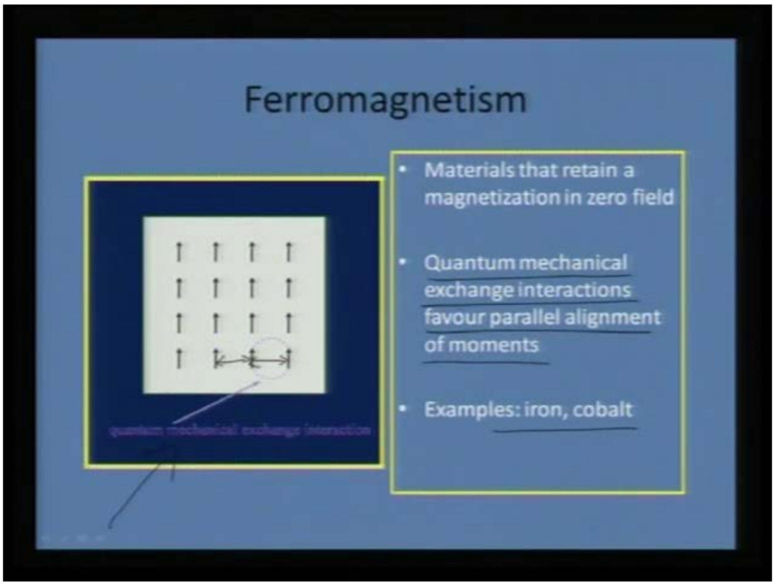

Therefore, it can be viewed with the two different models and we can evaluate the behavior of a typical paramagnet. When we come to ferromagnetism, this is purely viewed based on quantum mechanical exchange interaction and materials that retain magnetization even in zero field. So, there should be net polarization of this dipoles, in and absence of the magnetic field. Therefore, the quantum mechanical exchange interactions favors parallel alignment of moments, examples are the magnetic elements like iron, cobalt and also nickel.

The exchange interaction, therefore depends on the correlation length, how closely they are placed and once they are in optimum distance, when there is a exchange involved then, this will result into a bigger cluster and therefore, there will be a net magnetic moment.

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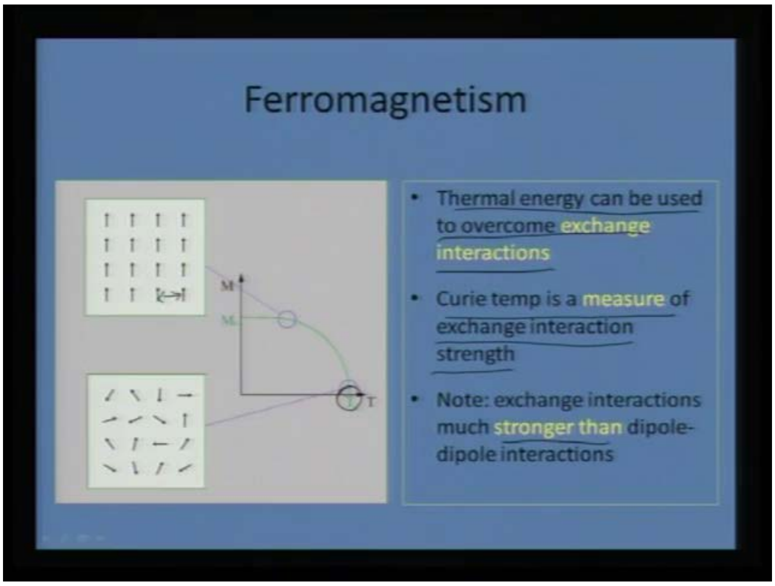

Now, if you try to trace the behavior of this magnetization as a function of temperature, you would see that, at lower temperatures, these moments are aligned parallely and therefore, there is a strong correlation. Thermal energy in such cases can be used to overcome those exchange interactions and once you keep heating the sample, now this align moments can get disorientated. And as a result, the magnetic moment can be removed and then, we get into a state where, you have this T c. Therefore, curie temperature is a measure of exchange interactions strength and exchange interactions are therefore, much stronger than dipole dipole interactions. This is just a comparison, the strength of this exchange interactions are therefore, much stronger.

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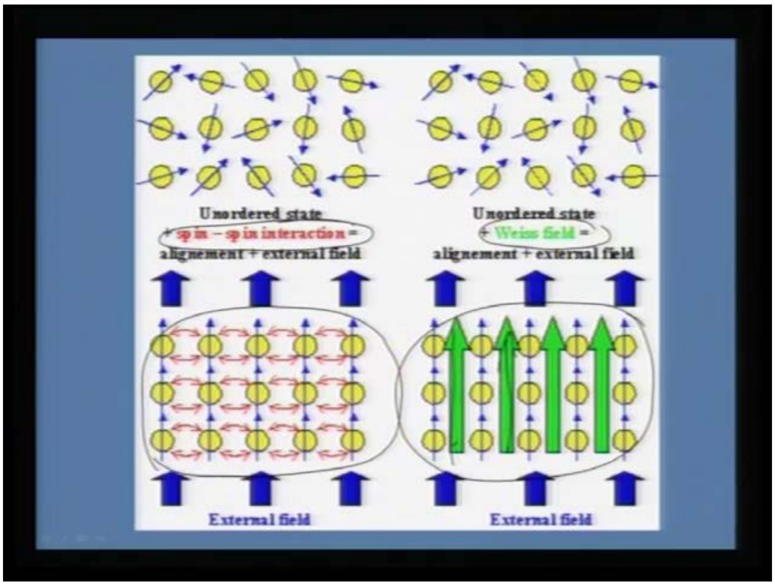

And we can actually view this ferromagnetic arrangement in two different ways, one totally as a quantum mechanical system where, you only talk about spin spin interaction in the presence of a field. So, all this neighboring spins, they do interact and therefore, there is a net moment that is evolved from a unordered state to a ordered state. And that is actually coming through the external field, it can also be viewed as a Weiss field where, you do not take into picture the spin spin interaction.

You just force whatever be the state of the moment, you just force it using a Weiss field, a Weiss field means the external field actually takes care of overcoming all the other barriers, therefore you let the external field do the job, so this is called a Weiss field. So, there are two ways we can bring about a ordered system from a unordered state.

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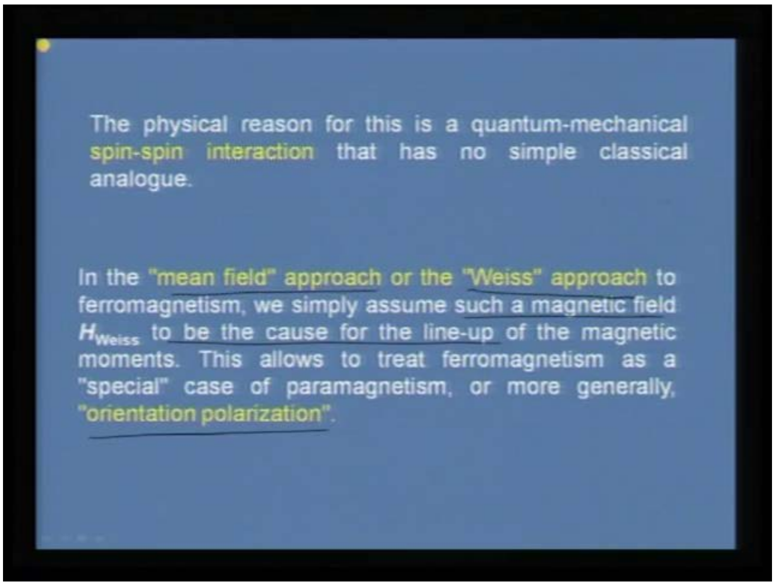

So, the physical reason for this quantum mechanical spin spin interaction that has no simple classical analogue, but in the mean field approach or the Weiss approach, the ferromagnetism simply we assume that, a magnetic field can line up the magnetic moments. And therefore, it is generally called as orientation polarization where, you just use a external field to align the samples.

