Classical Physics
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Lecture No. # 1

So, we start with most the basic concepts of all in physics - mass, length and time. And I would like to start by asking you to imagine that we have no tools, no mathematics, no physics, no equations, but just our senses, nothing more than that, and we ask - what kind of masses, lengths, and times can be perceived with just our senses and nothing more than that; so no instruments of any kind, and no analysis of any kind; just our bare senses.

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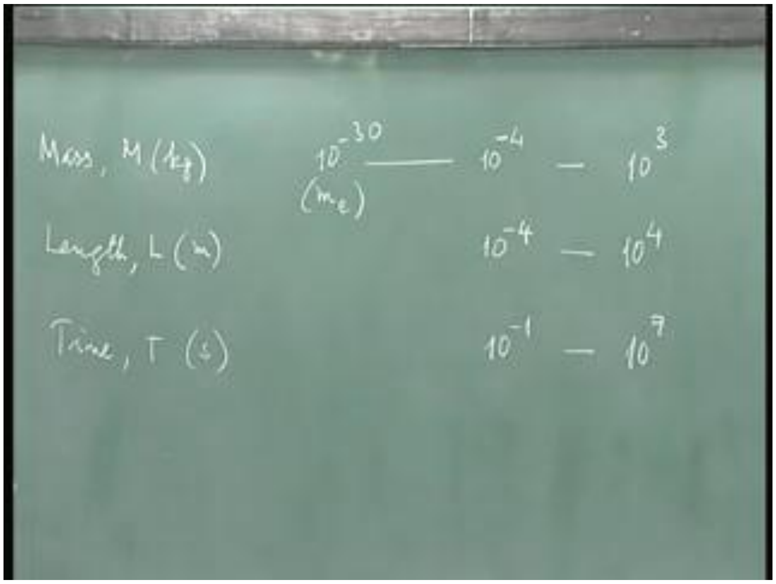

Mass, M (kg) 10^{-30} (m_e) —— 10^{-4} — 10^{3}

Length, L (m) 10^{-4} — 10^{4}

Time, T (s) 10^{-1} — 10^{7}

And let us start with mass, for example, and ask in terms of masses - we will use standard international units throughout - what is the smallest mass that you think you can estimate? By holding it, weighing it in this fashion, like this… what you think is a smallest mass?

A gram, one gram.

A gram, certainly, a gram, you can tell. You can tell the difference between a gram and a kilogram, with our intuition. How about a nanogram and a picogram? Could you tell the difference? You could not do this; certainly, a fraction of a gram would be a safe estimate.

So let us put this down - mass in kilograms; let us put this down, and say that you can start estimating something which is of the order of a gram or may be a fraction of a gram - so that is 10 to the minus 4 kilograms. And what is the heaviest mass you think you could estimate? 10 kilograms? You could certainly tell the difference between 10 kilograms, and a 100 kilograms? certainly. How about a 1000 kilograms?

You will not be able to lift it.

Well you will not be able to lift it - that is a good point, and in fact, if I gave you a lump of metal, and did not tell you it is density, then you have no way of knowing whether it is 10,000 kilograms or 100,000 kilograms or a 10,00,000 kilograms, at all. So, whatever you can push just about is the upper limit; may be 100 kilograms; let us play safe and have another order of magnitude - a 1000 kilograms. So that is 10 to the 3 kilograms - the upper limit of what you can do with just your senses.

What about length? Let us measure this in meters. What you think is the smallest length you could perceive with your eye - with a naked eye? A fraction of a millimeter; may be half a millimeter or something like that. So we will play it safe, once again, and I am going to say that a millimeter is 10 to the minus 3 and I say that a very sharp resolving power, so 10 to the minus 4 meters, for example, up to….

And what is the longest distance that you could estimate, without instruments? Well, you could not tell the difference between the distance to a planet and distance to a star with a naked eye, unless you have other piece of information. And on a clear day, if you stand on a very clear place, and look up from a mountain peak, you could perhaps see 10 kilometers. But you see, the point is, if you did not have other objects for reference, you have no way of estimating how far things are; if you had a blank wall with no texture on it, and no signs, no signs, no way of distinguishing what relative scales are and so on, then you have no way of knowing how far things really are. But perhaps 10 kilometers is a good estimate; you certainly cannot tell the difference between a 1000 kilometers and a 100 kilometers.

