Physics of Materials

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Lecture No. # 06
The Ideal Gas

Hello, welcome to the sixth class in the physics of materials lecture series. In the last class we looked at the initial stages of how you go about putting together free electron theory for conduction in metallic system. So, we will continue with this discussion. What we saw last class was we compared, we took the idea that 1 of the models for metals is that there are ionic cores and there are electrons freely running across the extend of the solid. So, we have a block of metals the electrons the so called free electrons are free to run across the extend of the solid. So, that is the picture that we have.

And to the extend that the those are free to run across the extend of the solid. We treat them almost as though they where behaving like molecules of a gas. So, with this idea or this picture or this analogy between a gas and solid the intent is to see if there is a theory that we can use for gases which we are familiar with and extend it to solid. So, gas being a state where the atoms are free to run around and this minimal interaction between the atoms or molecules of the gas is generally much easier to model, much easier to write equation to describe the behavior of the gas.

So and therefore, it make sense that at least our initial attempt to try and understand what is happening inside the solid starts off with something that we understand of the gas which we extend to that of the solid to the extent that the constituent within the solid have at least some resemblance to what in the behavior to what a gas does. We also did some calculation in the last class to what extend we are justified in making this analogy, to what extend we can make this connection between behavior that we see in a gas and behavior that see amongst the electron in the solid.

The positives aspect that we noted was in favor of making this comparison was that depending on the crystal structure even up to 50 percent of the solid might be vacant. So, I specifically pointed out you pick up a solid metallic object in your hand, it is not immediately apparent to 25 percent or 50 percent or even more depending on the ionic radii and so on even more can actually be vacant space. It does not look like that, very solid continuous object that you have in your hand. It is just that vacant space is evenly dispersed across the extend of that solid that we do not perceive it like that when you pick it up in your hand so but, never the less if you can actually do the calculation, if you look at the atomic radii of those atoms present or their ionic radii which in this case maybe smaller and you just look at the total volume that is available given the crystal structure, there is lattices parameters attached to the crystal structure which we can experimentally verify using x-ray diffraction or other such techniques.

We can experimentally verify that lattices parameters. If you take all that in to account you realize that you know anything like 50 percent, 25 percent, 50 percent or even higher to be vacant space within the solid. Therefore, given that their such a large vacant space and the fact that the electron is such a tiny particle relative to gas molecules taking this two into account. It is it seems, it comes across to us that it is reasonable to treat it as though these are gas molecules, treat the electron inside the solid as though they were gas molecules running freely across the very large volume and from that perceptive it seems that it is reasonable to extend this gas loss to free electrons which are present within a solid. We also did some other calculation to compare the number density so to speaks of particles of the particle density that is prevalent in this gas at s t p to that which is prevalent in the solid, the number of electron that are, the density of electron present in a solid.

We find that there is a 3 orders of magnitude difference in the particles, the number of particles that gas particles that are there, upper unit volume at s t p when you compare that with number of electrons present per unit volume in a solid in a metallic solid. So, we took silver as an example. We came up with some numbers. So, we find 3 orders of magnitude difference. In other words there are every molecules that you find unit volume in a gas there are 1000 electrons that you find for the same unit volume inside the solid. So, this is the huge difference, 3 orders of magnitude difference is very significant difference and therefore, there is reason from this perspective to be cautious on making such a jump in trying to make a connection between the behavior of the gas and behavior of an electron gas in a solid but we still believe that over all there, is it is not far fetch to make this connection, it is not far fetch to try and make some equations out of it.

So, we treat and it is also rewritable it is straight forward to do so, to write the equations down. So, we just run through the process, we make put this equations down we will see what we get in terms of electronic conductivity, we will see what will get in terms of thermal conductivity and we will see how well this kind of theory is able to predict experimental values in both cases and also how well it is able to predict the relationship between thermal conductivity and electronic conductivity because as we said one of earlier classes in general we find the metallic system which are also good conductors of electricity also happen to be good conductors of heat, given all this things we would like to see how well this theory is able to predict all of this, the electronic conductivity, the thermal conductivity and the relationship between them.

So, this is where headed with this. What we will do today is we will review of few the important results from the kinetic theory of gases because those will be results that we will directly utilize in our calculations when it comes to electrons in a solid. So, that it what we are going to do. So, we will please remember at this moment the discussion is pertaining to gases in a volume. So, we will extend the results so at the moment still gas in the unit volume in some volume.