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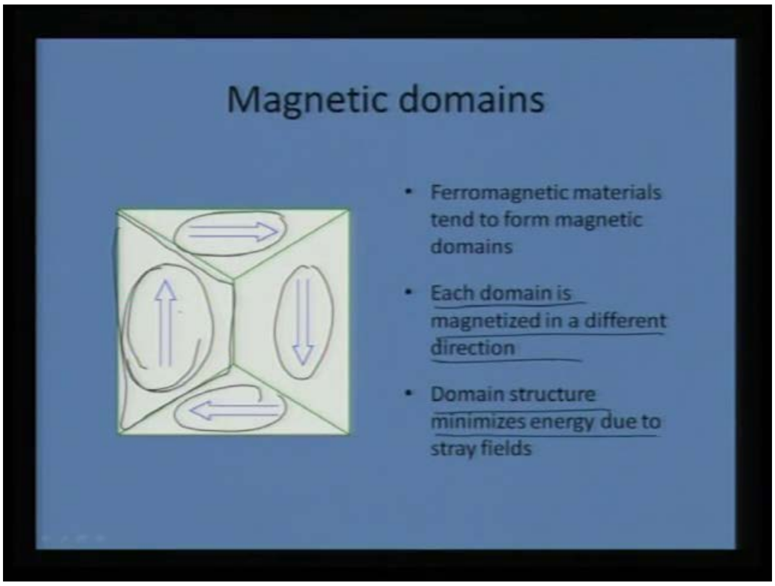

When in ferromagnetic compounds, when you try to influence the material, which is already having a net polarization of magnetic dipoles then, you develop into another situation called magnetic domain and that is the strength of a ferromagnetic material. So, when you apply a field, immediately all the neighboring spins will actually in one sense, percolate together to form a domain. And this domain will have a net moment of this order and there can be other moments also, but those are actually aligned in different directions.

So, a domain picture evolves where, not necessarily all the domains have to be orientated in the same axis where, the magnetic field is applied. So, each domain is magnetized in a different direction, domain structure therefore, minimizes energy due to stray fields and what happens to such a domain.

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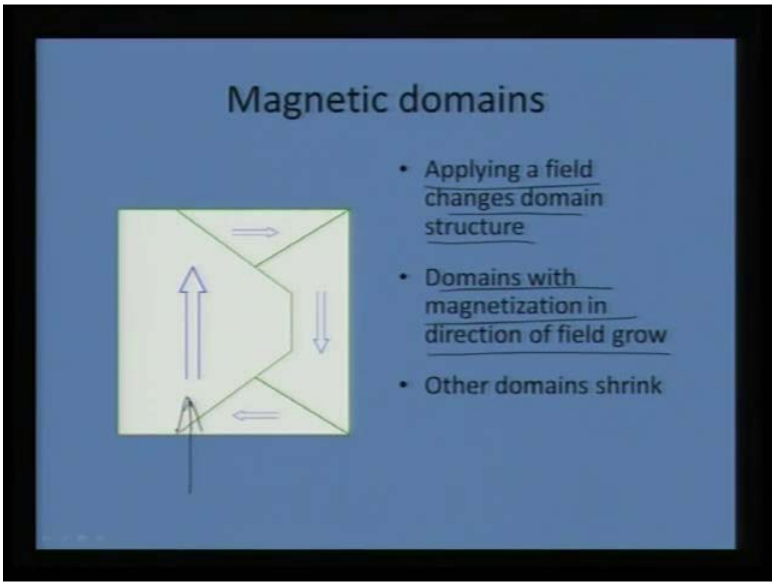

When you try to increase the field along a particular direction for example, it is in this direction then, this particular domain which was originally in this size, will start growing bigger. And the other domains will start easing out, in other words they will covalence with this bigger domain so as to form a domain picture like this. So, applying a field, changes the domain structure, so you can actually manipulate and how easily that this domain structure can be altered depends on the strength of the magnetic material. So, domains with magnetization in the direction of the field grow, other domains shrink.

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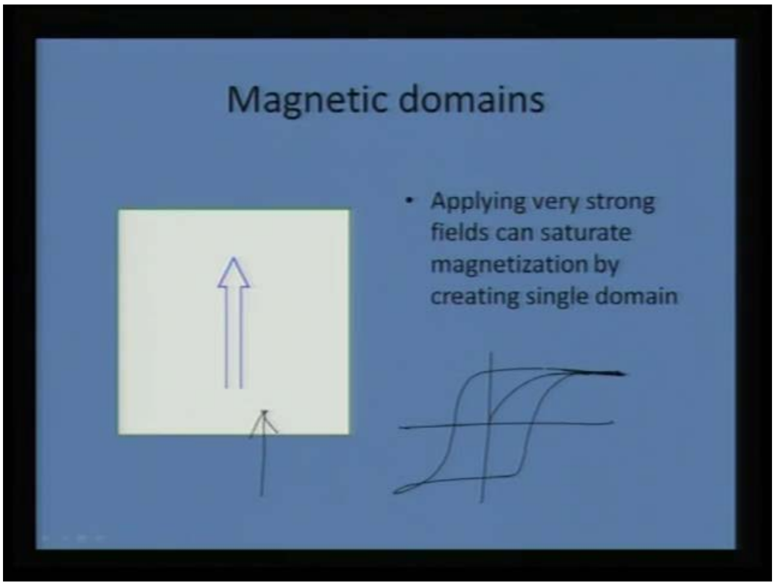

And as a result, when you try to overcome this energy then, you almost covalence all the domains together into one single domain. In other words, you call this as a single domain behavior where, no other domains are there and everything is aligned in the field of it is axis of your magnetic field. So, applying very strong moments then, you can actually revert it into a single domain and that is what, we see from the typical hysteresis. We are talking about this situation somewhere here where, all the domains have come into the this form.

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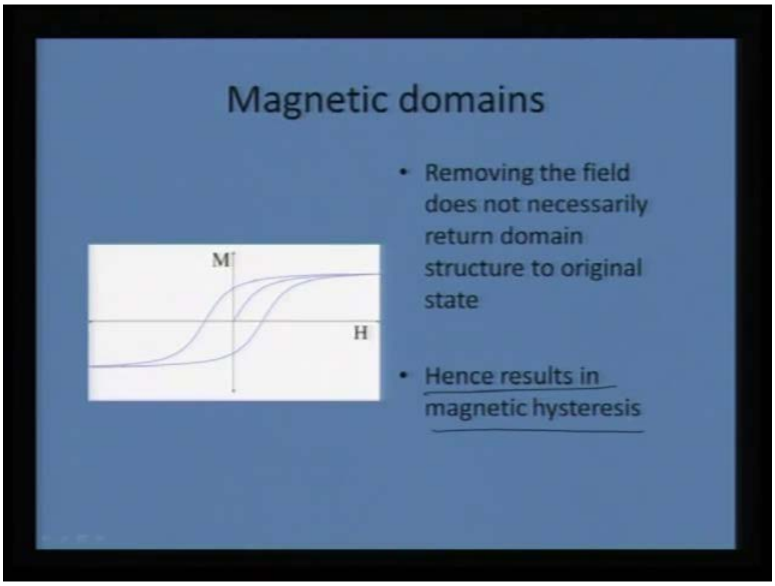

And therefore, when we remove the magnetic field then, it does not mean that, all the domains have to come back to it is initial state, it can take a different domain pattern and as a result, you will get a net magnetic hysteresis. Now, we will also see, how this domains can rotate and we will make correlation with the nature of the hysteresis loop in the next slide. So, in the previous slide we said, as we reverse the field, a magnetic hysteresis develops and we also said that, the domain does not need to reverse back to it is initial state.

