Mechanics, Heat, Oscillations and Waves
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Lecture – 01
The Nature of Physical Laws

I would like to begin this course on basic Physics with a few very general remarks on various aspects of this course about Physics itself in general, what the nature of the subject is like, what it is we are going to focus on and so on. And just to remain myself and to make sure I do not forget anything, I have written down here a set of topics if you like or points. And these are the points we will discuss in today's lecture and continue with these points as we go along.

The first thing is about the edifice of physics. What I mean by this is that, over the last 400 years or so this termed out that we have build up with the help of experiment, observation, analysis or instruments or various proves into nature, the mathematics and so on. We built up a sort of picture or a building if you like which we call Physics. The aim or objective of this picture is nothing less than the understanding of the universe itself, the physical universe; and the laws of nature as they revealed themselves in the workings of the physical universe.

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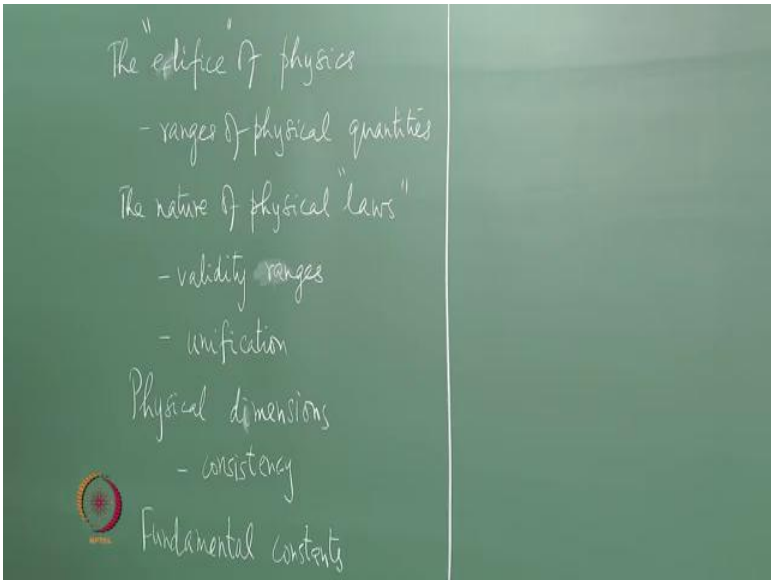

So, this is what I mean by the edifice of Physics, but the very first thing that we have to understand immediately is that this building is a huge building. We have discovered that it really has many, many, many more flows than we have daily, used to in our daily experience, and that is make precise by understanding what is meant by the ranges of physical quantities. So, let me take a few minutes to tell you how vast this scope of nature is and how small our own facility with the small portion of this range is.

And in order to make this discussion accessible to you, let us speak in terms of quantities with which we are familiar namely mass, length and time. I believe that we understand at a earlier stage in the study of science or physics that mass, length and time are primarily our basic quantities in some sense. So, let us look at these quantities.

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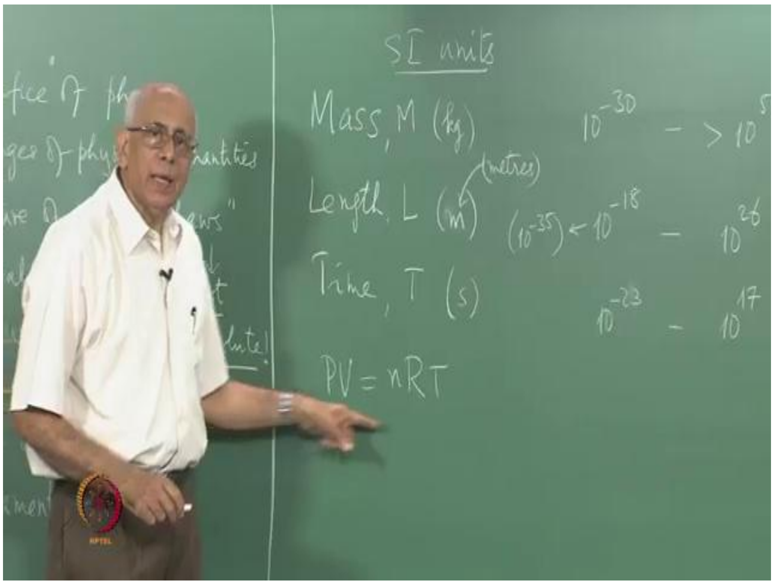