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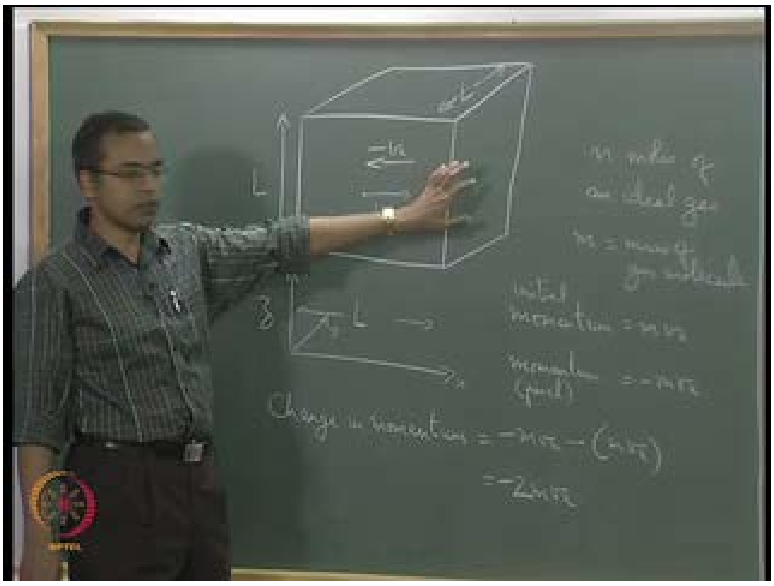

Now, let us take a volume. We will take a box of side L, a cube of side L and we will designate this as your positive x direction and in to the plane of the board will be the positive lie and vertical direction will be z. So, we have this x, y, z coordinates system we are using here and we have let us say that we have n moles of an ideal gas. We have n moles of an ideal gas inside this volume. So, that is what we have that is the system that we are working. What we will do we will start with 1 particular we would say an atom or molecules of this gas and let us say moving with velocity v x in the x direction.

So and we will say the molecules have mass m. So, the momentum of this particle for this is the initial momentum of this particle. We will say that goes and let us assume that it is the cube of side L. So, all side are L, all the dimensions are L, this is just for our convenience we start with something like this so that it we are able to something out of the results. So, we have the momentum m v x headed in the positive x direction. So, this is what is state for with this respect to particular molecule. Let us say it collides with this phase out here and then it bounces back and will assume this is the large box collision is elastic.

So, it bounces back momentum after collision. So, we will say this is final, this is initial, equals it will back it will headed back after collision with v x in opposite direction so we will just call this minus v x, it is the velocity. So, momentum is now minus m v x. So, final momentum is this. So, for the particle which has now bounced off of the surface, change in momentum with the final momentum minus the initial momentum minus m v x minus so it is minus m v x final momentum minus of the m v x which is the initial momentum. So, this is simply minus 2 m v x. So, for this particles to which moves which had a component of velocity in the x direction v x as it bounced off of the surface that is out here, the change in momentum for it is minus 2 m v x that is the result we have.

Therefore, the momentum that it has transferred to front surface is the opposite of this. So, this is the change for it so the opposite change will since momentum is concerned the opposite would have occurred for the box, so the momentum transferred to this front face or to this face not a front face it is a side face.

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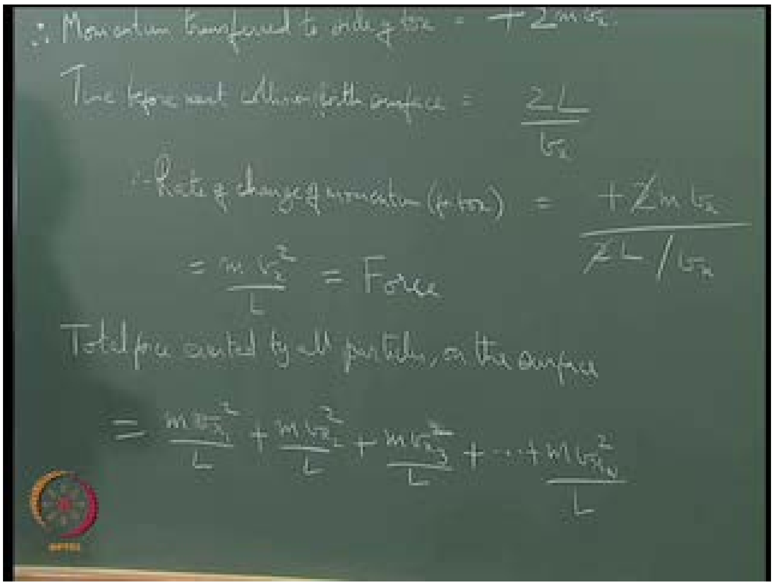