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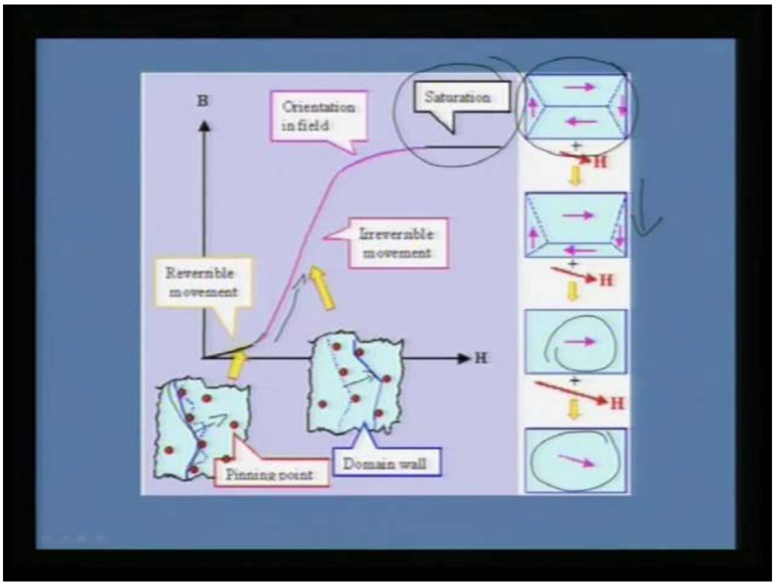

And this is one curve a qualitative measurement picture, which will give you an idea about, how the domains rotate as a function of field. As you would see here, these are the magnetic domains and once you apply initial field, there is a area where the slope changes at this point. And this is nothing but, your pining point or it is called flux spinning where, the magnetic dipoles are reluctant to move with the field.

As a result, a boundary is created here and this wall is reluctant to move, but once you start increasing the magnetic field strength then, you can see that, this wall has moved here and as a result, a bigger domain has developed. And once this spinning is actually overcome then, as you increase the field then, you can see that, a bigger domain can emerge out of it. So, once a domain picture evolves then, you can keep rotating the domain according to the field direction and that is what you would see here.

We have also seen this picture in the earlier slide and once this pinning is overcome then, the domain actually grows in size and then, it would also become a single domain at the saturation. So, this is the way the domains actually form and they dissolve into a one single domain picture. Now, these single domains have a strength and this single domain also have a dimension, roughly the single domains have a dimensions of 100 nanometers. But, suppose you make a particle which is less than the single domain particle, less than this domain size then, you call that as a single domain.

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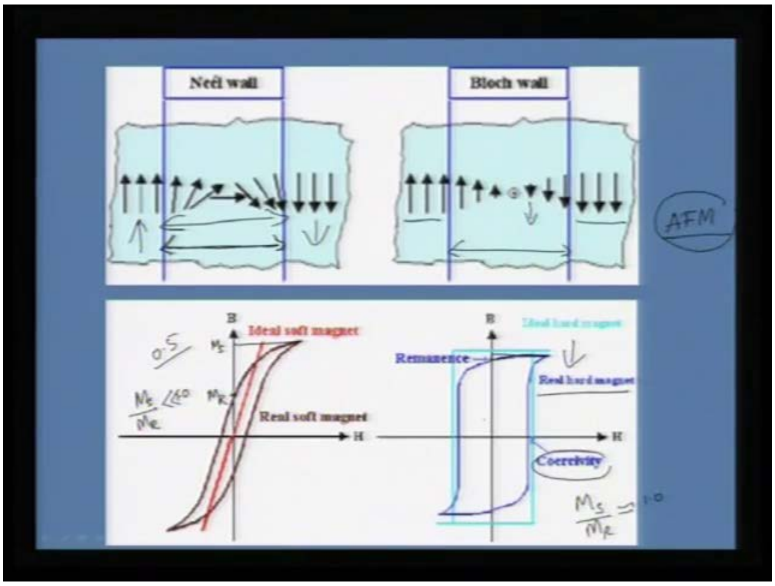

We will look at that situation in one of the next slides and what would happen when we are trying to rotate this domain, two things can happen. One, this can get frozen over a period of time where, the domains are actually turning and they would go into a opposite face. In this case, the net moment is in this direction, in this case it is in this direction, but along this dimension, you see that, the dipoles are rotating. And this measure is actually called Neel wall or this is called as a antiferromagnetic block where, you have reversal of this pin and this takes this much of energy for the moments to rotate.

Therefore, this domain wall is called as Neel wall and in some cases, you can experience another situation where, it is up spin. But, the domain is actually not rotating, but it is actually minimizing at a point where, the moment will get reverse to opposite direction. And therefore, that strength where, it is neither completely aligned or completely inverted and this measure is called as Bloch wall. Depending on that, you can look for different shape of hysteresis and this is one such shape, which is a typical hard magnet where, you will almost get a rectangular hysteresis loop.

And this is seen for hard magnets where, you have a very large coercivity and very high remnance, because this is your saturation. And saturation and remnance ratio, M s by M r will be almost close to 1, in such case you can call this as a hard magnet. But, in a soft magnet, you would usually see that, the saturation is somewhere here and your remnance somewhere here and therefore, your M s by M r is going to be very less than 1.

And in such case, you categorize this as soft magnet, usually the magnitude of a soft magnet would be of the order of 0.5, M s by M r ratio would be 0.5. Therefore, you can find out, what sort of a domain moment is in your material and what is the strength and the coercive force that is involved in such materials.

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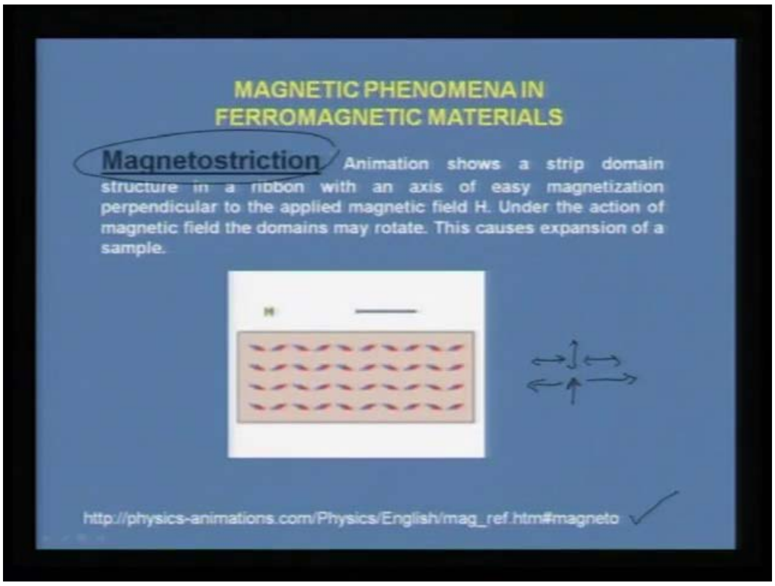

Now, in the ferromagnetic materials, you actually come across different cases, a ferromagnetic material in general can be classified into different sates and that depends on the way, the domains rotates. For example, this is animation which unfortunately, I am not able to access, therefore I would just give this link as a reference where, you get a very good animation of a rear phenomena in a ferromagnetic material, which is called magnetostriction.