Sir, you are not allowed to run?

Pardon me.

You are not allowed to run?

No, I am saying with your bare senses, and that is it. Of course, if you start running, and you say, what, you know, endurance is and so on, that is a different story; but let us just say, you are standing and you are trying to do an experiment, to see how far you can see. 10 kilometers, safe thing, that is about 10 to the 4. These are just orders of magnitude - 10 to the 4 meters.

And what about time? What is the smallest time that you could perceive, in seconds? Oh! the blink of an eye lid. Certainly a pulse is of the order of a second, but you can measure time scales smaller than that, the blink of an eyelid, that is about how much?

A fraction of a second 10 to the minus 1 seconds; 10 to the minus 1 seconds.

Incidentally, while we are talking about it, why do we blink?

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You would like to have clear layers? Certainly, you would like to clean the eye every now and then, you would like to have a layer. But how is it that when I blink, I am sorry, I am going to go off into digressions of this kind, how is it when you blink things do not go off?

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Yes, but if I did this experiment, we blink in a tenth of a second, now, and we blink may be every 5 seconds or so; every 5 seconds if I switched off the lights in this room, it will be tremendously distracting to you; this can be done; this a very easy experiment to do. You find it tremendously distracting, if every 5 or 10 seconds lights went off for a tenth of… a tenth of a second at a time – that is what you do when you blink. But it does not happen when we see, when we look around. Why do you think that is the case?

Probably got used to…the brain got used to…

So close answer; it is a close answer. The processing section of the brain closes down simultaneously; otherwise, you will not have this feature at all; very cleverly designed; it will be tremendously distracting otherwise. So even the processing center closes down; that is the reason, why you do not feel that you are blinking, unless you do it consciously, of course; close your eye, then of course, you know that it is dark and so on. But otherwise, reflex blink, you do not see as a shutting off of the lights at all, because even the processing is not done during this period.

Well, anyway to come back here, it is a tenth of a second, here. What is the longest time that you can actually perceive without any instruments, without any external signal, without the seasons, without the stars, and so on? Little more than an hour. People have done this experiment – they have actually put people in cells, with all the comforts of life provided; with uniform lighting so they cannot tell the difference between night and day; with the same bland foods, so you cannot tell whether it is, you know, breakfast or lunch or dinner and so on, provided there in a cavity, you open up this recess and you get this food, very familiar from the hostel life, right? They are trying to get you to used to this.

And then, you are supposed to go and press a button every two hours or so, and pretty soon you realize that the experimental subjects starts pressing the button every 3 hours or so, or every 4 hours or so. So, she assumes that a certain amount of time - 2 hours - has elapsed, when really 3 or 4 or 5 hours have elapsed, and eventually even the rhythms of the body get knocked out, and gradually all the cycles change, and I think this experiment has been done, and people have gone to the stage, where they find, they think a day is like 50 hours long. So your perception of time goes off, unless you have other indications, you have other longer cycles and so on, but even the physiological cycles changed, everything changes along with this.

So, I would say, may be you can tell the difference between a month and a year, but you certainly cannot tell the difference beyond that. We will play it safe once again, and say this whole thing on the right hand side - the upper limit - is of the order of a 100 days, for instance, and a day is about 10 to the 5 seconds, so 100 days is about 10 to the 7 seconds.

That is the world of middle dimensions, the world in which we have some intuition. But now, we start asking - what does the universe do? On what scale is that operating? Then, of course, you are in for a tremendous surprise. This is the world of middle dimensions; I would like to put this in quotation marks, the macroscopic world in which we live, which we have got used to. There are other parameters; there are other physical variables like velocities and so on, which also have comparable numbers, but we have started with mass, length, and time, and let us stick to that.

