Nature and Properties of Materials
Professor Bishak Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Lecture 39
Magnetic Properties

We have talked about so far these many non-mechanical properties of the materials, let us just try to kind of list them, we have talked about optical properties, we have talked about thermal property, we have talked about electrical property, which is in 2 phases we have talked about the conductive materials and the resistive materials. Now one more we would like to add on that the final one that is the magnetic property that is what we will be discussing today that is the magnetic property of the materials.

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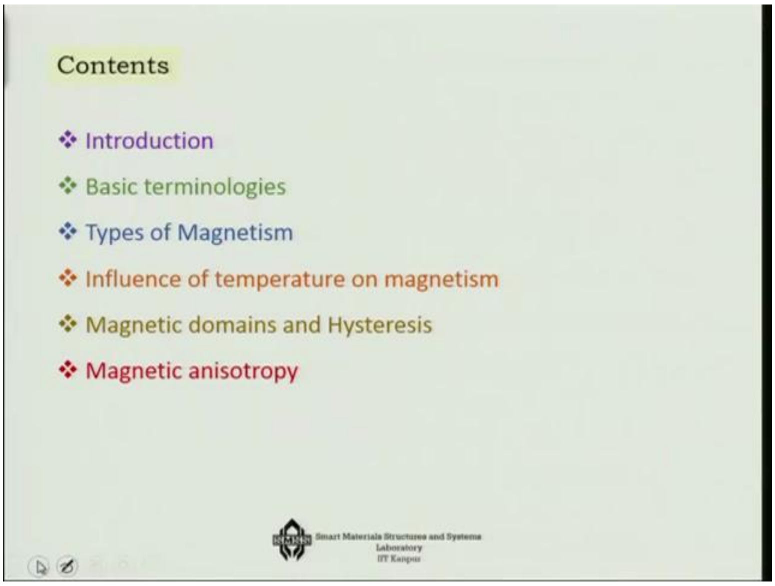

So you add that with your list of knowledge on the mechanical property, I can say now at the end of the course at the very fag end of the course, now you have more or less a very good kit of material properties with you to go ahead design of product development. So in this lecture, we are going to give a small introduction to the magnetism and basic terminologies, types of magnetism, influence of temperature on magnetism, magnetic domains and hysteresis and magnetic anisotropy. As that magnet is always a very-very mysterious material. People say that even Cleopatra used to take a bath in magnetic beads thinking that it has some kind of correlation ship with the longevity of a human being.

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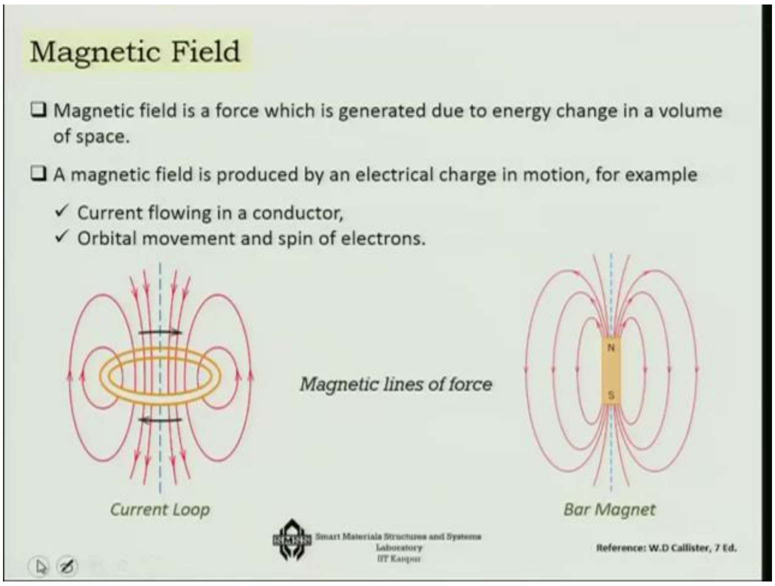

It all happened because of that Mystic Force that you cannot see of course, but the force is there which is working on you, so it is considered to be a very Mystic Force. So magnetic field is a force which is generated due to energy change in a volume of space and this is produced by an electrical change in motion for example, if there is a current flowing in a conductor or orbital movement and spin of electrons. So if there is a current loop, you will see that there are the magnetic fields, which are happening here so in any current loop.

And if you consider a permanent magnet like a bar magnet for example, you would see that the magnetic field is generating from North and getting over at South that how the magnetic lines of forces the magnetic loops are working on the system. So basically you can have the magnetic field due to the intrinsic property of a material or you can have it by external electric field in the system.

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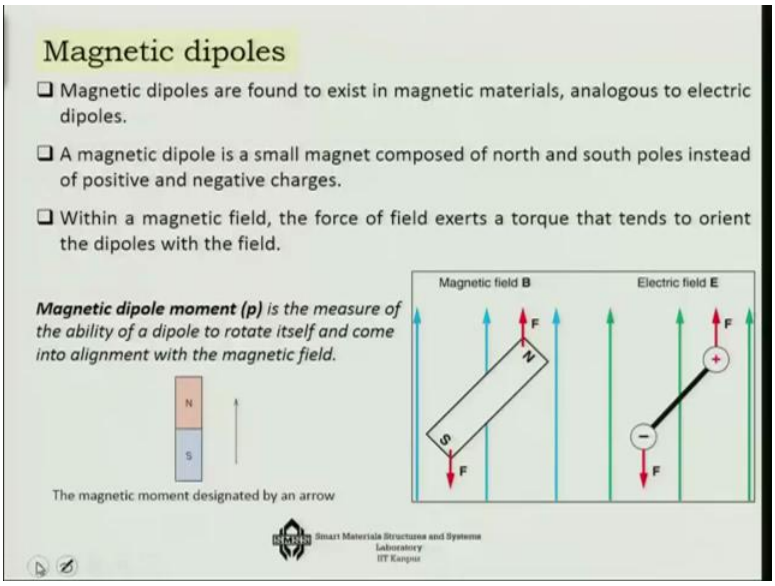

Now, similar to our electric dipoles, there are magnetic dipoles. In this case it is not a positive or negative charge, but it is this north and the south poles, so magnetic dipoles are found to exist in magnetic materials which are very much analogous to electric dipoles. And this magnetic dipole you can almost think like a miniature magnet which is composed of north and south poles instead of positive and negative charges. Within a magnetic field, the force of field exerts a torque that tends to reorient these dipoles with the field.