Magnetostriction actually comes where, your domains actually rotate with your field and as a result what would happen, you can see the blue and reds magnetic dipoles, they actually rotate in this form and then, it will go this way and then, it will go this way. So, when it actually goes from this to this, you actually have a shrinkage in volume and then, expansion of your sample size. Sample will become larger in this dimension and sample when it actually is orienting, that dipoles are orienting this form, there is natural contraction of your sample.

And therefore, we can say, in the presence of a applied magnetic field, depending on the field direction. And because the magnetic dipoles are rotating, there will be a expansion or contraction of your sample size. And that is what we call it as magnetostriction, which is a phenomena that happens peculiar of a ferromagnet.

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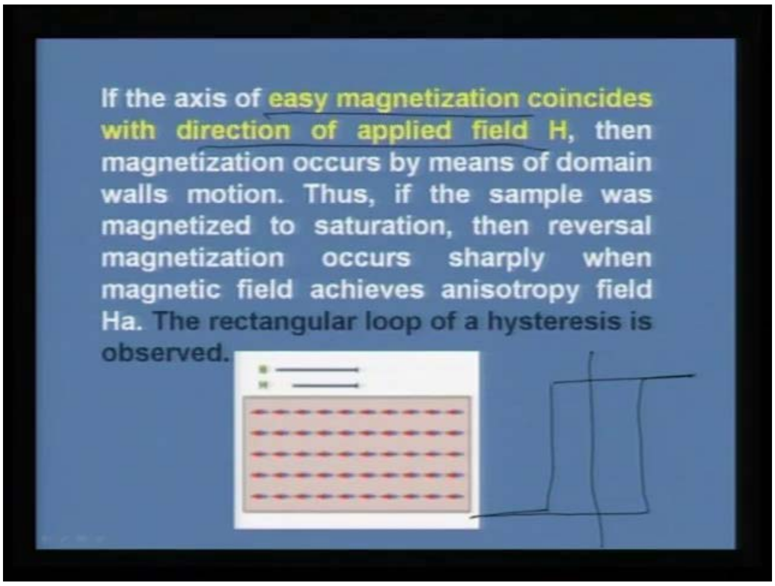

Suppose, the easy magnetization axis, easy axis of magnetization, other words coincides with the direction of the applied field then, you would actually expect a rectangular loop like this. This is the situation when the easy axis of magnetization is overlapping with the direction of your applied field then, you would see here a rectangular loop of this form.

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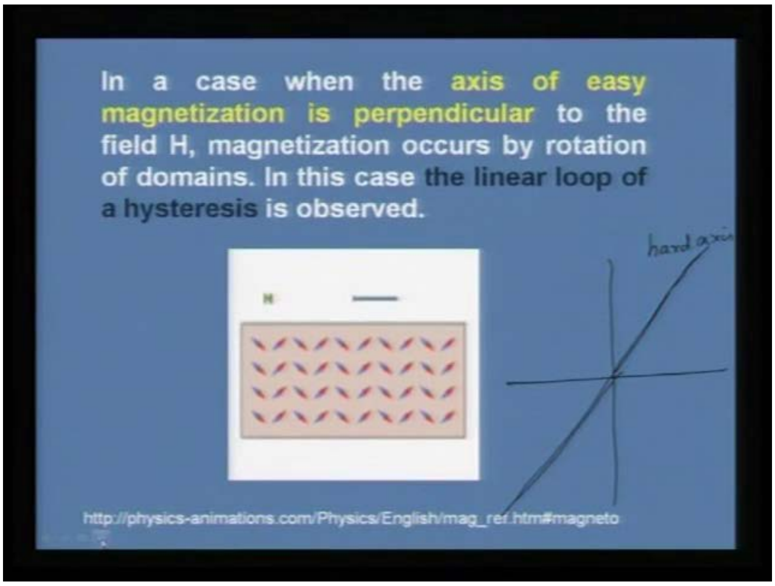

In case, the easy axis of magnetization is perpendicular to the field axis then, you would see a linear loop, therefore in that case, the ferromagnetic loop will be more like this. And in other words, you call this as a hard axis, you can clearly see that, this is the hard axis of magnetization. And suppose, this is a single crystal, one would be intelligent to immediately change the direction of the field. Then, from a hard axis, you can immediately see such a rectangular axis for a magnetic material. Therefore, the easy axis of magnetization, which is intrinsic of your crystal lattice or the way, the moments are arranged in your crystallographic plane, will determine whether you will get a rectangular loop or a linear loop.

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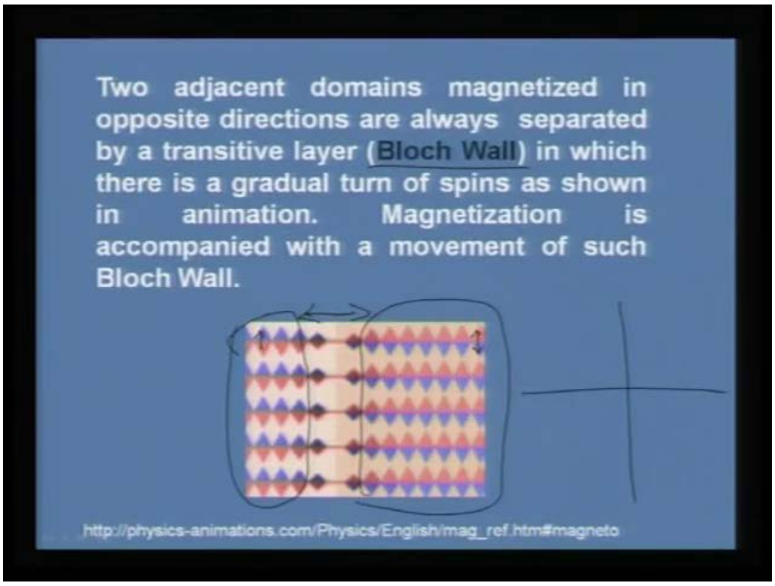

So, this is one way that the ferromagnetic compounds evolve and if two adjacent domains magnetizing or magnetize in opposite direction and are always separated by a transitive layer, which we call it as a Bloch wall, in such case you would actually see a Bloch wall movement. For example, in this case, you can see the dipole in this direction where, there is blue top and a red bottom dipole fashion and in this case, you can see it is a red on the top, blue on the right.

So, this is one domain and this is another domain and in between this, there is a Bloch wall and in such cases, you would see a stepwise shift in the magnetic hysteresis, which we call it as a pining or this is due to the Bloch wall movement. So, this Bloch wall movement can actually go in both directions, both in the left and the right then, this will become very evident that, there is a Bloch wall.