Now, what do you think is the smallest mass that we know of with our instruments, whatever we have detected? What is the smallest mass we have detected? What do you think is the smallest mass you know of?

We have gone smaller than that. An electron is certainly is less massive than a proton, so it is… how much is that? About 10 to the minus 30 kilograms. Let us say 10 to the minus 30; we do not know of particles with smaller masses than that at the moment. But let us say 10 to the minus 30; this is the mass of an electron and there is a vast gap between these two guys.

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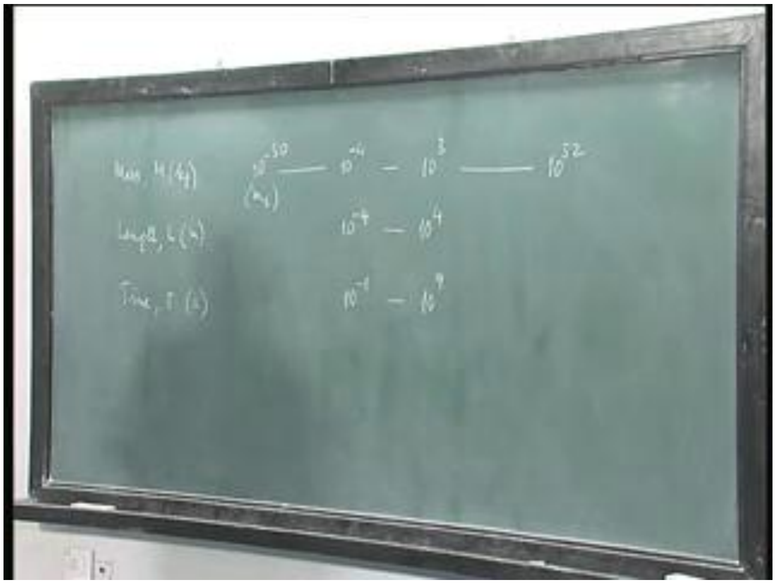

On the upper limit, what is the largest mass you can think of? The mass of the known universe. Certainly all the matter in the universe; we do not know how to estimate this; we do not the size of the universe too well. Now, what you think we should write here? How big do you think it is?

Now, we could do the following: we could assume that we have a whole lot of stars and try to estimate the total mass of the stars; the total mass of all the stars would mean multiplying the number of stars by an average star - like the sun, for instance. Now what is the mass of the sun?

About 10 to the 30 kilograms.

About 10 to the 30 kilograms; we could estimate this, and remember, the way we would do this, is always to assume that you are on a desert island with no information, no Wikipedia, no internet, and you have only sand to write on, and you need to make all these estimates for your survival; this is the way to learn any subject; you are compelled to do this. Then, of course, I could start by saying the sun is a hot ball of gas, I estimate the average density of a gas, multiply it by its size, and then so on and so forth. But 10 to the 30 is about right; 10 to the 30 kilograms.

And how many stars are there?

About 10 to the 22.

About 10 to the 22; there are 10 to the 11 galaxies, and about 10 to the 11 stars in each galaxy; so that gives us 10 to the 52; and this thing here, is an estimate. Of course, you could do this in another way; you could start by asking what was the density, what is the density of matter? Known matter, ordinary matter in the universe, and then you could multiply this by the radius of the known universe; you can multiply this by the size.

Now what is the size of this universe? That is a very tricky question, very tricky question; it depends on what you mean by size. You could say a very naïve way of doing this would be to say - well I know the age of the universe and what is the age of the universe?

18.7 billion years.

18.7 billion years old; 0.7 that is important; it is known; it is established. The first decimal point is known, you multiply that by a light year, because it is that old and this would mean that this is like a radius of the edge of a universe, stars are receding from you at the speed of light, essentially. So this is a good estimate; and when you make that estimate, it turns out that the answer is about 10 to the 52, once again comes right there.