∴ Momentum transferred to side of box = $+2mv_x$

Time before next collision with the surface = $\frac{2L}{v_x}$

∴ Rate of change of momentum (for box) = $\frac{+\cancel{2}mv_x}{\cancel{2}L/v_x}$

$= \frac{mv_x^2}{L}$ = Force

Total force exerted by all particles on the surface

$= \frac{mv_{x_1}^2}{L} + \frac{mv_{x_2}^2}{L} + \frac{mv_{x_3}^2}{L} + \cdots + \frac{mv_{x_N}^2}{L}$

Momentum transferred is plus 2 m v x. So, that is the positive opposite of what happen to the particles is been transferred to this front of the box. Now, we know the change in momentum. So, we know change in momentum for the particle which we now change in momentum for the box. These are 2 things that we know, from here we would like to get some expression for force, then some expression for pressure. So, force is rate of change of momentum. So, we like to know the rate at which change in momentum is occurring, this is change in momentum we would like to know rate at which is occurring. So, if you go back to this picture here we have a box of side L and velocity here is v x.

So, once you have a collision here for it to come back and collide at this surface once again, it has to travel all the way back here, make a collision with the face surface on this side and then come all the way back to the front to this face. So, it has to travel L and it has travel back L that basically what will happen before it can make a second collision with this surface. It has to travel a distance 2 L and its velocity is v x. So, the time it will take travel to a distance. So, this the time it is going to take before it collide against the same surface. So, it is transferring the momentum and the time interval over which it is doing this transfer is effectively this because that is when the next transfer will occur.

Therefore, rate of change of momentum for the box 2 m v x by 2 L by v x so 2 will canceled so this is equal to m v x square by L, this is rate of change of momentum for the box as the result of the single particles repeatedly colliding with 1 surface of that box.

So, that is the rate of change of momentum of the box due to the particles that is moving with this velocity v x and rate of change of momentum is effectively force.

So, the force is defined as the rate of change of momentum. So, force exerted by the particle repeatedly colliding with that surface is this expression m v x square by L. So, this is for that specific particle. So, if we had other particles they may have different velocity and so for each of those particles we would have to identify the specific velocity and use that specific velocity. For the particle that we have considering it is this, this is the expression of which m is fixed for all the particle in the system all of them are the same kind of gas molecule, so m is same for every particle you consider of the box, L is also the same because that is the box, we do not have the different box, this is all the same.

Only difference from particle to particle is the velocity there is the bound to be some distribution of velocity some particles may have higher v x, some may have lower v x, some may have same v x and so on. So, you have variation here. Now, total force exerted by all of the particles, exerted by all of the particles on the same surface is this simply the sum of this expression for all of the particles and as I said m is the same, l is the same, only v is going to change. So, depending on the particles we will call it particle 1, particle 2, particle 3 and so on and we will assume that there are total of n particles there. Capital n particles. So, we basically have m v x 1 square by L plus m v x 2 square by L plus m v x 3 square by L plus dot dot dot all the particles, this is what we have. We have the sum of the m v x v x 1 square by L plus m v x 2 square by L plus m v x 3 square by L plus all the particles plus m v x n square by L.

So, this is the total force exerted by all the capital n particles that are present within the system. We already know that we started by saying n moles of ideal gas present inside therefore, this n if you have avogadro number this capital n is simply small n is times avogadro number that is your total number of particles present. So, we will write this as a summation here.

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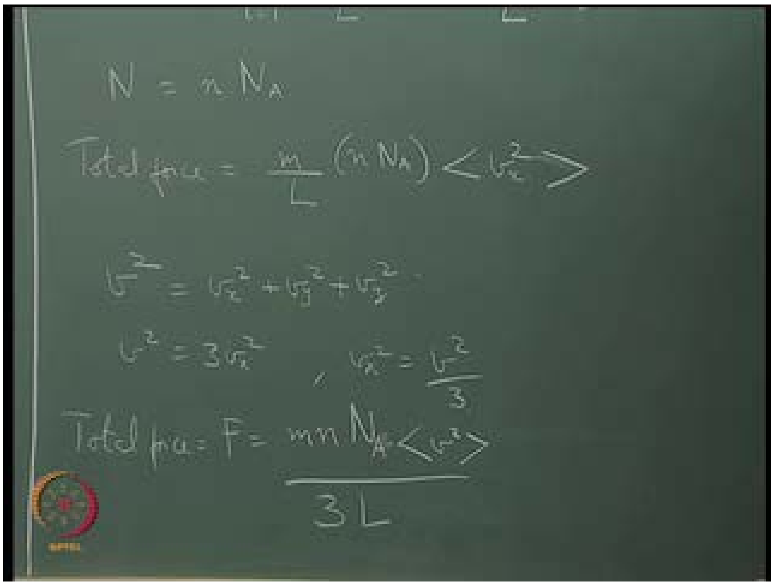