So it is already for example this is a magnetic dipole okay and then I am applying a magnetic field here B, so this field will actually apply a force here F, which will force it to align itself towards the direction of the magnetic field. Now it is very similar to the electric field based movement of the system. So magnetic dipole moment is the measure of the ability of a dipole to rotate itself and come into alignment with the magnetic field. Much the easily readily it can do, the more magnetic is of course the material. And we generally denote this magnetic moment by an arrow like this.

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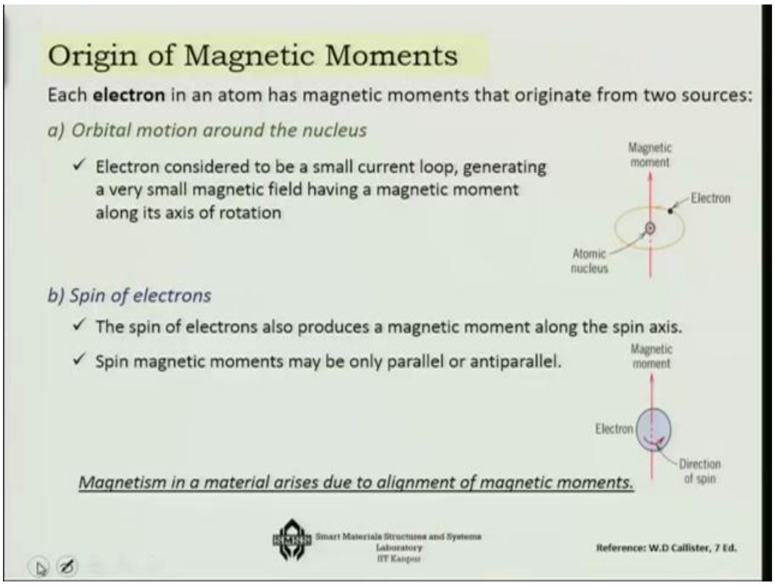

Now, what are the origins of such magnetic moments? Well, there are 2 sources; one is the orbital motion of electrons around the nucleus because they are like very-very small current loop each electron orbiting around the nucleus of an atomic nucleus of a system. So each electron during their motion must generate a magnetic moment along its axis of rotation, magnetic moment gets generated. Then there is this spin of electrons, this also produces a magnetic moment along the spinning axis of the electron, so it is like each individual electron now which is spinning and that is creating a magnetic moment.

So there are 2 motions that are there right, maybe you can think of it very much analogous to the motion of earth around the sun that you have motion of earth around its own axis, which is like the spinning motion and you have also the orbital motion, so the orbital motion generates one of the magnetic moment and the spinning motion generates another magnetic moment, both of these are bound to happen because why because the electrons carry the electric field, so the change of electric field that is going to generate the magnetic field. So magnetism in a material arises due to alignment of magnetic moments that is in a microscopic scale, we will talk about it.

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Now, every material has atoms, so it has orbital and spinning electrons then are all materials magnet? The answer is no. So even at microscopic scale it does not happen, so why it does not happen?

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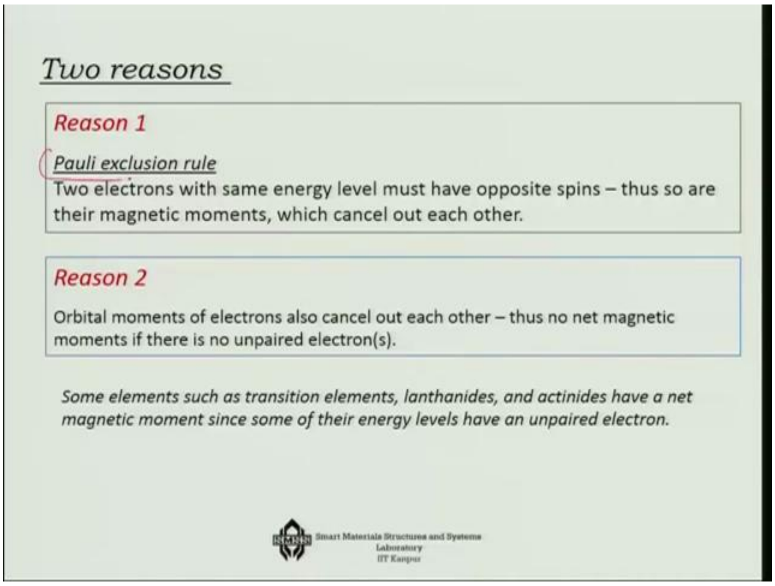

Two reasons, one reason it is called the Pauli exclusion rule, which says that 2 electrons with same energy level if it has, then it must have opposite spins. So thus, their magnetic moments are going to cancel each other, so even though there are if there are 2 electrons, they cannot get the same spin, they will be in the opposite spin as a result, magnetic moment due to spinning is going to cancel. Then as far as the orbital moment is concerned, that also cancel out each other and there is no net magnetic moment if there is no unpaired electron.

So the clue is that if you have unpaired electrons, only then this result will get manifested in the microscopic scale otherwise, they are going to cancel each other. Some elements such as transition elements lanthanides and actinides, they have a net magnetic moment and some of the energy levels have an unpaired electron that is why they show this kind of a magnetic moment.

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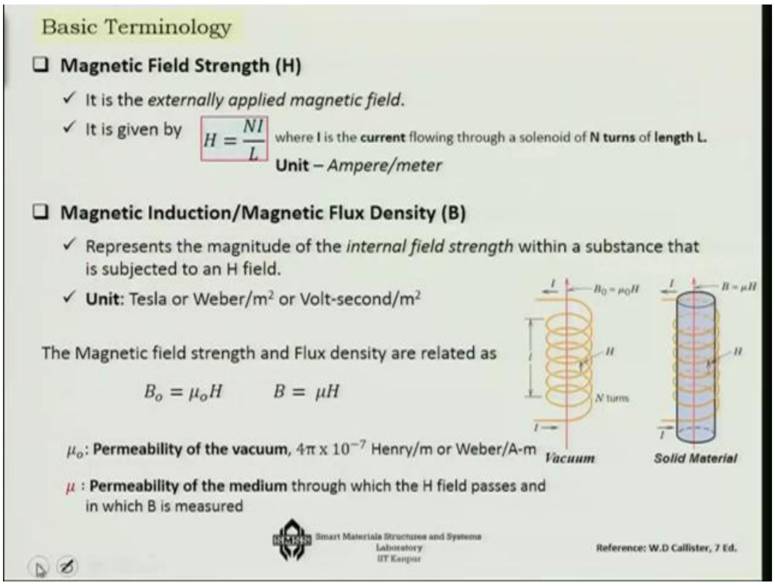

Now there are some basic terminologies with respect to this magnetism, 1st thing in the magnetic field strength H, this is the externally applied magnetic field and it is generally described in terms of 3 parameters, number 1 is N that is total number of turns and the length that is L on which you are giving the turns, suppose this is a solenoid then the length of the solenoid okay L, so this is the L and the current I okay so if I increase the current in the coil I get more magnetic field.