There are other ways of doing this. Of course, this assumes that you are at the center of the universe and the rest of it is simply expanding away from you; but that is not necessarily true at all. But there are similar estimates, which would tell you the commoving radius of the universe, and it is of the order of 10 to the… 10 to the… it is of the order of 40 billion light years or so, it is in the same ball park; and therefore, the whole thing is… we will assume this 10 to the 52 this side; of course, there is dark matter, there is dark energy and so on, and forget about that, but whatever it is, for the purposes of this argument it is of the order of 10 to the 52, roughly.

Now, what about length? What is the smallest length that you know of?

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Certainly experiments on electrons have told you, that there are no structure whatsoever. We have done nuclear physics, we know the size of a nucleus is 10 to the minus 15 meters - femtometer; if you go beyond that, inside the nucleus etcetera, but we can construct, we can conceive of an extremely small length from the three fundamental constants of nature - Planck's constant, speed of light in vacuum, and Newton's gravitational constant - these are the three fundamental constants of nature and they are very, very important.

So you have Planck's constant, speed of light, and Newton's gravitational constant - those are the natural constants; mass, length, and time are some things, which we have created in some sense, but the constants we have available in nature have different dimensionalities; not mass, length, and time necessarily.

What are the dimensions, physical dimensions, of Planck's constant?

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Joules/second is units. Now what are the dimensions? It is energy multiplied by time; so its ml squared t to the minus 1, and c is, of course lt inverse, and gu you can find from Newton's force equation. So with these three constants, it is clear you can create three numbers - three combinations - which have dimensions of mass, length, and time, and they would be called the Planck length, the Planck mass, and the Planck time. And the Planck length turns out to be of the order of 10 to the minus 35 meters. Construct this as an exercise - a combination of h, c, and g which has dimensions of length, and that is of the order of 10 to the minus 35 seconds.

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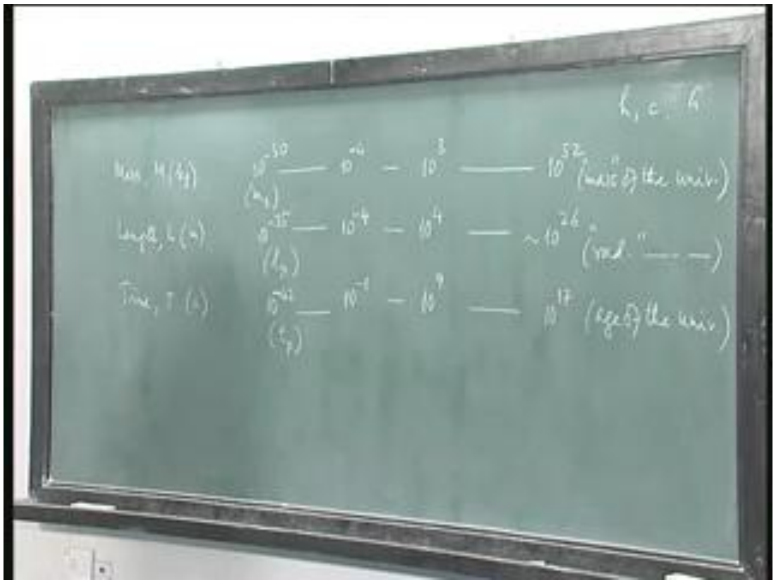

So, this is l - Planck, much, much smaller than this. And what is the longest, largest length we can think of? The radius of the universe. We have got various estimates for the size of the universe, but it is an upper bound; we do not even know if it is finite or not, but let us write this down as 10 to the power may be 35 or 26 meters, very roughly; but is enormous, as you can see.

What about this? What about time? Again, Planck time is the smallest time we could construct, we could think of as time itself, and that turns out to be the order of 10 to the minus 42 seconds, and this is t. This here, I should write mass of the universe; and this is radius, these are on quotation marks; and what is the longest time that you could think of?

The age of the universe.

The age of the universe, which is 13.7 billion years; therefore, this thing here is about 10 to the 10 years, which is 10 to the 10 multiplied by 10 to the 7; so 10 to the 17 seconds; of the order of 10 to the 17 seconds - age of the universe. But remember, these are orders of magnitude. Now just think, this range here is invariably about 7 to 8 orders of magnitude, give or take 1 or 2 orders of magnitude, very tiny window, but nature is operating on a much, much bigger scale; it is operating on a length scale, mass scale, which is like 80 orders of magnitude, to the extent we know about. A length scale, which is at least 60 orders of magnitude possibly much, much more, may be even infinity.