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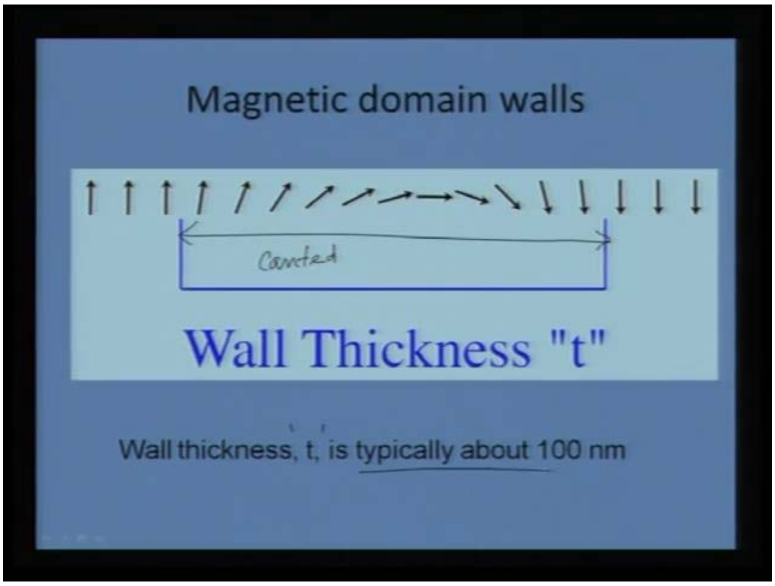

So, in magnetic domain walls, you can actually measure the wall thickness where, there is a canting of spin. Spin is actually canted from this place to this place, therefore you can even measure this canting, which we call it as a domain thickness or wall thickness t and this is typically of the order of 100 nanometer, this wall thickness.

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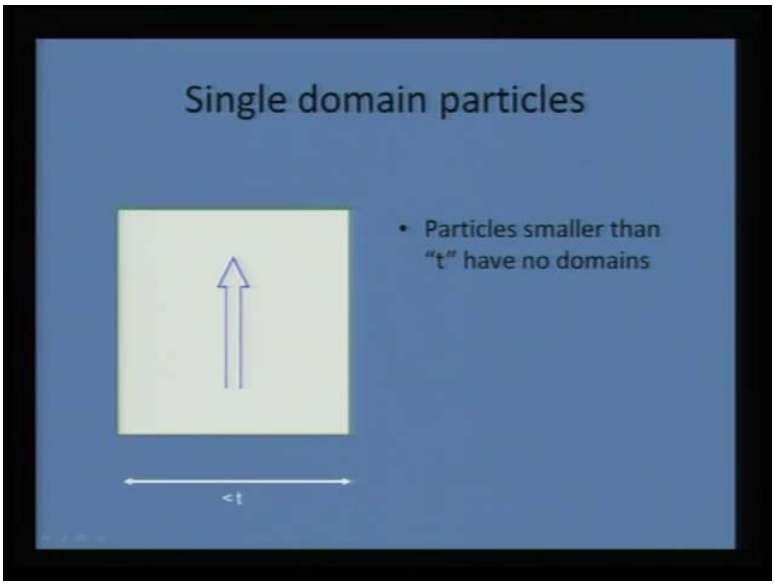

For a single domain particle, actually you do not have domains, particles smaller than t, this t. If the particles are smaller than 100 nanometers, generally we say that, it is a single domain behavior, which we can easily calculate from a given formula.

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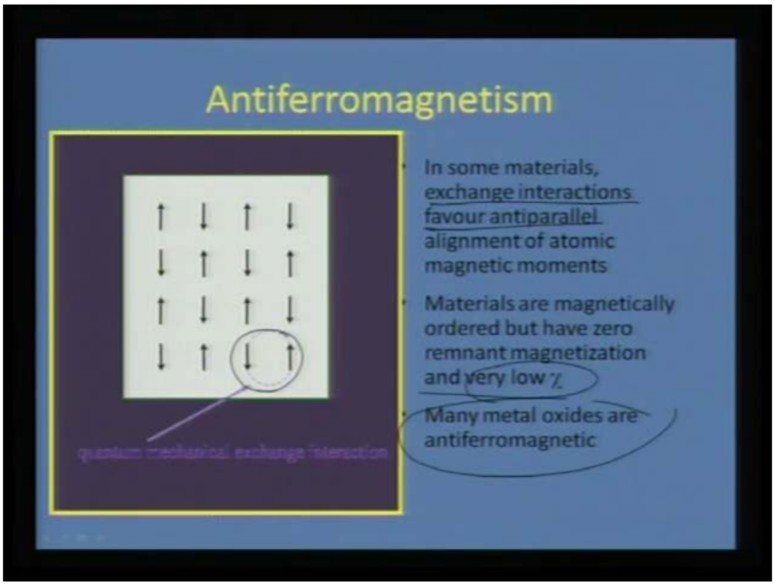

Now, from a antiferromagnetic situation, we can immediately turn down to see, what if the neighboring spins are correlated, but they are correlated in opposite direction. In some materials, this exchange interactions actually favor a antiparallel alignment and only then, the system is stabled. So, in such cases, you experience a antiferromagnetic behavior and they will have a very low chi. They will almost resemble that of a diamagnetic material, because diamagnetic material shows negative chi. But, this will be almost as close to a diamagnet, but a with sufficient chi which gives a idea that, it is a antiferromagnetic metal. Most of the metal oxides are antiferromagnetic in nature.

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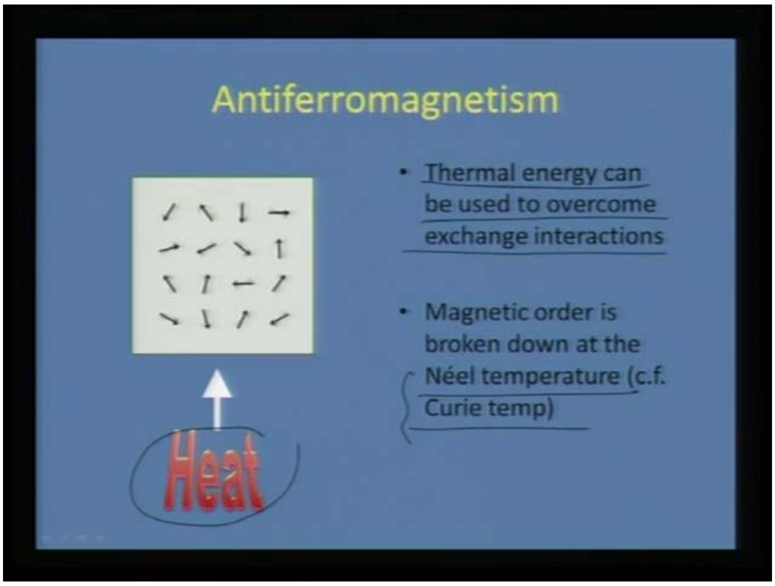

Now, we can actually try to overcome this picture of a antiferromagnetism by thermal energy to overcome this exchange interaction. So, what you try to do, as you did in the case of ferromagnetism, you can try to decouple this exchange interaction using heat or thermal. And therefore, you can break down this magnetic order, which is called as Neel temperature and this Neel temperature is just the complementary to curie temperature.