If I increase the length, then the magnetic field intensity comes down, if I increase the number of turns, if I make it more dense then I get actually more magnetic field out of the same length, so the number of turns plays also an important role. Now, next to H, H is fine H = N I over L that now and which has a unit of ampere per meter. Next to that is the magnetic flux density B, this represents the magnitude of the internal field strength within a substance that is subjected to an H field. So H is the field strength, but the density of that field which gets all around that density is actually measured with respect to B which has unit of Tesla or Weber per square meter or volt second per meter square.

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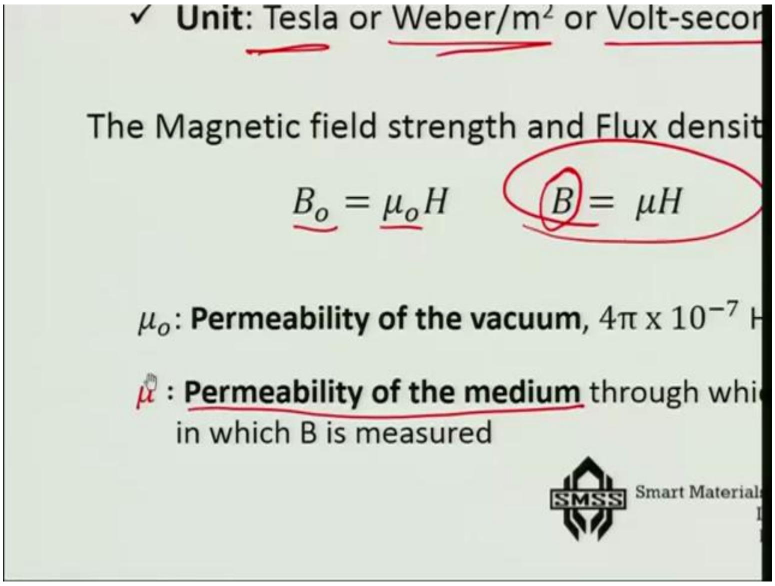

The simple relationship here is B = Mu H, for vacuum of course it is Mu 0 H, so where Mu is now the permeability of the medium through which the H field passes that means if the medium is more permeable, then with the same magnetic field strength you are going to get higher magnetic flux density, so permeability Mu is a very important factor for us.

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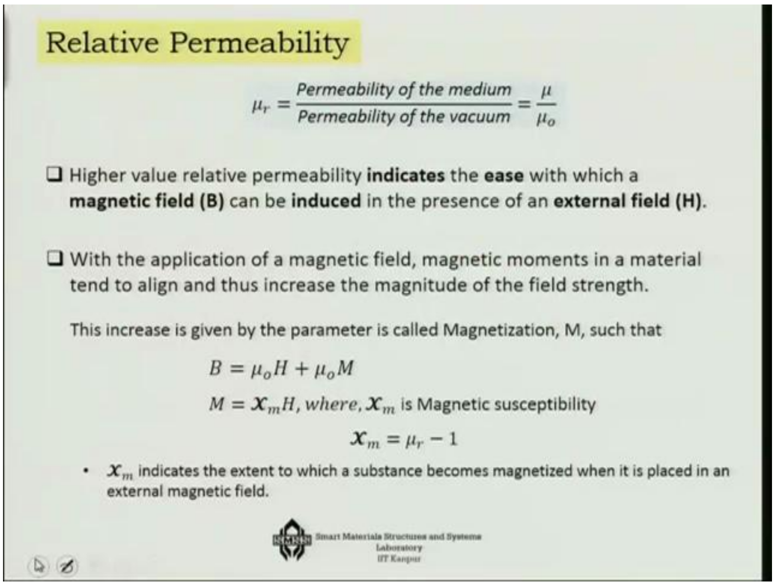

Next the permeability of course is measured here in terms of the relative permeability Mu r okay, Mu over Mu 0. And higher the value of the permeability of the medium, then Mu r is higher which is fine with us. The other point is that, just like polarisation there is something called magnetisation M okay which presents in a material. So with respect to external will relationship was b = Mu 0 H, but what if the material is like I already told lanthanides, et cetera, so there is a magnetisation that is there.

So we have to extend it to Mu 0 + H Mu 0 M, where M is once again it can be expressed as a function of the field strength H with the help of something called Kappa m, where Kappa m is the magnetic susceptibility and this is Mu r - 1. So essentially the property once again remains the same that is the relative permeability because Kappa also depends on the same, so this is how the magnetic field and the magnetic flux density are related to each other. Now let us talk about the manifestation of this magnetism on different materials.

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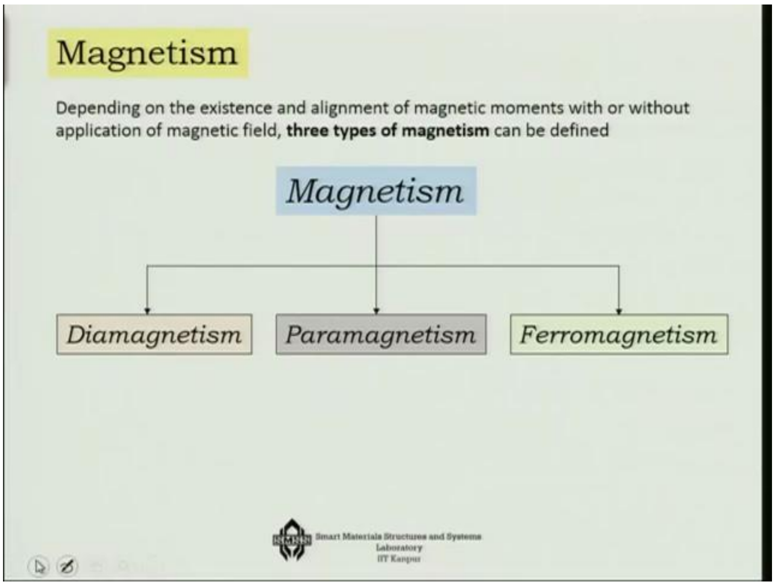

There are 3 types of magnetism that you will generally see, one is called Diamagnetism, another is called Paramagnetism, another is called Ferromagnetism course, there are some of the other variations but these are the basics 3 that you will see in a material. What is the Diamagnetism?