$N = n N_A$

$\text{Total force} = \frac{m}{L}(n N_A) \langle v_x^2 \rangle$

$v^2 = v_x^2 + v_y^2 + v_z^2$

$v^2 = 3 v_x^2 \quad , \quad v_x^2 = \frac{v^2}{3}$

$\text{Total force} = F = \frac{m n N_A \langle v^2 \rangle}{3L}$

This is simply m v x i square by L. Now, it is a big cumbersome. So, in fact you will we will actually even simplify this so m and L are constant as I pointed out. So, m and L are out, so m and L are constant. So, they are already out. So, we actually have sum of the squares of all of the velocity of all of the particles present in the system. So, that is what we have here. In reality it is going to be cumbersome for you to actually know. In fact not cumbersome it is just not practically feasible for you to actually know the velocity of every single particles present within the system.

Therefore, what we actually do is if there is a way in which we can figure out an average velocity, we will assume that know there is an average velocity. If you know the average velocity then the sum is simply the average velocity times the total number of particles. So, that basically all it is, that is the sum and capital n as I pointed out is simply the number of moles times avogadro number. So, N a is Avogadro number, this is the number of moles, that is a total number of particles. This capital n is total number of particles present in the system therefore, we have total force times total number of particles which is this N a times the average of the squares of those velocities and it is simply denoted by this notation here.

So, this notation simply means average of the squares of those velocities. So, v x v x 1 square plus v x 2 square plus v x 3 square like that up to v x n square divided by capital n so that is therefore, that will be the average square squares of the I mean average of the squares of the velocities. That it is what we are looking at. So, this sum here has been replaced by average times for total number. So, that is basically how it is. Sum over all the particles has been changed to the average for all the particles kinds the total number of particles.

So, this is what we get for the total force. Now, you would also recognize that we are only taken the x component into account. So, we are only discuss the x component in general if we look at the square of the modules of the velocity, it is going to be v x square plus v y square plus v z square. So, given particle could have a velocity some in arbitrary direction v so it has an x component, y component and z component. So, this 3 are there. So, in general the actual velocity that you have square of the actual velocity will be v x square plus v y square plus v z square and in general if we take all the particles into account as such there is no since we do not have any specific preferred direction, there is no specific preferred direction, particle could have equal probability that it has certain velocity in x direction or the y direction or the z direction.

So, there is no preferred direction where it is likely to have higher velocity. In general we can treat that v x square will be of the same magnitude as v y square and also the same magnitude as v z square. So, in general since we are assuming equally random direction, random velocity and so on that there is no preferred direction, preferred orientation, preferred direction for higher velocity. In general these 3 will be of essentially the same magnitude. Therefore, we could write v x square.

So, this is same as saying v square is equal to 3 v x square, assuming everything is random this is the same as saying this. Therefore, we can write for a given particle this is in general going to be the case, in general. Roughly it is going to be this is going to be the case. Therefore, now we can this is just the general velocity we are now removed the components x, y, z are all equally probable. So, that is this already accounts for all of them. So, we need not we are not looking only at the x direction. We have generalized the situation.

Therefore, now total force simply m n N a. So, we have m the mass of the molecule, n is the number of moles present in that volume L cube that we have been discussing, N a is the avogadro number n capital a here, N A is the avogadro number. This average of the square is essentially the mean of the squares. So, when we calculate root mean square velocity that is the square root of this. So, this is mean square, mean of the square that is all it is, we have not taken the root here, mean of the square is the value that we are interested in that is what we have here m, n, avogadro number, mean of the squares, 3 times the extend of that solid L of that box L.

So, this is the expression we have for total force. Now, we have an expression for total force and we still have our original picture of the box of side L therefore, cube of side L. So, from this we would like to come up with an expression for pressure, pressure is simply pressure excreted on this face for example, is simply the force excreted on this face by the area of that face.