And here is mass, here is length and here is time and let us use the symbols M, L and T for these quantities. And now, I ask the question was this smallest mass that we can think of or we have understood or come to terms with and what is the largest mass that we encountered so far. And we immediately realize that to write specific numbers down I need a choice of units and the first think you be have to agree upon is that in modern science today, it is mean accepted that we use what are called SI units was Standard International units.

So, all my numbers are going to be in SI units, in these units mass is measured in kilograms denoted with kg, the symbol. The length is measured in meters for which this small m symbol is used and time is measured in seconds for which the symbol s is used, you are familiar with this. So, I am going to stick to these units in kilograms for lengths, this is meters here, so not mass. So, it is kilograms, meters and seconds and these units this smallest mass that we encountered is perhaps the mass of the electron and this is of the order of 10 to the minus 30 kilograms.

So, in kilograms it around 10 to the minus 30 upwards through the masses of protons, neutrons, nuclei, atoms, molecules, people, stars, galaxies and so on. Write up to the other end which is the estimated mass of the universe itself. Now, this of course, we do not know how big the universe is, so we do not know precisely what it is mass is. But, we have a reasonable estimate of it.

We can estimate what the number of stars in this sky is, what is the number of galaxies, what is the number of stars in each galaxy and the average and from add in all that together, and then adding the mass estimated mass of the hydrogen clouds in between galaxies, in between stars, and then multiplying the whole thing by another fact of nearly 100. Because, we believe there exists and no that matter and that energy finally, we have an estimate which is at least of the order of 10 to the 55 kilograms.

So, that is a huge 85 order of magnitude range in masses that a physical science as exposed. Then in length, the smallest length you can encountered is proved that the highest energy accelerators and this length is of the order of 10 to the minus 18 or so given take an order of magnitude about 10 to the minus 18 meters. And actually, it will turn out that we can think of and I am going to come to this very shortly, you can think of a much smaller time length scale and that is of the order of 10 to the minus 35 meters and I will come back to it, I have put it in parenthesis here for a specific reason.

Because, it is not the length of the specific object, but rather a fundamental length itself and we will see what I mean by that. At the other end, the longest length we can think of is the radius of the known universe and this is of the order of 10 to the 26 meters. So, once again you see that there are 44 orders of magnitude here. In time, the smallest times we can probe directly have to do with what are called nuclear forces or strong interactions and these are characteristic times case of the order of 10 to the minus 23 seconds.

So, I emphasize again we have instruments, we have probes by which we can actually compute or actually measure indirectly lengths, time scales of the order of 10 to the minus 23 seconds. At the upper end, the longest times scales you can think of is of course, the age of the universe itself and today it is believe the universe is 13.8 billion years old. So, in orders of magnitude inside is of the order of 10 to the 17 seconds.

So, once again you have 40 orders of magnitude here in time, more than 40 orders of magnitude in length and nearly 80 orders of magnitude or whatever in masses huge canvas. These are orders of magnitude these are not just factors but orders of magnitude. So, nature's canvas is a very vast one and what we have used to in our daily life is a much, much smaller range here. So, it is not surprising that we have to sometimes modify the laws of physics or use better laws of physics, when you want to understand what is happening in the very small or in the very large.