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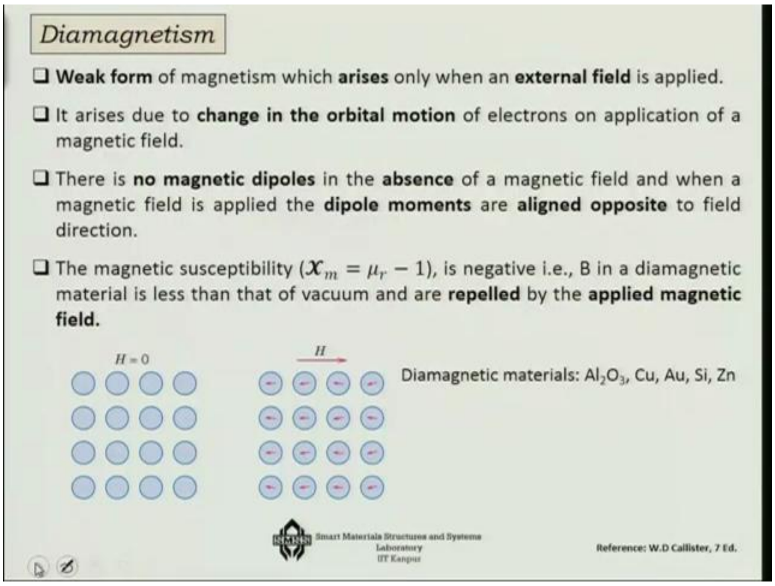

This is actually the weakest form of magnetism which arises only when external field is applied. This arises due to the change in the orbital motion of electrons on applications of magnetic field the orbital motion is going to get change. There are no magnetic dipoles in the absence of a magnetic field and when a magnetic field is applied the dipole moments are aligned opposite to field direction. Like initially there is no dipole moment and the moment you apply the magnetic field, you are going to see that the dipole moments are coming; they are trying to balance opposite to the direction of the magnetic field, so this is the diamagnetic material.

The magnetic susceptibility of course in this case is Mu r - 1 which is negative and B in a diamagnetic material is actually less than that of vacuum and are repelled by the applied magnetic field. The examples of diamagnetic materials are like Al2O3, copper, Gold, okay silicon, Zinc, et cetera. One of the good uses of diamagnetic material is in terms of shielding from the electromagnetic interaction, so we try to use this type of material so that if you imagine that you have a series of such diamagnetic materials there as a protective coat.

And you have a very sensitive electronic circuitry in that are there here okay, so some ICs are there. Then if you apply a magnetic field, this immediately generates the opposite direction of this magnetic dipoles, which will nullify this effect and as a result this IC will be saved from the effect of the magnetic field intensity, so that is how the diamagnetic materials are very-very useful as a protective coating against electromagnetic interference, we call it EMI interference okay.

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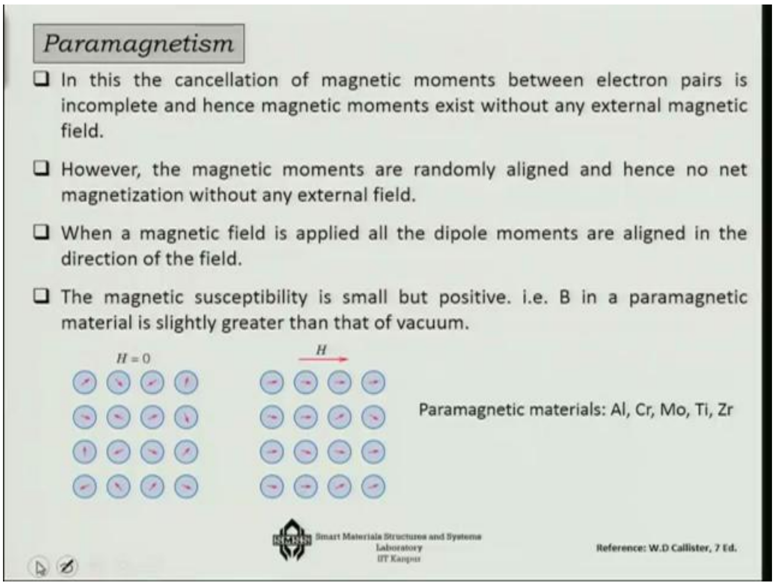

Now paramagnetic materials, in this the cancellation of magnetic moments this actually already has some unpaired electrons means it has some internal magnetic moments, but in general they will not manifest why, because they are random so they are going to cancel each other. When a magnetic field is applied for paramagnetic material, they are going to align themselves towards the direction, so they are the traitors, they are going to align themselves towards the direction and hence they are slightly more magnetic than the diamagnetic materials.

Examples are aluminium, chromium, molybdenum, titanium, zirconium, et cetera. So that is the paramagnetic materials, no little go to another group. But before we go to the Ferromagnetic, this is like a chart which gives us the susceptibility of diamagnetic materials because there we are measuring it in terms of the susceptibility, not the permeability.

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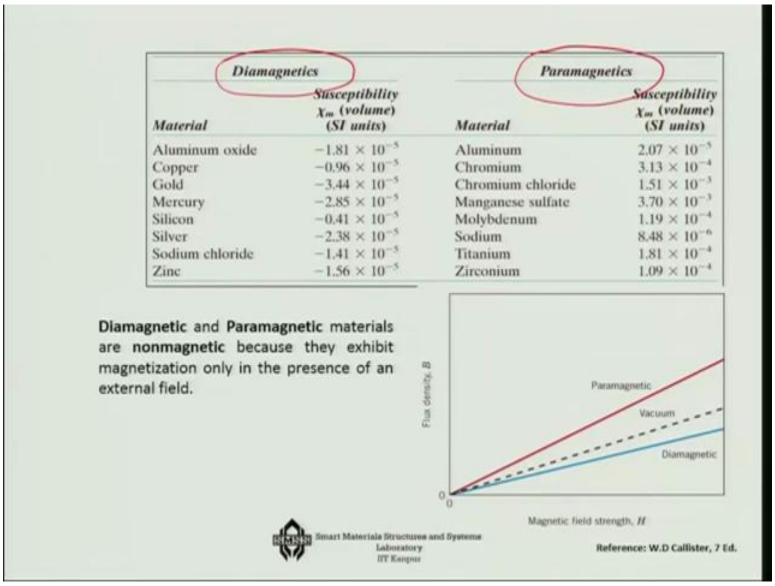

So it is like the if you consider aluminium oxide on the diamagnetic, one of the highest in terms of susceptibility of course even higher is the gold, mercury for example, then silver for example, then there are other materials like sodium chloride, zinc, et cetera. In terms of the paramagnetic materials, the one which will top the list is the sodium as you can see, some metals are also paramagnetic like let us say aluminium, chromium, then there are some compounds like chromium chloride, magnesium sulphate, molybdenum, titanium, zirconium, et cetera.