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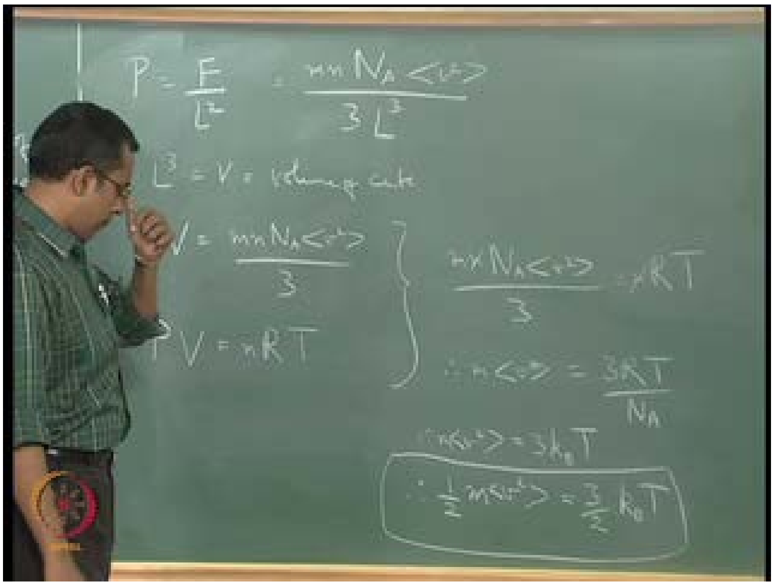

So, we have pressure equals f by L square and that is therefore, equal to m n N A, we had 3 L, now it becomes 3 L cube. This is what we have and L cube as we can, as we can imagine is simply the volume of this cube. So, If we rearrange now we have p v equals m n N A. So, we started out by looking at this cube, we have come up.

We have try to see what kind of change in momentum exists for a single particle. Therefore, try to come up therefore, identified the expression for the change in momentum for the box then converted that to a force, excreted by the single particles on that box and then force based on all the particles effect of all of the particles undergoing a similar change in momentum, generalized for the velocity in the system and then we have come up with this situation where you have p v equals m n N A v square by 3.

Now, based on our knowledge of the ideal gas laws, we can we see that you know based how the ideal gas behaves, we have p v equals n R T. R is the gas constant per mole on per mole basis, n is the number of moles and T is the temperature of this system. So, we have these 2 expression. So, clearly we can equate them since both of them are referring to the same ideal gas and same expression we have on the left hand side.

Therefore, n R T or m n N A v square by 3 equals n R T. So, we can cancel out n and therefore, we have m v square equals 3 R T by N A. So, this is the expression we have m v square this is mass of the single molecules, square of mean of the squares of the velocities 3 R T by N A. So, this is what we get and we have the definition for Boltzmann constant which is simply the gas constant per on a per molecules basis which is since this gas constant is on a per mole basis and you have N A molecules per mole. So R by N A is the Boltzmann constant which is k b. So, therefore, is 3 k b t, for us more than m v square the quantity or the expression that is of use for us is half m v square which is the kinetic energy of the system. Therefore, we would like an expression for the half m v square which is half of this. So therefore, so we get this expression half m v square which is the translational kinetic energy of the molecules.

Translational kinetic energy of the molecules is 3 by 2 k b t. So, this is a very useful expression. So, we will make note of this. So, this is the translational kinetic energy of a single molecules on average. On average for single molecules this is the translational kinetic energy, this relates to this Boltzmann constant which is this gas constant per unit per molecule on per molecule basis and this is the absolute temperature that we have. This is what we get so this is 1 expression that we will find useful for our later purposes, we will extend this little bit more. So, we have an expression for the translational kinetic energy of a single particle.

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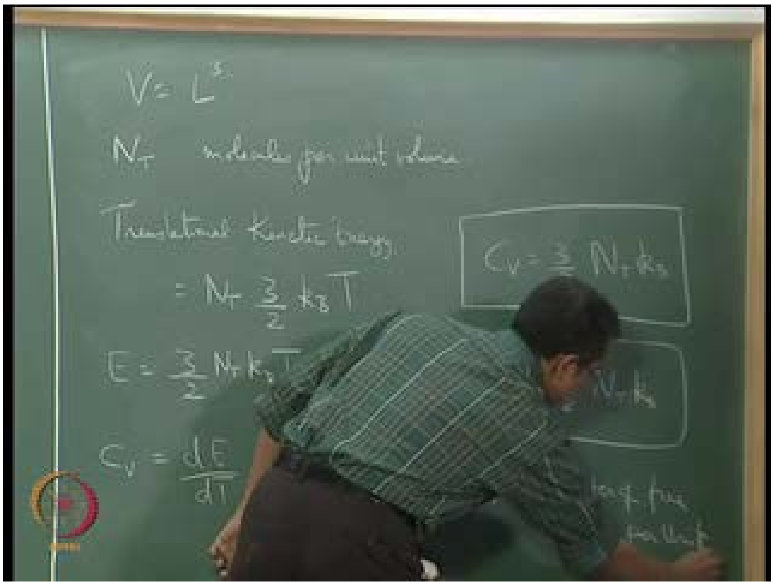