As suppose to what is happening in daily life for instance, if I want to know what the length scales and mass scales and time scales are for the motion of this piece of chalk, I would use Newton mechanics. On the other hand, if I want to know what do with electrons, individual electrons or individual galaxies for that matter, I would have to use most sophisticated kinds of laws of motion. So, the ranges of physical quantity is vast, of course, once I say masses, lengths and time scales have this large range, it is stands to the reasons it is obvious that derived quantity such as velocity or acceleration or force or energy will also have similarly very large ranges of physical variation.

So, having said that about the ranges and we come back to this thing over and over again, I am going to say something about the nature of physical laws ((Refer Time: 08:19)). Now, this is a very important conceptual, lot of understanding, what is meant by physics itself also it might appear trivial to start with the statement that I would like to make write away is that the laws of physics have a very peculiar nature. They are not like the legal laws that you have in a law for instance.

Nor or they like the laws which you dictate the laws of mathematics, what I mean by that is a physical laws here and not absolute laws. So, that is a very important point, not absolute. On the other hand, the laws of mathematics are absolute in the sense that once you define the axioms of mathematics, then the theorems that you prove in mathematics within those axioms are absolute truths. Given those axioms, these truths are internal absolutely.

On the other hand, any physical law that you can think of is a law which is got qualifying classes, which is valid only in some regions or regions of physical parameters, only for certain ranges of variation of physical quantities at this laws valid. To give you an example, if I go to ask the simplest of laws that you might think of Newton's laws of motion, he says the force is the mass times acceleration. This has many qualifying classes, it is not chosen absolute law for all kinds of objects or for all kinds of acceleration or forces, it is only true in the region what is called neutron in mechanics.

Namely the objects should not be traveling fast as compared to the speed of light, they should not have speeds which are fractions, good fractions of the speed of light in vacuum. It should be moving much slower than that, they should not be extremely small, we cannot apply Newton's law to a single electron, it is upon the very special circumstances and approximations.

Certainly the laws of Newton, the original Newton in mechanical laws are no longer valid when you come to an object as small as an electron or an object which moves as faster and the electron can under the suitable circumstances. So, in that sense physical laws are not absolute, they apply in certain regions or ranges of physical parameters, not the entire range in general that appears in nature. But, a much smaller range and this is one of the very important task of physics is to find out what are the ranges of applicability of various physical laws.

For instance, if you say Boyle’s law in the theory of ideal gasses tells you that the product of the presser times of volume of an ideal gas is a constant for a given mass of gas, at a constant temperature. On the other hand, this laws is not true for all gasses which is certainly not true, if the interaction between the molecules in a gas becomes significant, then the law breaks down and we have to replace it with the modified form of Boyle’s law and more sophisticated form of law.

So, in this sense physical laws are not absolute, this is very important point, it looks very trivial, but it is crucial to bear that in mind. Because, then you begin to understand what the nature of this law is and we begin to understand why it is that these laws can be have to be constantly refined in some sense. So, we talked about the range of validity of this laws ((Refer Time: 12:02)), the next point I want to make is that there is a quest in physics, there is an effort being make and that has been there have true right from beginning of the subject itself to unify these laws and to reduce the number of independent laws.

Again I think an example will immediately tell you, what I am deriving at. If you took the theory of ideal gasses which you learnt in the context of thermo dynamics perhaps, there is something called Boyle's law, there is something called Charles law, there is is something called Henry's law and so on. There is a variety of laws in this case, but the fact is these are all based on a single law and that single law is this so called equation of state often ideal gas.

The statement that the pressure times the volume of an ideal gas is equal to the number of moles times the gas constant times the absolute temperature. This ideal gas law has within, it contains within it all these independent laws that I talked about such as Charles law or Boyle's law and so on. For instance, if you kept that number of moles at the gas constant and the temperature constant themselves has a constant, P V is a constant that is Boyle's law.

So, there is the quest to unify and to reduce the number of independent laws and that is the primary driving force in this certain physics to try to unify these laws. You would have heared about this quest for unifying the fundamental forces of nature that is part of this program. In fact, it is more sophisticated part of this program, is to try and see if all the interactions in the universe that we know of can all we brought into one unify picture, not yet succeeded, but this is the quest.