So these materials are non-magnetic because they exhibit magnetisation only in the presence of an external field. And if I increase this external field H, then the magnetic flux density increases, for the time magnetic material it is still much lower than the vacuum and for the paramagnetic material, it increases slightly with the help of the magnetic field okay H, so that is the diamagnetic and the paramagnetic material. Let us now come to the next group that is the ferromagnetic material.

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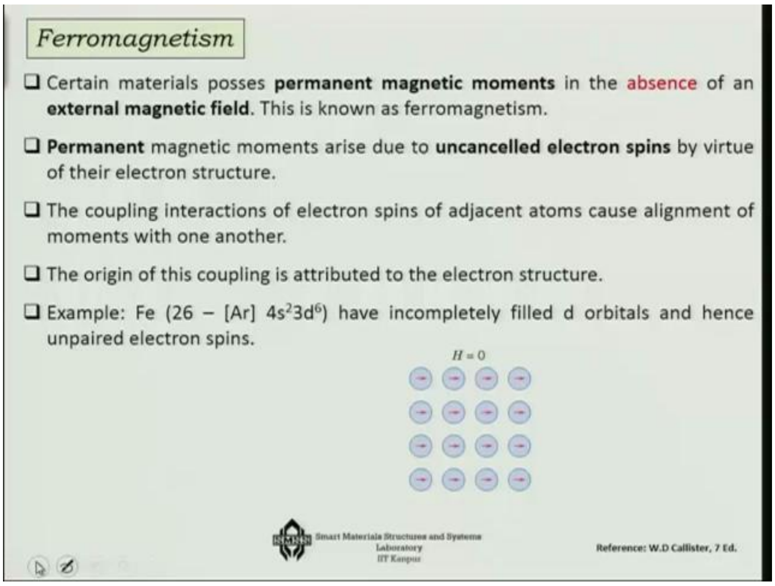

Certain materials possess permanent magnetic moments in the absence of an external magnetic field, this is known as ferromagnetism. It is related with ferrous because iron is one of such components. Permanent magnetic moments arise due to uncancelled electron spins by virtue of their electron structure. The coupling interaction of electron spins of adjacent atoms cause alignment of moments with one another. So not only they have the magnetic moments, but even with H = 0, they are approximately aligned against each other that is the beauty of such material.

The origin of this coupling is attributed to the electron structure, this is the maximum will talk about it in this particular series. So iron for example you see the structure, it has incompletely field orbits and hence it has unpaired electron spins, so this is one such material which shows ferromagnetic effect. Now, there is something which is also known as Anti-ferromagnetism.

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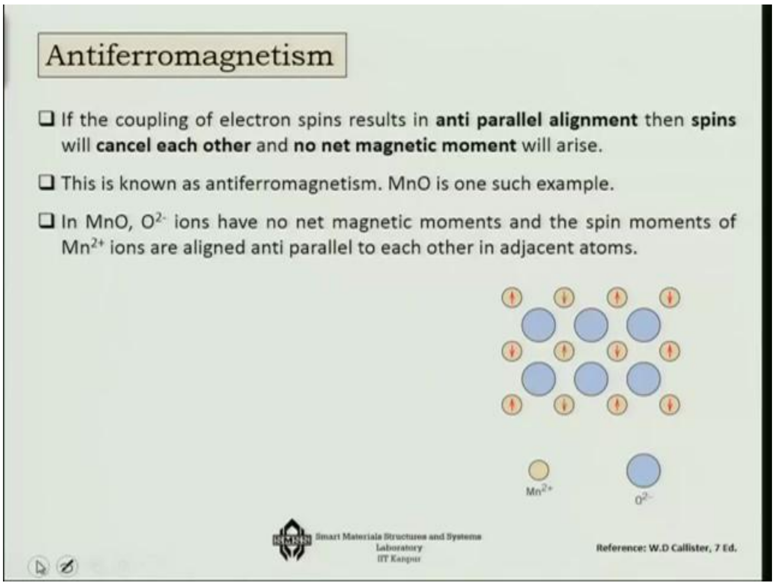

If the coupling of electron spins results in antiparallel alignment, then spins will cancel each other and you will not get a net magnetic moment which will arise. So even though there are magnetic moments, they are aligned but it can happen that they are opposite in directions okay, so then it will become anti-ferromagnetic system. One of the interesting examples is manganese oxide, which shows no net magnetic moment because of the anti-ferromagnetic system that it has.

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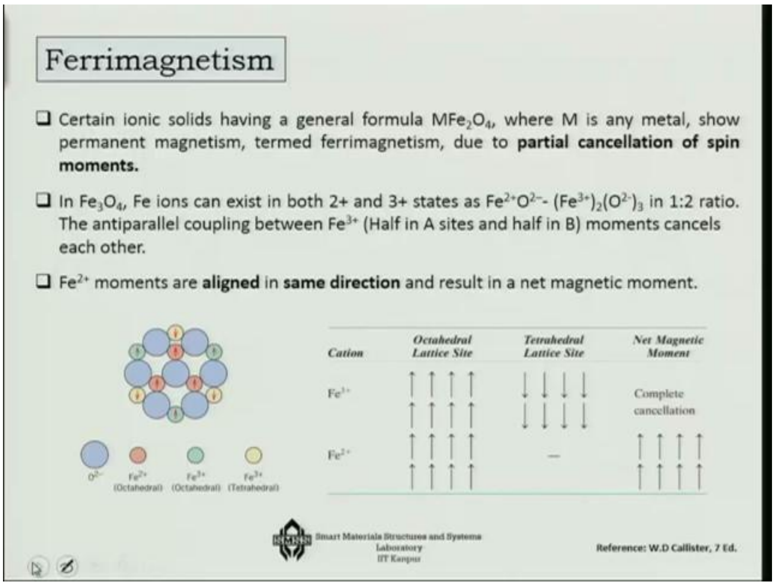

Then another interesting version is called Ferrimagnetism and this happens in ionic solids which has particularly a kind of common formula of MFe2O4, where M is any metal. This shows permanent magnetism, but it is termed as ferrimagnetism due to partial cancellation of spin moments. For example in Fe3O4, the iron ions can exist in both 2 + and 3 + states as Fe 2 + O 2 - and Fe 3 + O 2 - in 1 is to 2 ratio. The antiparallel coupling between irons half in A sides and half in B moments, these moments will cancel each other.