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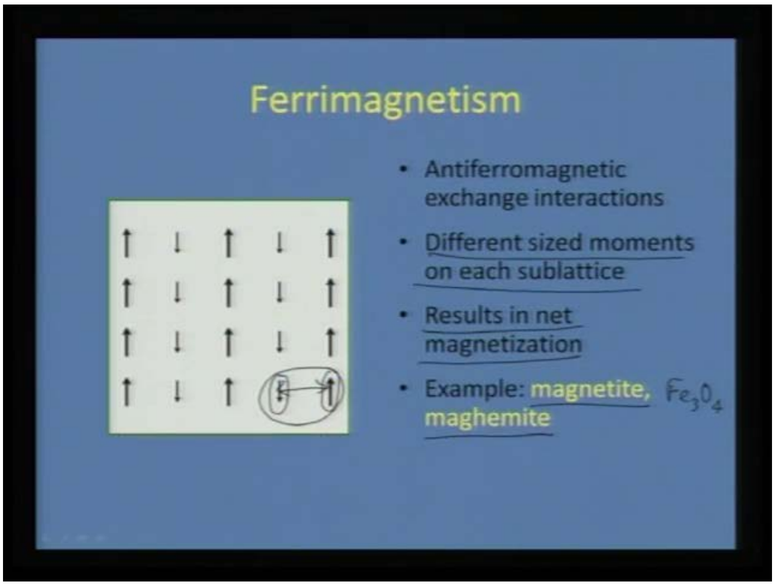

So, in both cases, thermal effects can actually defreeze such exchange correlations and there is another interesting situation where, you have a antiferromagnetism. But, this is not a antiferromagnetism, because one of these two are exchange coupled, but the magnitude of this dipole is less compared to the magnitude of this dipole. Therefore, there will be a net resultant magnetization, as in the case of magnetite or maghemite. So, these are compounds for example, magnetite is your Fe 3 O 4, this is not a ferromagnetic per se, but it is a ferrimagnet and different sized moments on each sub lattice is noticed in this sort of ferrimagnets.

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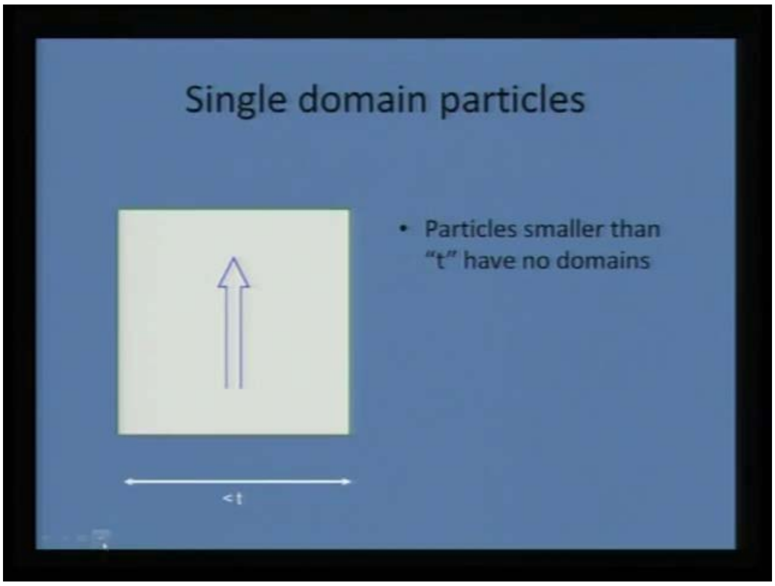

Now, when we come to a single domain particles as I told you, if you escape that domain wall thickness then, you can call this as a single domain picture. And in that case, single domain magnetization can also introduce a interesting small particle magnetism.

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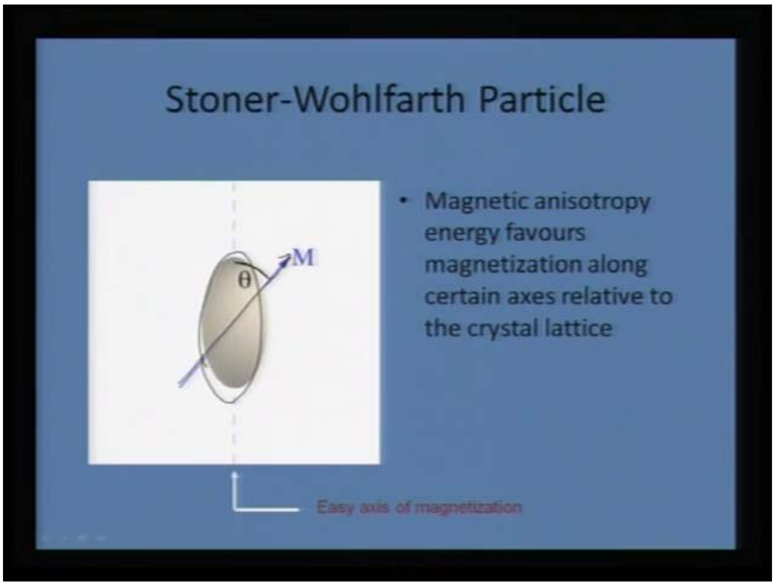

And this is actually understood based on Stoner Wohlfarth particle where, if it is a ellipsoid type of a particle like this where, your magnetization is actually orientated by a factor theta with respect to the easy axis of magnetization. Then, the magnetic anisotropy energy favors magnetization along certain axis relative to the crystal size, so this can become a very interesting issue.

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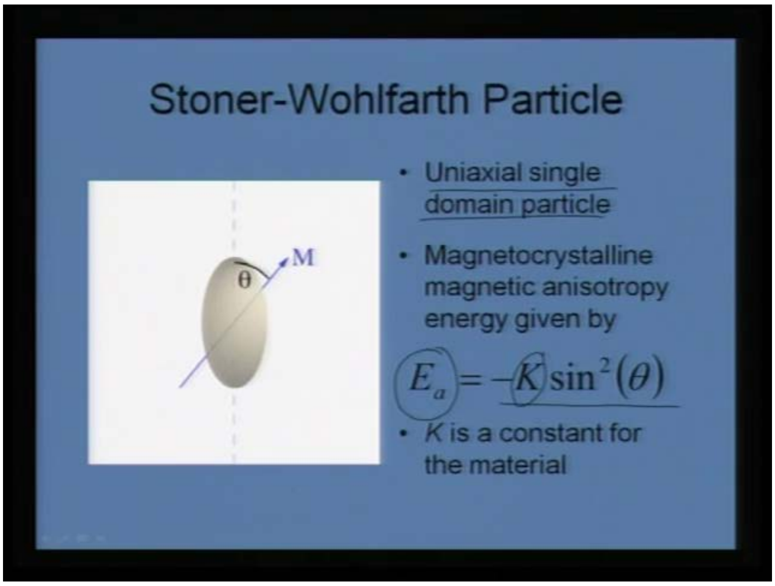

If we can try to understand, how this single particle magnetism works, the single particles are actually uniaxial single domain particle and the way they make a angle theta with respect to the easy axis of magnetization, gives you a anisotropic energy, magneto crystalline anisotropy energy and that is actually correlated to sin square theta. So, where, K is actually a constant dependent on the material, therefore your magneto crystalline anisotropy E a is proportional to sin square theta.