So, having talked about the nature of physical laws ((Refer Time: 13:59)), we will say more about this as we come along. Let us go onto the very crucial topic which I am going to spend a lot of time on namely the physical dimensions. With every physical quantity, we attach a physical dimension and this dimension is based on the primary dimensions, physical quantities, dimensionality namely mass, length and time.

In other words, every physical quantity has some physical dimensions. There are physical quantities which are dimensionless, to give you an example which we are going to use very shortly.

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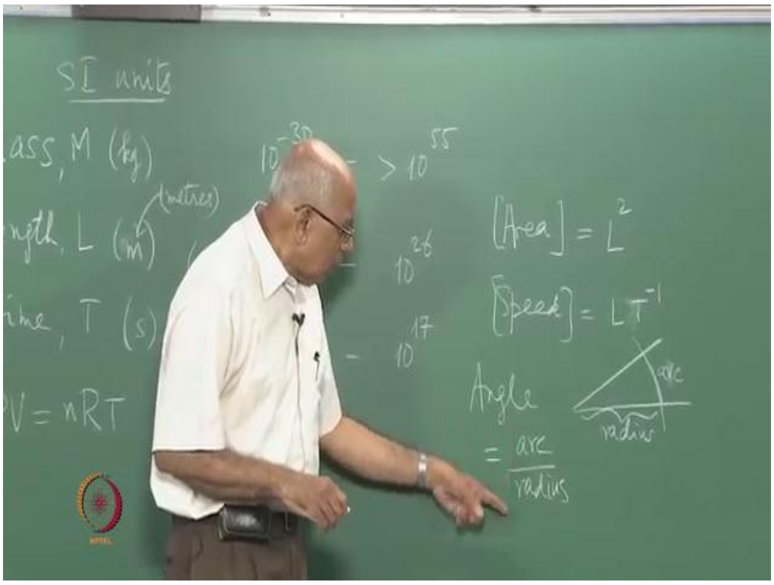

A quantity like area, the physical dimensions of it and I am going to put a square bracket here to denote the physical dimensions of a particular quantity. This here is the square of a length and I will write this as L squared and of course, we measured areas in square meters in standard international units. So, in that sense there are quantities which have physical dimensions, which are powers of combinations of M, L and T in general.

Velocity, for example have speed equal to L T inverse which stands for L divided by T. So, it is measured in meters per second as you known and so on. So, physical quantities have dimensions which if they have dimensional which are combinations of M, L and T certain powers of M L and T including negative powers and possibly even fractional powers be seen for that means. On the other hand, there are lots of physical quantities measurable quantities which are dimensionless.

For instance, pure numbers like 2 or 3 or 4 and so on without any units attached to them, they are dimensionless quantities, here is another dimensionless quantity angle. So, if I want to know the angle between two state lines, what I do is to draw an arc of a circle, and then take this arc and this is the radius and this angle is arc divided by radius. Since, this is dimensions of length and this is dimensions of length, these two cancel each other out and angle is dimensionless.

Whether you measure it in degrees or in radians is a separate matter of detail, in physics we always, in science we generally measure angles in radians always. So, I will assume that is always the case, unless I state explicitly to the quantity. So, here is a physical quantity which is dimensionless, if you like it is M to the 0, L to the 0 and T to the 0. So, it is completely dimensionless. What is crucial is that these physical dimensions help you to check the consistency of equations.

So, what I mean by consistency is that, dimensional consistency is that the left hand side of an equation must have the same physical dimensions as the right hand side always and we measure in the same units.