Fe 2 + moment on the other hand, are aligned in same direction and result in a net magnetic moment, so you can see it here that from the lattice structure Fe 3 + for example okay, they also in the lattice structure will be showing similar to Fe 2 +, the octahedral lattice side. But in the tetrahedral lattice side, you will see that they have this opposing magnetic moment, whereas they do not have and as a result, they have a complete cancellation for Fe 3 + net magnetic moment, but for Fe 2 + you are going to see some magnetic moment in the system.

So this Fe 2 + moments are aligned in the same direction and they result in a net magnetic moment, so hence wherever you have this Fe 2 + with the octahedral lattice side, this is going to show the magnetic moment whereas, the Fe 3 + octahedral and Fe 3 + tetrahedral are going to cancel each other, so this is a typical of a Ferrimagnetic material, where you have a partial cancellation of spin the moments okay, not a complete cancellation of the spin moment. Now let us summarize the whole thing okay.

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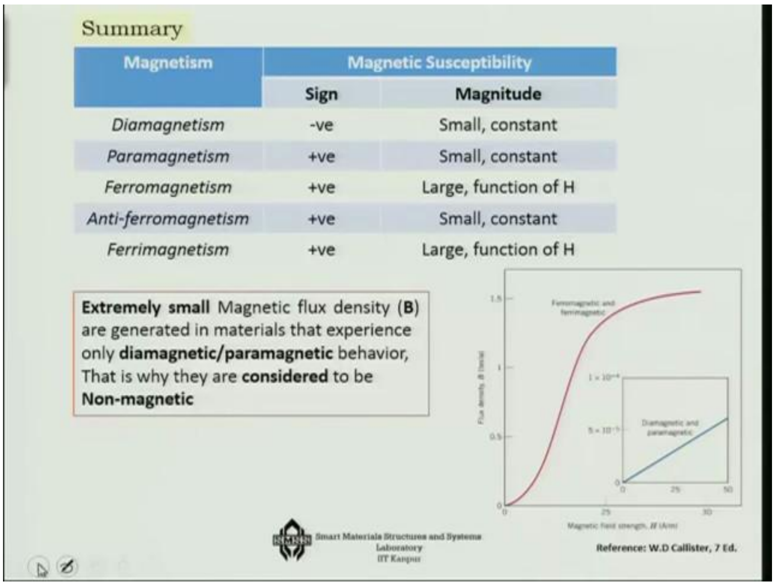

So Diamagnetism, sign is negative for susceptibility, magnitude is small and constant. Paramagnetism, positive susceptibility, small, constant. Ferromagnetism, positive, large, function of H. Antiferromagnetism, positive but small constant, and ferrimagnetism positive, large, function of H. Extremely small magnetic flux density B are generated in materials that experience only diamagnetic and paramagnetic behavior, that is why they are considered to be non-magnetic. So for a ferromagnetism material, how does it behave? How does the magnetic field changes with respect to the magnetic field strength H?

So this is a typical H versus B curve as you can see it here that it is initially the B is increasing at a very fast rate and then there is a saturation that is happening okay. So, essentially you have for example in a unit volume you have all these dipoles okay, so initially all these dipoles will very fast try to align themselves as a result the magnetic + density increases sharply, after some point of time what we will see is that all of them are nearly aligned as a result to the field so that means nothing more is happening in terms of the flux density, so there is a saturation that will happen to this kind of a system.

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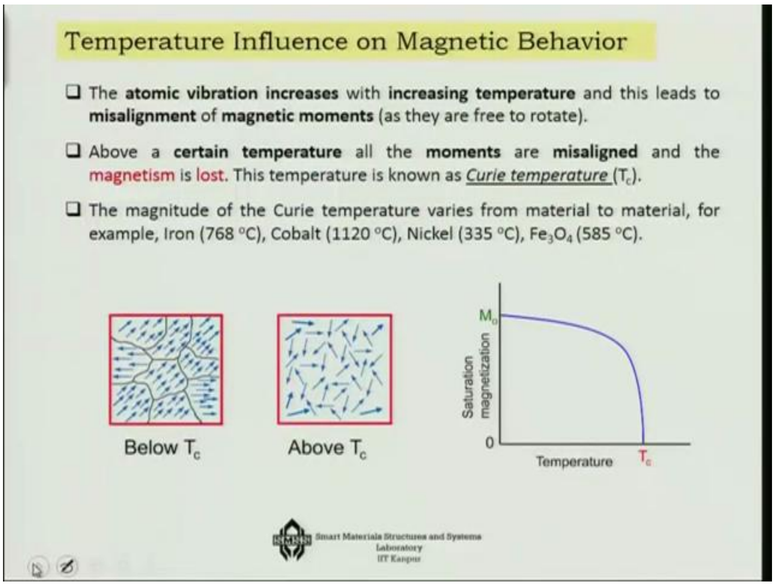

So how this property does changes with respect to temperature because many times temperature becomes a factor in our applications? Now, we know that atomic vibrations increases with increase in temperature and this leads to misalignment of magnetic moments as they are free to rotate. Above a certain temperature, all the moments are misaligned that means they become random in nature and hence the magnetism is lost, this temperature is known as the Curie temperature. Beyond that, it will be so much misaligned that the magnetism is lost.

So below the curie temperature you are getting the alignment, about the Curie temperature you are getting this random distribution. And if you want to plot temperature versus saturation magnetisation, you will see that it sharply drops beyond a particular temperature. This temperature of course varies from material to material for example, for iron it is 768 degree centigrade, cobalt 1120, one thing you can notice that it is close to its melting point, nickel 335, Fe3O4 about 585 degrees centigrade, so that is the temperature influence on the magnetic behavior.

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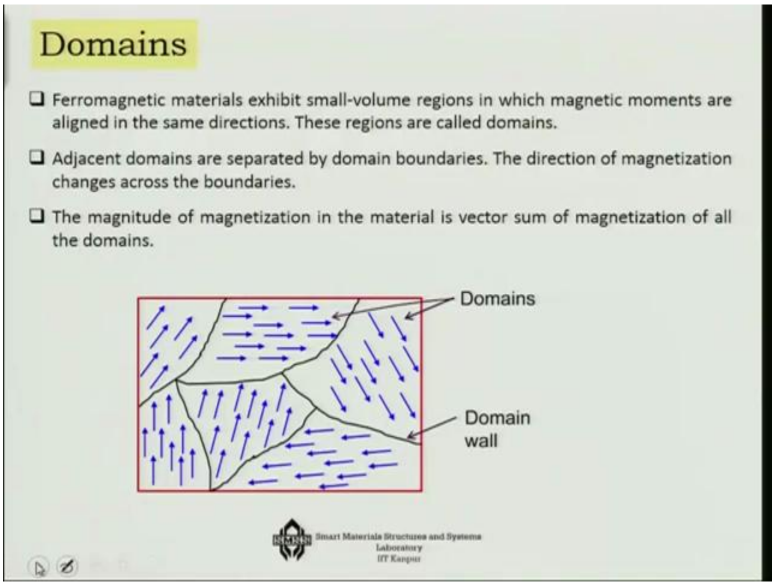

Now, below Curie temperature we have already seen the existence of the domains mean there are regions where the magnetic dipoles are all parallel okay. Then there is another region where then again they are parallel inside that set. So ferromagnetic materials exhibit such small volume regions in which magnetic moments are actually aligned in the same direction, these regions are called domains. The different domains are separated by the domain boundaries. The direction of magnetisation changes across the boundaries.