In a time scale, which as of now is already about 60 orders of magnitude, could become much, much larger. And these are orders of magnitude, these are not just factors; you are not just doubling or tripling the range, you are actually multiplying by 10 each time, and this is absolutely incredible, and it is just mind blowing to see the range on which nature is operating.

Therefore, I put it to you, any intuition, which you develop to conduct your daily lives in this world of middle dimensions, there is no reason why that should continue to hold in this range; there is no reason at all, and the so-called understanding of classical physics, the intuition you develop, and so on, the physical intuition is a myth; it is simply something, which has been hardwired into your brains for reasons quite different from the understanding of nature. Therefore, there is no reason to expect that whatever loss, whatever regularity you find in this range of orders of magnitude should continue to hold good in this range, within this range, and indeed, it does not.

So with the induction of instruments - microscopes on the one hand, and telescopes on the other - you are really able to broaden your range in which you can probe nature; all the way from this side to that side. And simultaneously it turns out you need other tools - you need mathematical tools; it turns out in order to understand how nature operates in this scale. So the real miracle is that you have a language, and you have the means to understand this range in some sense, even though it is not necessary for survival.

Now, you could ask - why is it that I cannot perceive of times smaller than this? Why is it that I cannot look at… I cannot tell the difference between a picosecond and a nanosecond?

Why do you think that is the case? You did not need it; you do not need it for survival; you do not need it evolutionarily for survival. The time scales you needed to put it, very crudely, this is a delicate question, but you can give a very rough, very crude argument - after all it was all about survival and what you needed was to have a reflex time, that was sufficiently fast to ensure your survival.

So, to put it in very, very graphic terms - certainly, not to be taken literally - our primate ancestors had to make sure they did not fall down into the jaws of predators. Depending on the gravity, the rate of fall is controlled entirely by the gravity, depending on that you needed time, when you let go of your mother ape and you started falling, you needed time for the muscles of the hand to send a message to your brain, and the brain to send a message back to the muscle to say - hold on or you going to fall down. A fraction of a second was sufficient for that; you did not need a picosecond, you did not need a femtoseond. So you did not have to waste brain power and neurons processing that information, you got hardwired into this world, and that was enough on this side.

All these things are guided by that. Mass, for example, you do not need to know the difference between a microgram and a picogram, but you do need to know the difference between a gram and a kilogram. And once again, in this metaphorical language, it is essential to know, it was essential for our ancestors to know, that you have to be much more effective to throw a rock at a predator rather than a leaf.

So, they had to know the difference between a gram and a kilogram; they did not need to know the difference between a microgram and a picogram. And that is why the brain did not waste any time trying to process information from this range or on that range, and this is why we would think you understand Newtonian physics, because you see masses, you see, as you see time, you can actually push these rocks around and so on.

But I put it to you that there is nothing intuitive about it; it took a long, long time to discover that when you push an object, you change its velocity and not its position, then you change its position as a consequence of changing its velocity. After all Newton’s law says the force is proportional to the rate of change of momentum or the velocity not the position; only bacteria, which are swimming in a nucleon fluid at terminal velocity only for them is the force propositional to the velocity, but nor for us. So even Newton's law is counter intuitive, very counter intuitive, and its consequences can be equally dramatic.

So do not confuse facility in a certain range of mass, length, and time with understanding of this range of length, mass, and time - they are very different things. And it turns out, that the language you need for understanding, making predictions is mathematical, inherently mathematical, we do not know why, we do not know the deep reason why. We have no reason, we do not understand as yet, why it is that our brains, which are hardwired evolutionarily for survival in a certain range of parameters, has been able to come out with directions using a language and abstraction called mathematics, which enables it to probe the rest of the region. And why it is that with the aid of these instruments which we have developed, we are actually able to investigate the rest of this range - a good bit of the range - and understand it in some codified sense. So it is not a… that is a surprise; that is a surprise.