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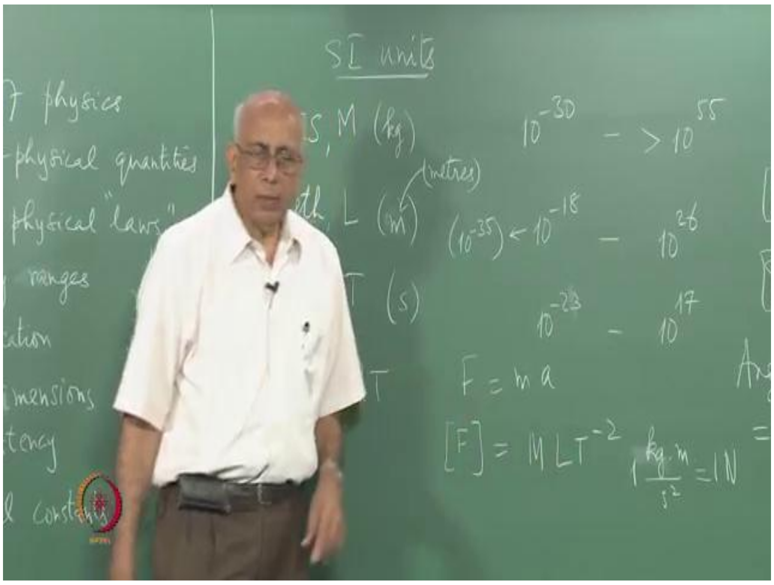

For instance, if you took a log like the force is equal to the mass times acceleration, when for this law to be consistent, the physical dimensions of force must be equal to the physical dimensions of a mass times an acceleration. So, since this is M and this is L T to the minus 2 that is the physical dimension of a force and what is important for you to remember is that, once you say a force has physical dimension of mass time acceleration namely M L T to the minus 2, then independent of what force we are talking about this statement remains true.

So, notice that I do not say whether this is a mechanical force or gravitational force or an electric force or a magnetic force, chemical force I do not care. Every force has necessarily got to have the dimensions of mass, times, length times T to the minus 2. Now, you might find it convenient to call the units in which you measure it by a short hand by some name of the other. For instance, normally I would say given this equation I would say force is measured in kilograms times meters divided by second square, but there is a convenient name for it.

So, instead of writing carrying around M kilogram meter per second square, I call this one of this is 1 Newton. So, I introduce a new unit called the Newton, the unit of force. It simply stands for 1 Newton is just 1 kilogram meter per seconds divided by seconds square that is it. So, that is a matter of convenient, so I may or may not want to do this in our cases, but whatever it is it this important point is that the force has a unique decomposition in terms of this primary dimensional quantities mass, length and time.

Similarly, every physical quantity can be written in terms of a few primary quantities conventionally taken to be mass, length and time. Now, you could ask when ((Refer Time: 19:34)) I should also say is that it, is that all or you need more, is three enough in all cases. Well, it turns out that this is an interesting question that the convenient way of handling this problem is to add quantities to this primary quantities, is these three has the needed arises.

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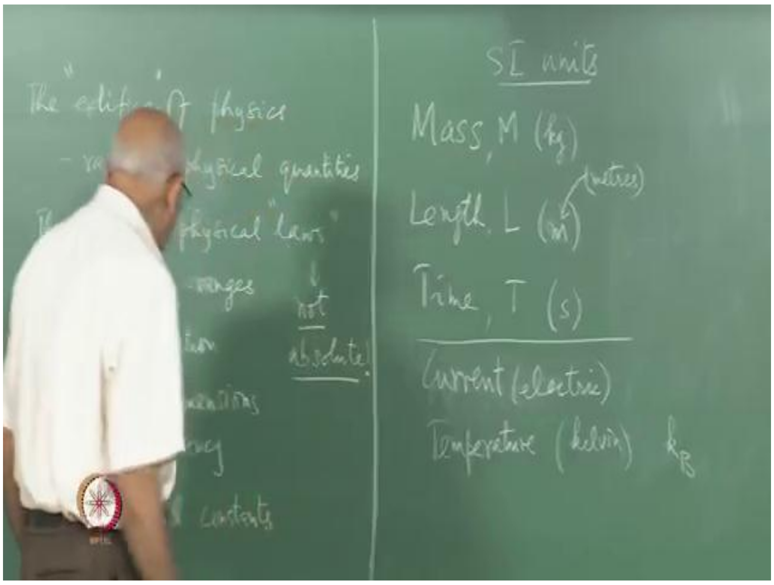