So, supposing you have on a, we started off with a volume V equals L cube. Given that the we now have an expression for the translational kinetic energy of a single molecule. Supposing we have Nt. Supposing you have Nt molecules per N subscript T molecules per unit volume. In case you do this then the translational kinetic energy associated with of the kinetic energy, total kinetic energy from all these molecules running around is simply Nt times 3 by 2 k b t.

Therefore, E equals 3 by 2 Nt k b t. So, this is the energy of the kinetic energy therefore, the energy held by the those molecules upper unit volume because this is this is the number of molecules per unit volume if you took some other number then you could be on the volume on that basis. So, volume corresponding to this. So, this is energy per unit volume effectively. Now, if you want the specific heat of the system on a per unit volume basis we now have the energy on a per unit volume basis as a function of temperature. Therefore, c v is the differential of this with respect to t and this is simply 3 by 2 Nt k b. So, c v is simply 3 by 2 Nt k b.

So, this is the specific heat per unit volume associated with the system of all these molecules running around at that temperature t inside that box. So, on a per unit volume basis we are able to come up with this and so this another useful expression for us we just put it down here again c v equals 3 by 2. So, we have 2 important expressions, we have 1 for the translational kinetic energy half m v square equals 3 by 2 k b t and 1 for the specific heat at constant volume which is 3 by 2 Nt k b.

So, this is what it is and as I mentioned this Nt is the number of molecules per unit volume. Now, all of this discussion we have done keeping in our the system we have spoken about the ideal gas system and therefore, the molecules present within that system are all ideal gas molecules. So, they are fairly massive so you could have organ or something like that which is mimicking an ideal gas present within that box. We are and these are results that we have derived on the basis of the assumption such a gas is occupying this volume. What we are headed towards is that we are going to take this results and apply it on a gas containing effectively gas of electrons.

Therefore, what will happen our system the way our equations will change is that specifically this m which we would normally associate as the mass of that molecules and therefore, would be very large mass in general, this m will now become the mass of the electron. This equation though we have derived for a ideal gas we are extrapolating it is for the gas of electron that we have in the metal, we are assuming the those are all ideal they are behaving close to that of ideal gas molecule kind of behavior and therefore, the equation we will use will be the same except that we will this m that we have here, we will know change from the mass of the molecule to the mass of the electron.

These velocity will be the velocity of those electron inside that solid object, those electrons as we said are now free to run around across the extend of the solid. So, whatever we associate as their velocity in manner that we can identify a velocity associated with those electron, those velocities we will incorporate here. This Boltzmann constant those are all universal constants, nothing is going to change. So, this part of the equation is going to remains the same k b this is the temperature at which the system is. So, this is going to look exactly the same. This expression here is the specific heat at unit for unit volume as I said so if you take a solid when you look at a specific heat of a solid as opposed to that of a gas. In a gas we are directly talking of the gas molecules.

So, when you raise the temperature of a gas, those gas molecules pick up that energy they run around all around the place. The velocity is go up and so on, that is how the temperature of the solid that is how it is able to exhibit higher temperature that gas that container containing the gas. Now, in a solid we actually have 2 things, we have especially in a metallic system we have those ionic course which are present.

So, that is definitely still present in the solid. In fact when you pick up the solid that is what to be actually feel, that is that solid piece that you feel. All those ionic course that are present. Then you also have this free electron gas that is running all around the system. Now, when you raise the temperature of that solid the energy is being absorbed by those electron which are running across the extend of the solid as well as those ionic course. So, together all of them are actually absorbing the energy. So, it is not that it absorbed only by the electron or absorbed only by the ionic course.

In a metallic system we have a very distinct I mean capability of distinctly identifying or at least distinctly associating our analysis with a free electron gas present there. So, we will assume for the moment there is the free electron gas and with the free electron gas we have the ionic course, the temperature of the entire system is going up so the ionic course also absorb energy, the electrons also absorb energy. So, when you talk of specific heat per unit volume you have to accept the fact that in that unit volume there is there are electrons as well as ionic course ok.