Not the fact that electrons behave like waves or like particles or whatever you might have heard, not the fact that Newton's inverse square law of gravitation, although universal is actually an approximation - these are not surprises, really; it would be a surprise if it were not so. If everything was decided by a few simple equations, that would be a surprise, no reason why that should be so and it is not so; just is not so.

So classical physics is one portion of this range, which we will be enabled to uncover using rather simple rules, but not necessarily trivial rules fairly complicated rules. And as the course goes along, I will show you that classical dynamics is actually quite intricate; has very, very precise structure, a very interesting structure; and that quantum mechanics is a very non trivial extension of this; and the relationship between the two is not yet fully understood; we do not fully understand what is going on in quantum mechanics in a certain sense, but I will also point out, that enough people have sensed, that quantum mechanics is easier than classical dynamics, which is much more intricate mathematically, much more intricate.

And then, of course, there are other problems associated with rest of the curriculum, such as statistical physics - what happens when you have large collections of objects? How you understand them? Why you need probabilistic concepts? Why you at all need statistical concepts? This is something which is worth understanding and it will turn out that we will acquire at the end of this course, hopefully some perspective, why all this is happening, and where we stand today, and what kind of progress we could expect, and this would have, of course, come after you finish the next course. But for the moment, we will stick to classical physics in which we will switch of Planck's constant, and this curriculum also does not have much about gravitation, although I will mention this once in a while. So it will be non relativistic, it will be non quantum mechanical, and of course, we will ignore gravitation for some part, at least. So, it turns out that you might as well set, you eliminate g, set c equal to infinity, and h equal to 0, and that would be the classical physics we are go going to look at. But you must be aware, then these are boundary conditions, these are limiting cases that rest of it is really part of a much bigger hole. So this is what I would like to convey in the rest of this course.

So, is there any question on what I have done, said so far? Wherever necessary I will use orders of magnitudes, estimates, and wherever we think we need to do something more rigorously, we will look at those things; we will work out things much more explicitly. I will try and do everything on the board, so that all equations are understood, understandable, but there may be cases where I might just quote a result, quote, especially mathematical results, I might once know well, quote them and say these are well known theorems, and will not bother about proving them, but we will understand them, we assume that regular proofs are available, and we will try to understand them on somewhat physical terms.

Now when I say physical, I would like to state, explain, that I do not mean necessarily mechanistic; everything need not be mechanistic at all. For example, electric and magnetic fields exist, we know that; they have classical limits, classical, electric, and magnetic field exists, but you cannot give a mechanical model for it, not in terms of wheels, gears, pulleys, and so on; this is not possible; they are fields; every point in space and time would have a field, and they may or may not be detectable or perceptible to you with one instrument or another, but it does not mean they do not have reality, they do not exist, they are not hard objects like this. So the universe does not just consist of rigid bodies, just does not consist of classical waves, there is much more to it than that.

For example, electromagnetic waves, which are already in that sense non-mechanical, they already go beyond your normal mechanical intuition, and yet, they are completely classical in a certain sense. So, you have to allow for larger possibilities as we go along. So this is the sense in which I would says something is physical. I assume also, might as well say this right in the beginning; I assume also you are familiar with complex numbers.

We will freely use as much mathematical tools as we can, and I have been asked this question in the past - if all measurements are real, why do we need complex numbers? That is a good question, but it should really be asked in class twelve; at that stage. It is just that you need these numbers, you need matrices not real numbers, necessarily; you need combinations of numbers; you need n tuples, multiples of numbers and so on, and complex numbers is one such thing. So the word - imaginary number - does not mean anything as far as I am concerned.

So if you ask me - what is the physical meaning of 2 plus 3i? I would ask you what is the physical meaning of minus 3; for that matter, what is the physical meaning of three halves or what is the physical meaning of 3? These are all abstractions as you can understand, and we try to put them into correspondence with physical objects, and that is all that is being done. So it simply a code and this is the sense in which we would like to understand things.