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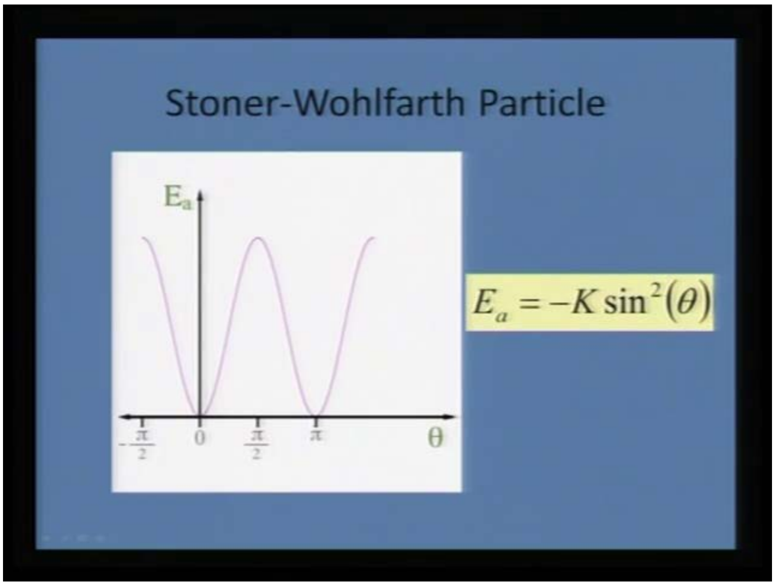

And in that case, you would see this sin function will vary as a function of theta.

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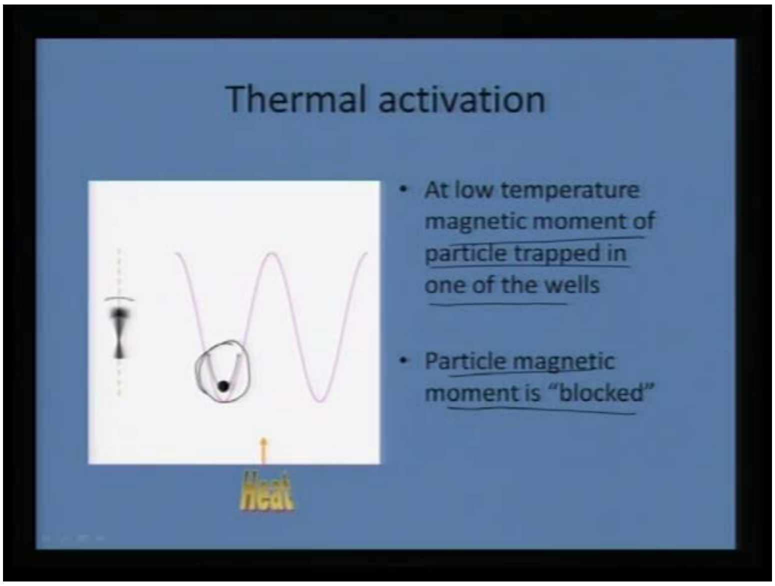

And what can happen in such cases, the particle can actually get trapped in one of this wells. At low temperature, this magnetic moment of the particle can be trapped in one of these wells, and therefore this particle moment is actually blocked. So, in order to derelease this one, this blocked particle then, you need to heat it and then, it goes into a paramagnetic situation.

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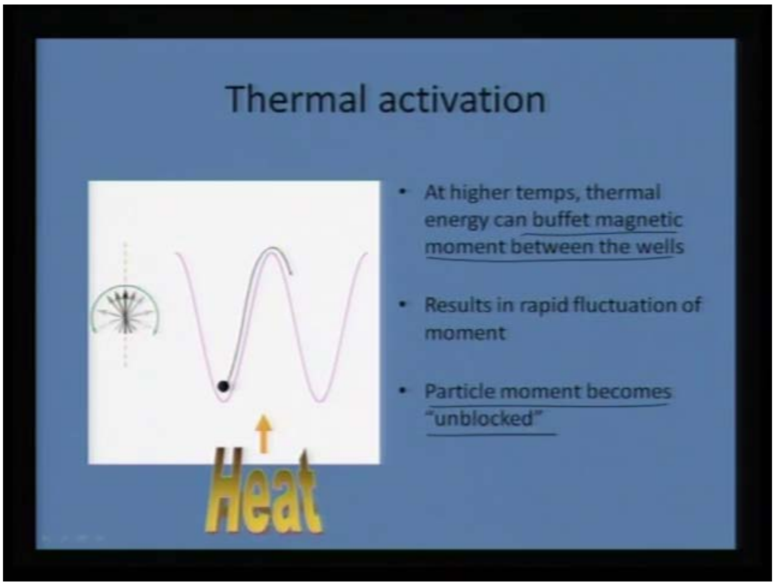

So, at high temperatures, this magnetic moment which is trapped can be overcome and then, we can try to unblock this moment using thermal energy.

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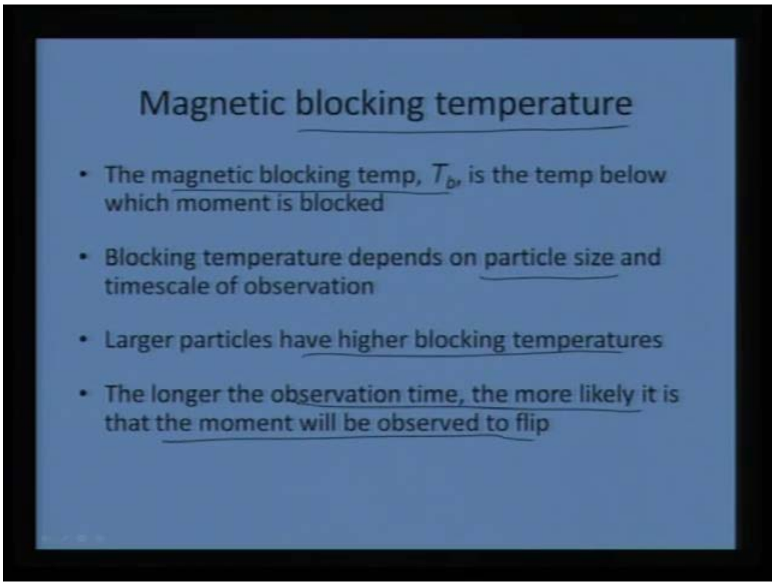

And therefore, we come across another interesting situation in terms of single domain magnetism where, we talk something about blocking temperature. The magnetic blocking temperature T b is the temperature, below which the moment is blocked. Therefore, there is a critical temperature, beyond which this blocking can be removed, below that the moments are nearly frozen, which we call it as blocking temperature and this depends on the particle size and to some extent particle shape also. Larger particles have higher blocking temperature, the longer the observation time the more likely it is, that the moment will be observed to flip.

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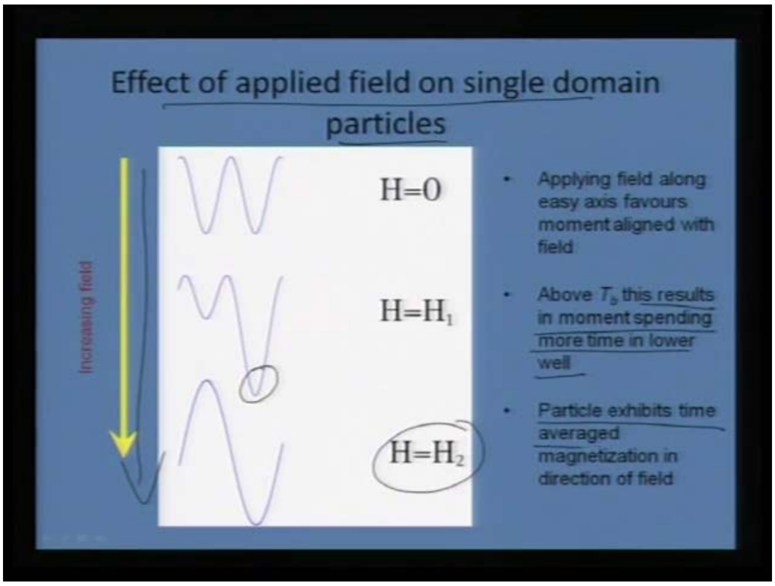

So, if you increase your field strength, sometimes this blocking can be removed that is, the effect of a applied field on the single domain particles. So, as you would see here, that applying the field along the easy axis, favors movement aligned with the field. Above the blocking temperature, this results in moments spending more time in the lower well and when you go to still higher temperature then, particle exhibits time averaged magnetization in the direction of field.