So, where as the analysis that we have done so for has talked only about the ideal gas and that behavior that ideal gas behavior we are extending only to the electrons, to those free electrons. We are not extending this behavior we are not making the comparison of these behavior with the behavior of ionic course. In our picture the ionic course are held in very rigid position or relatively rigid positions in the form a crystal structure or a lattices and so on. So, they are not free to run across the extend of the solid largely they are stuck where they are stuck but they do vibrate about the mean positions.

So, we will look that greater detail we have to keep in mind that those ionic course are not stationary, they vibrate about the mean positions. So, one of the way in which the solid absorbs energy as we raise the temperature of the solid is that the amplitude with which those ionic course vibrate actually goes up. So, when you when you look at specific heat what you looking at is the amount energy you have to provide to that solid for a unit increase in temperature that is basically what we are looking at some unit increase in temperature, what is the total amount of energy you have to provide that system. So, clearly if there is more than 1 mechanism which can absorb the energy you have to provide energy to allow the both those mechanisms to again the equivalent amount of temperature.

Only then the temperature of the solid actually goes up. So, when you talk of specific heat of solid per unit volume it is the specific heat of all of its constituent per unit volume. So, it is the specific heat of electron per unit volume plus the specific heat of the ionic course per unit volume. Now, in the expression we have derived we have focused only on the part of the solid that behaves like an ideal gas which is the electrons. So, this equation here is the c v equals 3 by 2 Nt k b will be something that we can extend only to those that to the free electron cloud, to the free electron cloud.

So, we will simply in our notation we will simply called as c v with a superscript e indicating the fact that this is specific heat at constant volume for the electrons. So, the specific heat at constant volume for the electrons or the electronic contribution to the specific heat at constant volume. If you wish to call it that.

This is the electronic contribution to the specific heat at constant volume, the ionic course also have a contribution to the specific heat at constant volume which we are neglecting. So, this is now the same expression 3 by 2 Nt k b and in this these are identical expression except I have added the superscript e. Here, so if you look at this original expression we derived for an ideal gas.

We are extending that to the electronic course present in the system. So, this is specific heat at constant volume, electronic contribution to the specific heat at constant volume, the other thing is that Nt is now the number of electrons, number of free electrons per unit volume. So, this Nt is now number of free electron per unit volume. So, Nt is now the number of free electrons per unit volume. This is again something you should pay attention to because the solid actually has a lot of electrons so when you have essentially given the atomic number of that solid, whatever is the atomic number that many electrons are present per atom in that solid.

So, that is the huge number of electrons. So, that is a very large number electrons of which only a small number, very small number which is equivalent which is essentially equivalent to the valancy of that atom, the most common valancy that it adopts. So, in the case of silver for example it is plus 1, only 1 electron per silver atom is contributed to the free electron gas, every atom in the in the silver metallic system so you have a block of silver in that every atom is contributing only one electron to that free electron gas. So, when you look at the number of free electron per unit volume it is only this 1 per atom that is getting counted even though that atom actually has many other electrons which are all bound to the ionic core which stay with that ionic core and therefore, it is a large number of electrons per unit volume.

For this calculation we are only looking at number of free electrons per unit volume. So, these are 2 distinctions that we should be very conscious of as we continue this analogy, as we continue this discussion, as we extend it from a gas to a solid the first thing we have to be cautious about is that we are talking of electrons and not the ionic course and importantly that the ionic course also make a very major contribution to the specific heat. In fact if you at higher temperature the contribution from the ionic course to the specific heat is way greater than what the electron contribute to the specific heat.

The electronic contribution to the specific heat is visible only at only very low temperatures. So, largely it gets warmed by the ionic contribution at the higher temperatures. So, that is the number 1 point you keep in mind. Number 2 point is the electronic contribution to the specific heat is also something that we are associating only with the free electron in the system, not all the electrons in the system. So, they are 2 major issues that we have to keep in mind.

Therefore, this equation when you extended to the electrons in the solid we keep those 2 things in mind, this is Nt is the total number of free electrons per unit volume and this is of course, the Boltzmann constant. So, what we have done today is we have looked at the kinetic theory of gases and derived or refreshed in our mind some of the major results of this kinetic theory of gases. Specifically, we have come up with an expression for the translational kinetic energy associated per molecules and we have also come up with an expression for the specific heat at constant volume.

We have done this for a ideal gas and we have seen with what kind of precautions we can extend this to a solid and therefore, identified how those equations are (( )) different when you actually talk in terms of what is occurring inside the solid and the fact that these are going to now be associated with the electrons in the solid. So, in our in at general scheme of things when you look at what we did last class and what we have done today, we have now said that we will extend this ideal gas theory into a solid and predict its electronic conductivity, predict its thermal conductivity. So, to do that we have to actually, we will do those two in the next couple of classes but, as we do those derivations we will borrow the, incorporate the ideal gas theory into those derivations and specifically we will incorporate these 2 results, these 2 results that we have just seen here today.