Now, the first part of this course has to do with dynamics, but before I do dynamics, I would like to mention here something along the lines of what I have already said, and what comes beyond dynamics, and this is the very famous picture, very famous diagram which I try to reproduce here in some sense.

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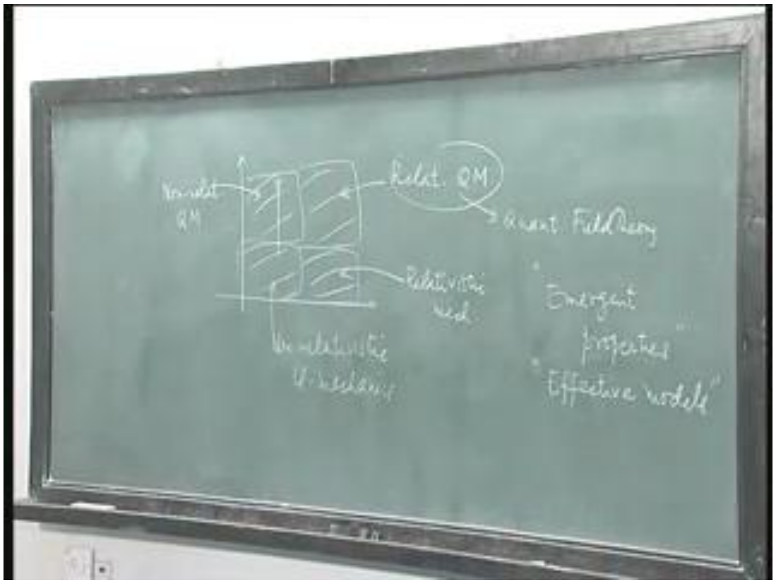

You have, we will put the axis in a little later, you have a very, very slow velocities compared to the speed of light, and on scales, length scales much bigger than atomic length scales, microscopic length scales, you would have non relativistic physics in some sense of macroscopic objects.

So let us put a little box here, and say this is the region, this is roughly the region of non-relativistic classical mechanics or Newtonian mechanics. You could continue to remain non-relativistic, but you go, go into domains, which are extremely small - atomic dimensions for instance, and then, you would have quantum mechanics. So you would have here, I joining it, very blunt, very crudely, you would have non-relativistic quantum mechanics.

On the other hand, you could look at fairly large objects, but go into high velocities in this direction, and then you would have take into account relativistic corrections. This would happen typically in astrophysics; for instance, you certainly you have to take into account relativistic corrections. You would also might have to do this along with this thing here, along, for if you look at motions of electrons, for example, but we will come to that in a minute.

So on this side you have relativistic mechanics or relativistic physics; you keep going, you could include gravitational fields, very intense gravitational fields, and so on. You would have special relativity, then you might have to make general relativistic corrections and so on on this side, very schematically.

But then, you could also go to very high speeds, and very small objects, and then you would need relativistic quantum mechanics on this side. And that is where a little bit of surprise comes in, because it turns out, that when you do relativistic quantum mechanics, you could start with this kind of problems we do in physics, academic problems, very idealized problems, just as in thermodynamics you start by studying the ideal gas, there is no ideal gas in nature of course, everything interacts with everything else.

But just as you use that as a useful model, similarly in quantum mechanics, you might study for example, the hydrogen atom - a single hydrogen atom in the universe, it is a very, very simple idealized model and you could study its quantum mechanics as well. So you could look at the problem of particle orbiting around in a traction, a traction center here, and then, you could do this quantum mechanically; you could do this relativistically. But the moment you go to relativistic quantum mechanics, it turns out that a new phenomenon occurs, and this of course, is the famous equivalence between matter and energy; it turns out that mass and energy are just two ways of saying more or less the same thing.

Since matter can be…matter and energy can be inter-converted to each other, things like the number of particles is no longer a sacred concept, when it comes to relativistic quantum mechanics, because matter and energy could go on getting interchanged. Now, once that happens, you can easily see, you could expect that there is no such thing as relativistic quantum mechanics for a single particle; it is not likely to be consistent, simply because you could have many, many particles created, a single particle is very, very energetic, and then annihilated once again, and reconverted to energy.