For instance, this was as far as mechanics is concerned with the moment you talk about electricity and the transport of charge and electric currents and so on, it terms out it convenient to introduce a new physical quantity, namely the electric current. So, we need to associate some kind of physical dimension and what is conventionally done is to say, I am going to define an electric current, a unit of electric current called the ampere and say that goes along with kilogram, meter, second and then ampere here.

Now, I will come to why you need this and what the reason for this extra addition is. Similarly, when you want to look at quantities which involve, when you want to look at problems which involve the exchange of energy, thermal energy of heat from an object to another, we also need another concept and that is the concept of temperature and that is measured in Kelvin's. The absolute temperature measured in degrees Kelvin and this introduces for you one more quantity.

Similarly, there are couple more there are introduced, but this is not very fundamental think in the following sense. The reason you need one more unit here is, because current is carried by charges elementary charges, specifically the charge of an electron that is a fundamental unit, this charge of an electron, the fundamental quantity here needs an extra unit. Because, does not come under M, L and T it is not a mechanical object at all.

On the other hand, it is possible to choose a system of units, such that I stick to these three M, L and T, but the prize you pay for it, is that when I talk about electric fields or quantities involve associated with electric or magnetic fields and so on. Then, the powers of M, L and T that I have for those physical quantities would turn out to be fractional powers. So, if you are prepared to accept fractional powers, you can simplify the number of physical quantities, primary quantities.

But, otherwise you have it is convenient to introduced one more, similarly temperature the temperature is an interesting history and will say more about this turns out the temperature need not have an introduce at all, it just another statement another way of saying energy which is a basic physical quantity. But, temperature got introduce before we understood clearly that heat is just a form of random molecular inertia, the random motion of molecules a kinetic energy associated with the random and motion of molecules is what ((Refer Time: 23:09)) itself as heat.

Before we understood this without it was necessary to introduce and extra quantity call the temperature. But, you say that is not an independent quantity at all, but having introduced it we need something to convert temperature into energy or go to from energy into temperature and that involves of fundamental constant called Boltzmann constant. I will say more about this in a minute when I talk about fundamental constants.

And because of the existence of this Boltzmann constant, we still retain temperature has an independent quantity and so just saying energy or average energy. And we introduce one more of this fundamental quantities, namely the degree Kelvin and we want to write down the physical dimensions of quantities. But, these are matters of detail which we will talk about later, coming here back to this the moment we have M, L and T and these are the primary quantities in which we are going to express all are physical quantities.

We need to also find out whether there are any quantities which appear over and over again in physics in which are constants of nature, if you like and I should say of you words now this stage about concerns of nature and we will come back to this over again. Because, this is non-trivial concept here and we need to understand very clearly what I mean by constant of nature of fundamental constants. So, here is a list of fundamental constants which are already familiar with, but you will immediately see that the fall into several categories.