Both of these results will be incorporated into the derivation that we would make for the electronic conductivity as well as the ionic conductivity I am sorry electronic conductivity as well as the thermal conductivity. And as I mentioned we recognized the fact that the general metallic system which happen to be good conductors of electricity also happen to be good conductors of heat. So, it turns out that of for all metallic system there is a relationship, there is a ratio for the thermal conductivity to the electronic conductivity.

So, as I mentioned in one of our earliest classes whole purpose of creating a model is to understand the system and the extent to which we have succeeded in the process depends on how well we are able to make a every prediction or rather we make a prediction.

How well does it match to what is actually experimentally observed. So, when we make prediction for the electronic conductivity and so we when come up with the expression for the electronic conductivity, we will look at the literature and I will show you some value for a electronic conductivity for a common metallic system and we will see how well the number compares. This theory we are coming up with will depend on something very fundamental to the system.

So, we are talking of mass of electron, velocity of electron and so on which are all fundamental to the system. So, from their actually come up with the value for electronic conductivity. Similarly, we would also look at something very fundamental to the system and come up with the value for thermal conductivity. Again, we will look at the literature, we will see look at value for thermal conductivity which are commonly seen for various metallic system and we will see how well our theory has predicted that thermal conductivity. So, these are 2 now independent predictions we have made.

Even as an expression we will able to take a ratio of the thermal conductivity to the electronic conductivity based on the expressions that we will derive and therefore, we will see what ratio we will come up with and we will discuss these in the next class. So, when we come up with ratio again there will be a value associated with that ratio. We will see how well that value matches with what is in the literature.

So, these are some things that we will do. In all these cases one of the issue that we have to keep in mind is in all these derivations we often make some approximations. Therefore, in general our prediction needs to be looked at from the perspective of an order of magnitude. So, if we are right order of magnitude there is a good chance, there is a reason to believe that our general approach and the manner in which we have made this analysis is reasonable. So, we will not so even when I look at the electronic conductivity value and compare it with what is there in the literature, our intend is not look at the exact specific value of what it is going to be.

So, it is for satisfactory plus if the metallic system has certain order of magnitude of conductivity and say 10 power 7 siemens per meter and the prediction comes out the roughly in that range. So, this is the this order of magnitude issue is another thing we wish to look at and so when we do this we will also see that you know some we are intend is to see how well this model has predicted all the experimental data that we see. So, not only will we see, we will try and identify all the places where it actually does the good job in making the prediction.

We will also try and see what are those specific instances where this kind of an approach of imposing ideal gas rules on the electrons inside the solid, in which in which condition does this approach actually fail. So, what kind of experiments are giving you results where this kind of an approach finding itself inadequate to give you correct prediction. So, that also gives us clues to where exactly this theory is weak and on that basis we will now able to modify and then try and see if there is much more robust theory that we can think of that we can incorporate.

This is the way in which gradually go from theory of this sort to more sophisticated theory and as I mentioned also in one of our earlier classes that to the extent that the theory makes a prediction that is acceptable to as in a range in a range of conditions, then within that range of condition we can continue to use the theory. So for example, as we go forward I will point out that there are reasons, we will find that there are places where the theory that we are using is going to be a successful and there are places where it is going to fail.

Just the fact that it has failed in some cases does not mean the whole theory entirely useless to us. To the extent that we used it within its limitations this theory is still acceptable to us. So, that is the framework within which we look at each of this theories. So, in our next class we will develop the electronic conductivity and then the class after that the thermal conductivity and then we look at limitations and successes of this theory and we will always keep this in mind that the failure does not mean it is utterly useless because even the subsequent theories that we come up with will each independently have an additional level of success that they will attain but still we will able to look at experimental data and find places where those theories are also still not adequate enough.

So, we will have to go through several levels of sophistication before we will find the theory which is actually quite comprehension which is actually do a pretty good job of explaining several aspects associated with conductivity at room temperature or a range of temperature for a wide range of material. So, only when will reach that far do we get the confidence that our theory is sophisticated enough, that it is accounting for enough number of details, it is realistic, it is realistic enough that it is actually working. So, we will reach that state and that stage we will have satisfactory theory for the material system. We are now in our process of getting that. So, with this we will halt this class and we will take up our discussion on electronic conductivity and how these equations get can be incorporated into it in our next class. Thank you.