The magnitude of magnetisation in the material is then the vector sum of magnetisation of all these domains. So once you integrate it across the domain, you are going to get the net magnitude of magnetisation in the material. Then the other part is the magnetisation saturation.

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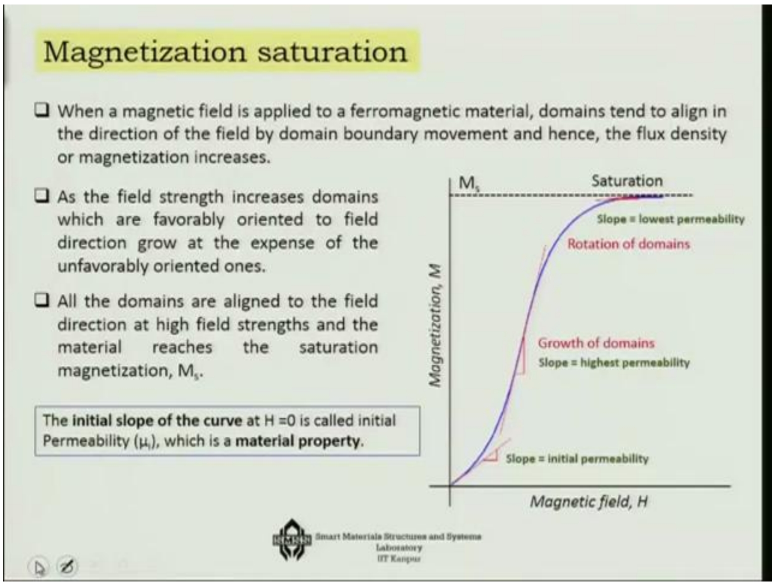

So, when a magnetic field is applied to a ferromagnetic material, these domains tend to align in the direction of the field by domain boundary movement and hence the flux density or magnetisation increases. This is just what I wanted to show you earlier that suppose this is your initial permeability and then suddenly there is growth of domains that means all these domains that you have seen in a volume suppose okay, you have some such domains. The domains are not stationary nature okay, so each domain size are going to increase with respect to the magnetic field, so it may become more chunk and bigger and bigger.

So this is the growth of domain and as a result the magnetisation also is increasing. But beyond a certain point, the entire all the domains favorably oriented to field direction grow at the expense of the unfavorably oriented ones that is this point. And then ones domains are aligned to the field direction at high field strength and the material reaches the saturation magnetisation M s, then this whole activity becomes once again very much saturated so there is no net change in magnetisation anymore with respect to the change of the magnetic field okay, so that is how we get that famous S curve in it.

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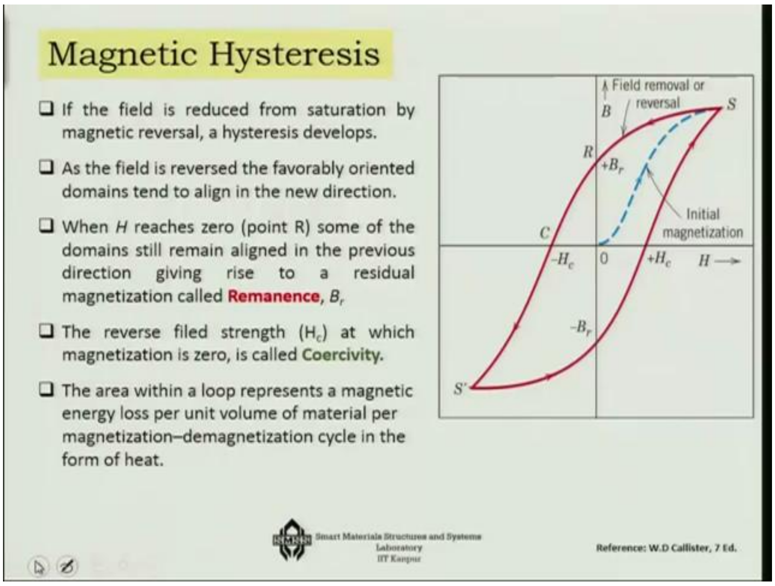

There is one interesting thing, if you change the direction of magnetisation then what happens. So if the field is reduced from saturation by magnetic reversal, there is a hysteresis that will develop. As the field is reverse, the favorably oriented domains tend to align to the new direction. When H reaches zero, some of the domains still remain aligned in the previous direction, this gives you a magnitude of Remanence this gives you a residual magnetisation called Remanence. The reverse field strength at which the magnetisation becomes zero is called the Coercivity.

Coercivity is the inverse field strength for the magnetisation becomes 0. There are 2 important things in magnetic hysteresis, one is called as I told you the Remanence okay that means when you are reversing the magnetic field, we will still find that some domains have not really aligned themselves or it is still keeping this alignment that is what the Remanence okay B r is. And then when you are having already a negative magnetic field, you will still find that suddenly it will become 0, so that is the coercivity okay when the magnetisation will become 0.

The other thing is that this is the initial route and then you are reversing the magnetic field, so up to this you are increasing and then you are reversing it and as we are reversing it, we are going down like this. And when you are again reversing the magnetic field, it is coming in a different line meaning thereby you will have an area inside, which is the hysteresis of the magnetic hysteresis.

So there is some amount of energy which will be basically loose, you are losing that that is what is signified by this hysteresis and that happens in every magnetization-demagnetization cycle. Where does the energy go? Well, it goes for heat energy for example, acoustic energy, et cetera that is the magnetic hysteresis in the system. There are 2 different types of magnets that we categorise in terms of this hysteresis; one is called soft magnet which has a narrow hysteresis curve and another is a hard magnet.