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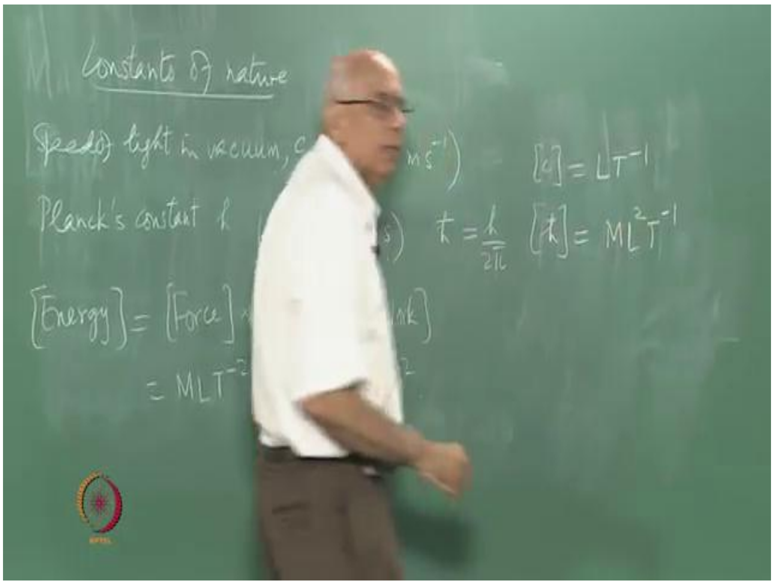

So, call fundamental constants or constant of nature, if I have to ask you to list all the possible constant of nature that you come across, the first choice a first gas would of course, be as something like the speed of light in vacuum conventionally denoted by c and that is a primary fundamental constant of nature. So, it terms out what is the value of c that is well known to you, it is worth remembering the value of some of these fundamental constant. Because, a very, very basic primary quantities, this is of the order of 3 times 10 to the power of 8 meters seconds in this.

Now of course, a speed of light the several ways of writing this number here, this has to do with so called standard international units I talked about. But, for our purposes at the moment will take it to the 3 times 10 to the power 8 meters per second. The other fundamental constant absolutely fundamental constant terms out to be Planck's constant, sometimes called Planck's quantum mechanical constant or quantum constant, this constant here is denoted by the symbol h which has a value of the order of a 6.6 times 10 to the power of approximate into 10 to the minus 34 joule second.

Now, joule is a unit of energy and you have to tell me what this physical dimensions of energy r. So, let us write that down just to see that we are clear about we mean energy has a physical dimensions of force multiplied by distance. Because, the work done by a force in transporting in an object this distance is found by the product of these two quantities. So, this energy has the physical dimensions of force times length.

And of course, it is the same physical dimensions of courses as where for instance, work is a form of energy and this is equal to M L T minus 2 times L which is M L square T to the minus 2. Again I emphasize, all possible energy has the physical dimensions of M L square T with the minus 2 and in standard international units when I measure mass in kilograms L and meters and T seconds 1 M L square T to minus 2, the unit is the joule it is call the joule and denoted by the symbol j and that is what appear here.

Now, in terms of force the joule is equal to Newton multiplied by meter. So, you can write it in several ways ((Refer Time: 28:16)) I could have return this j as n times M this stands for Newton's multiplied by meter, but this is the standard symbol for it 0. So, this is called Planck's constant it terms out actually the more useful then this is something called h cross and that h divided by 2 pi. So, you have to divide this by 2 pi and it is 1.3 something time instant to the minus 34 and that is called h cross and that is the quantity that appears most of in physical applications.

But, this is just a matter of definition just dividing by absolute number here 2 pi, remember the 2 pi does not have dimensions would have. So, what are the physical dimensions of Planck constant, it is joule multiplied by seconds in terms of units, therefore the physical dimensions at given by energy which is joule multiplied by time which is seconds.

So, let us write down right away that the physical dimensions of h cross or M L square T to the minus 1 is this has to be multiplied by the time that give the quantity ((Refer Time: 29:36)). What are the physical dimensions of c this of course, is immediately obvious this is c equal to L T inverse, it is a speed in, therefore it is distance divided by time. The ((Refer Time: 29:54)) fundamental constant that we recognize is something that is familiar to you, this is Newton's gravitational constant.