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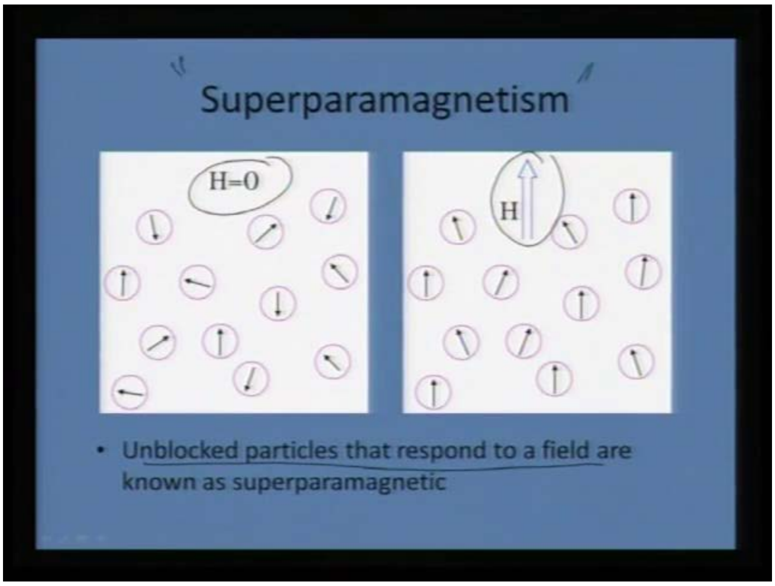

So, this brings you to another situation where, this is not exactly paramagnetism, but you come to a state of a super paramagnetism. So, super paramagnetism is not paramagnetic behavior whereas, where it is a magnetic dipole, but it is within the single domain picture and in that, it can display some of the paramagnetic features. So, these are termed as super paramagnetic behavior and in the absence of field, the moments are aligned in different direction and you can successfully try to rotate this moments close to the axis of your field. And therefore, unblocked particles can respond to a field known as super paramagnetism. So, how do the paramagnetic and super paramagnetic particles behave.

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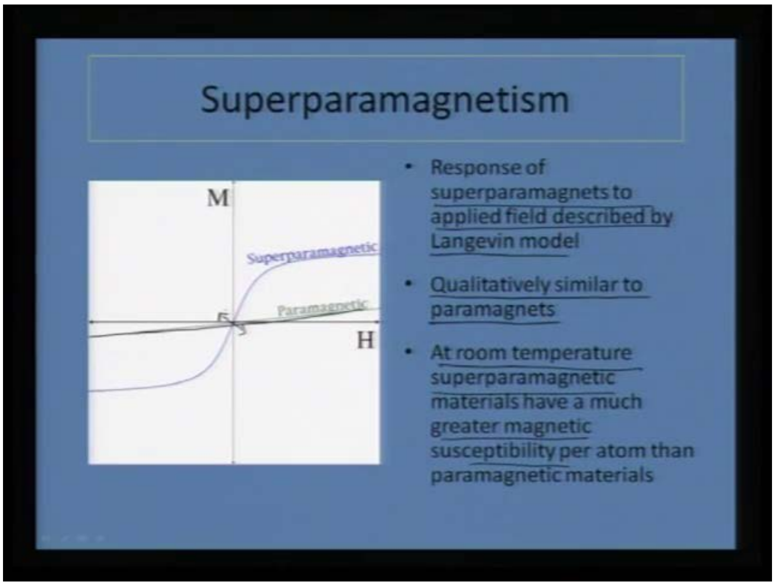

This is the typical fashion, so response of a super paramagnet to applied field is actually described by Langevin model. Qualitatively they are similar to paramagnets and at room temperature, super paramagnetic materials have much greater magnetic susceptibility than paramagnetic materials. So, typically, this is a way, that we can we can distinguish between a paramagnetic and a super paramagnetic particle.

As you can see here, there is almost no saturation whereas, in the super paramagnetic case, it may confuse you to be a ferromagnet. But, necessarily if you try open this area then, you would see that, it lacks coercivity, therefore you can call this is as a super paramagnetic situation and not a true ferromagnetic signal.

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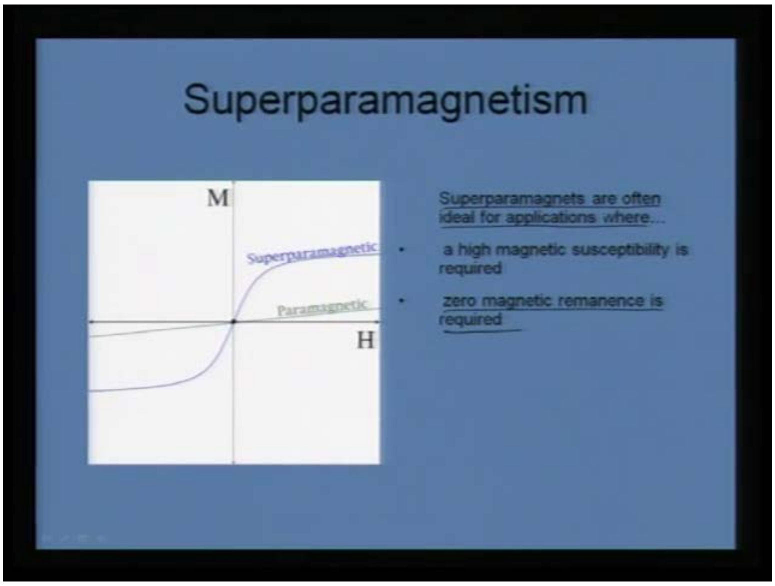

So, super paramagnets are often, they are ideal for applications where, a high magnetic susceptibility is required and zero magnetic remnance is required. So, when you actually take the field of, you should immediately go back, the moment should go back to zero, and therefore this can be used for many applications. And as a result, super paramagnets are used in variety of biomedical applications than in the typical paramagnets. So, we have sort of seen a varied situation depending on, how the magnetic dipole orients itself to the applied magnetic field.

We have seen the case of a paramagnetic gas, we have seen example of how a ferromagnetic cluster will evolve with the domain structure and how antiferromagnets differ from ferromagnets. And also, we have seen a case of ferrimagnetism and as a special case, the super paramagnetic behavior, so all these are embedded in the so called magnetic materials.

And we would see in the next few lectures, examples of how to analyze the true magnetic response, something may give a hysteresis, but it may lack the ferromagnetic order. So, how to distinguish experimentally and what are all the ways, we can study the magnetic behavior in materials. Specially, we will take examples from oxides and thin films and try to look at the various response to magnetic field.