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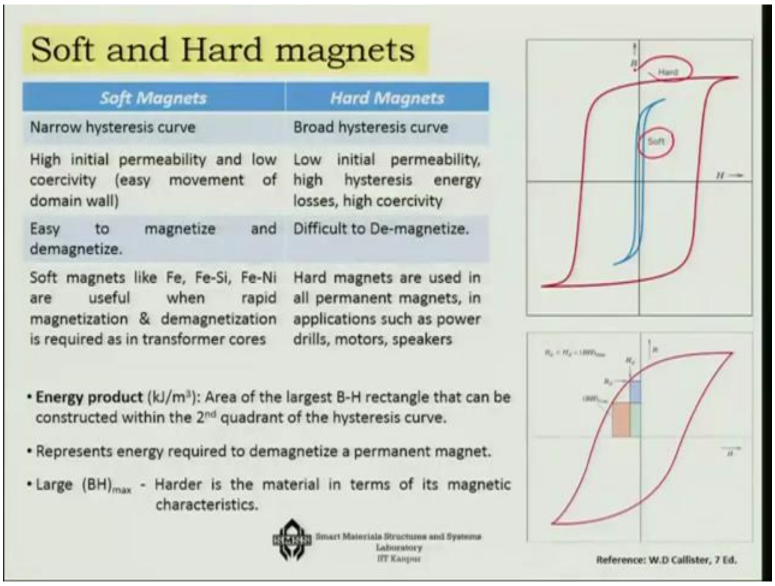

So the comparison is that indeed soft has a narrow hysteresis curve, it has high initial permeability and low coercivity that is easy movement of domain wall. And in terms of hard magnet, it has low initial permeability, high hysteresis energy losses, but high coercivity also, look at it, it has a high coercivity. Soft magnets are easy to magnetize and demagnetize, but hard magnets are difficult to demagnetize. Soft magnets like iron, iron silicon, iron nickel, they are useful when rapid magnetization and demagnetization is required in a transformer core for example. Hard magnets on the other hand, they are used in all permanent magnets in applications such as power drills, motors, speakers, etc, but they have high hysteresis field.

The energy product which is in terms of Kilo joule per meter cube that is the area of the largest B-H rectangle that can be constructed within the 2^{nd} quadrant of the hysteresis curve. This is the 2^{nd} quadrant of the hysteresis curve, so this is one of the measures that is the largest B-H rectangle that you can fit here that is a measure okay like this one that is the measure of the hysteresis.

This represents energy required to demagnetize a permanent magnet, based on that you can, so larger the B-H max harder is the material in terms of its magnetic characteristics. So we have talked about Mu the magnetic field permeability, now we have a new one that is the B-H max, which is important in terms of categorization of soft and hard magnets.

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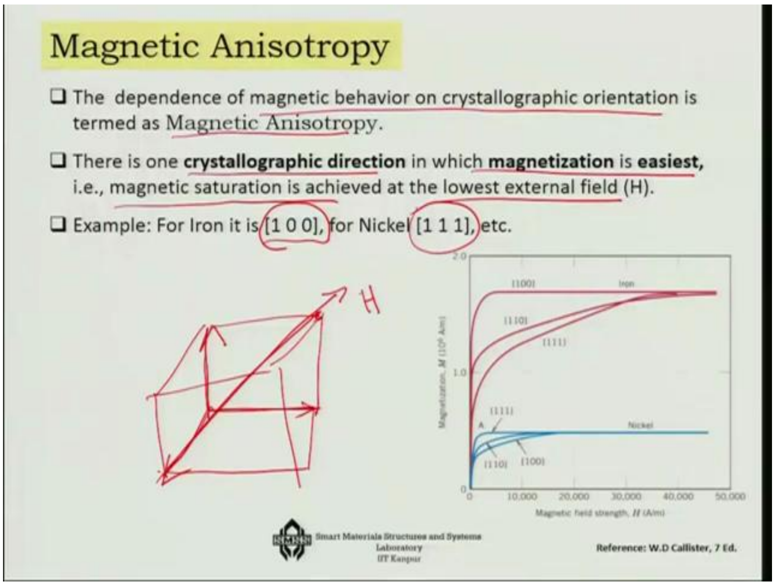

Next is magnetic anisotropy, the dependence of the magnetic behavior on crystallographic orientation is termed as the Magnetic Anisotropy because as that not all the directions it is easy for the magnetisation, so the crystallographic direction in which the magnetisation is easiest that means, magnetic saturation is achieved at the lowest external field these are called the easy axis. For example, for iron it is 1 0 0, we already told you that how for the axis setting we have already talked about it, so for iron it is 1 0 0, for nickel it is 1 1 1 okay.

That means for iron it is anyone of these principle axis, whereas for nickel these are the diagonal axis 1 1 and 1 which is what so if you try to put it for nickel okay, then it is the diagonal from one end to the other that is the axis in which if you apply H, that is the easy axis for it whereas, for iron it is any one of these axis 1 0 0, which are the axis in which you can actually do it. So this anisotropy exists and you have to know for each material, which is the easy direction because you can then very easily get it magnetized accordingly.

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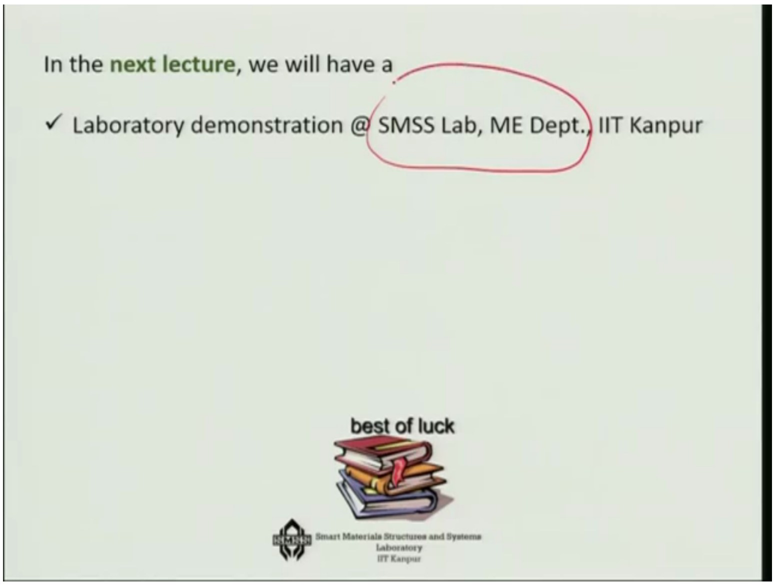

So this is where we are going to close all our lectures related to the material properties. Now, finally I want to give you some of the demonstrations at my laboratory this is the smart material structures and systems laboratory at the mechanical department of IIT Kanpur, where you will see some of these instruments and materials in function and that is how we will close our lecture, thank you.