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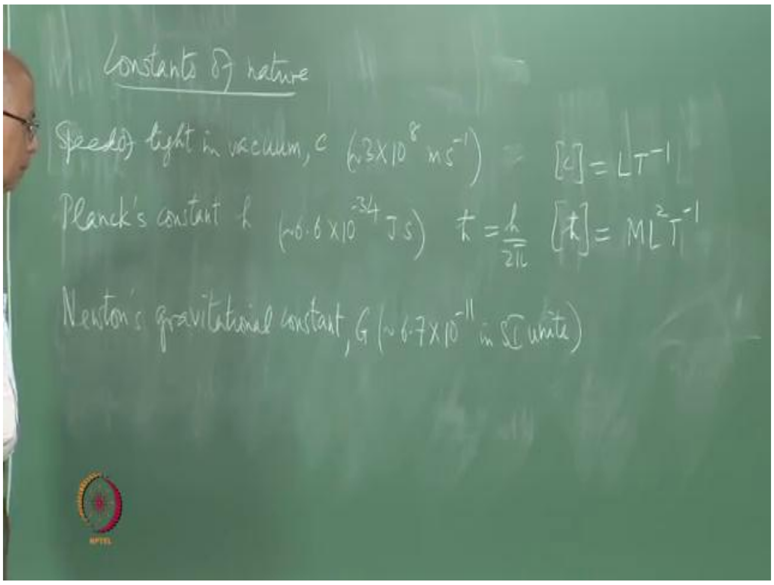

So. capital G it is value happens to be of the order of 6.7 times 10 to the minus 11 in standard international units and this units have to be discover by as yet we have to write this down. So, let me for the moment write in SI units and we will write this out in a second, to find what the physical dimensions of the G are we need an equation in which appears and of course, that appears in Newton's inverse square law of gravitation.

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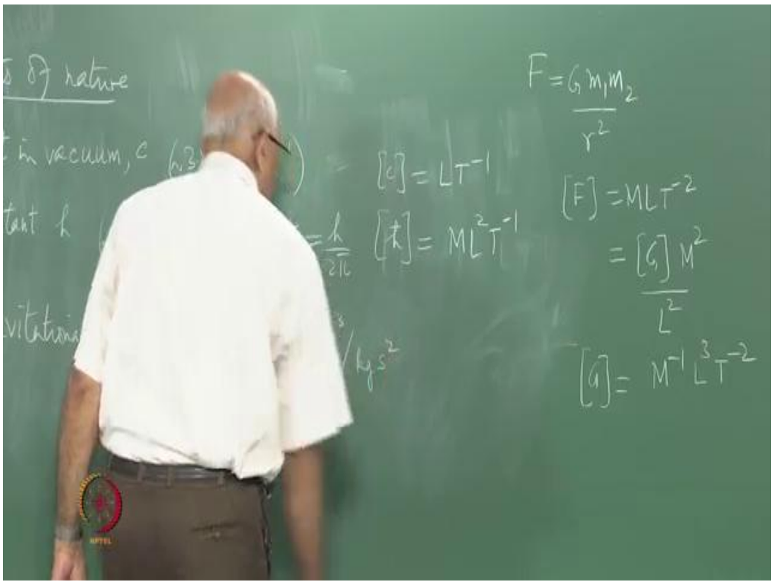

So, the inverse square law gravitation tells us that the gravitational force between two objects is the product of the masses multiplied by G divided by the squared of the distance between them. So, this tells as immediately by dimensional consistency that the physical dimensional force which is M L T to the minus 2 must be equal to the physical dimensions of G multiplied by the physical dimensions of M 1 and M 2 which is M square divided by L squared because r is physical dimensions of L.

So, that tells us that a physical dimensions of G must be equal to M inverse, because I take this right hand side L cube T to the minus 2. So, if you like I can write this in meter cubed per kilogram second squared this term form that the numerical value in these units is 6.7 times 10 to the minus 11. Now, these are three fundamental constants here and next time we will talk about what why these are no fundamental then other constant and other, other constants that we can think of and if so where you fit in to this picture, what way do the differ from these three fundamental constants. So, what you have to ((Refer Time: 32:38)) in mind this at these three at the moments seem to have a very special roll and the next task is to explain why.