This happens under certain constraints and conditions, but the principle is clear that this could happen, and therefore, it turns out relativistic quantum mechanics is intrinsically not really constructed, and what you need is the possibility that you can have any number of particles included in one single theory, and that leads you to relativistic quantum field theory. So, really, this thing is superseded by quantum field theory. And that has turned out to be the most successful language of all, necessarily very intricate, very involved, but in principle, it explains all that you know so far, and it is like the culmination, it is like the ultimate theory at this level of understanding that we have now of all the universe around us.

But there are very, very important gaps; one of them, of course, is familiar to you from reading popular literature. We found no way in which you can consistently combine relativistic quantum field theory with gravitation. We do not yet know how to quantize gravity - that is one problem. The other problem is the theory that we have now for elementary particles, at the fundamental level, is called the standard model of particle physics - is itself an adhoc theory. It is obviously and is very obvious from the fact that it has many undetermined parameters, many parameters which you put in my hand, many constants, it is clear, it cannot be a final theory of particle physics, there must be an underlying structure and we do not know what that is; so it still incomplete, but the day is young, this whole thing is about a 100 years old, as you can see; it started here about 400 years ago to reach this fairly fast, and the day is young, there is a lot more to come.

But it is a good idea to have this perspective, that this is where it is at the moment, but you do not necessarily need all the complications of relativistic quantum field theory if you want to look at sub portions of this. For instance, if you want to design and this is brings me to an important point - the whole thing is layered in such a way that depending on the regime of physical parameters, depending on the physical problems we are looking at, you might find it sufficient to use an effective theory; you do not have to use first principles theories all the time. If you would like to design a better carburetor for your car, there is no reason why you should know the underlying organic chemistry of the fuel; there is even less reason to know that each molecule is made up of atoms, and each atom in fact is made up of a nucleus and electrons, and inside the nucleus there are nucleons - the neutrons and protons - and inside the neutrons there are quarks, and they are held together by things called gluons; it is not necessary for you to know that in order to design a better carburetor; although that is true.

So this business of reductionism should also be carefully examined, while you would like to have under have reductionism, go to first causes in order to understand things from very basic principles, you must realize that at every level of organization, there is a set of effective loss and this is really all you need. The boundary between two regimes is very interesting. Always, these boundaries are interesting, where classical mechanics stops and quantum mechanics starts is it a fuzzy boundary, is it sharp? These are very interesting questions; where non relativistic physics stops, relativistic physics starts off ? This is again a very interesting question.

On the other hand, inside a domain, you could have an effective theory. This is what happens, if you study elementary chemistry, if you would like to understand reactions, you have a law called the law of mass action; you can derive the law of mass action for more fundamental considerations, but you do not effectively need to do this, if you want to understand chemical reactions in the large. So this is another thing one must understand and appreciate that although there are these fundamental theories, there may not be necessary in all cases, in most cases they are not; what you need is an effective theory, an effective model. And above all, you must recognize that when you take a whole lot of objects and put them together, the sum, the product - the end product - may be greater than the sum of the parts. There might be properties, which come out for a collection which do not exist in each individual component.

Individual atoms do not have colors, but when I put a sufficient number of atoms together of an object, it acquires a color, for example, and this is a property that emerges due to the fact, that you have a collection. And then a very interesting question is that at what stage does the color emerge? And that is true for every one of these properties -physical properties. So we must understand that this is also possible.

Individual water molecules do not do anything very interesting, but when you put a large number of them together, it turns out depending on the external conditions, they could exist in different phases; same interaction, the same interaction between two water molecules under different conditions could give you either ice or steam or water. So, clearly, this is a property of a collection and not a property of an individual molecule - that is another crucial thing we must bear in mind, that there are these properties, called emergent properties, which emerge when you put a lot of things together, and one of our pre occupations is going to be with these properties. So this is another thing, which I would like to write down here - emergent properties and effective, effective modules - use this phrases once in a while to mean precisely what I have just explained.

For example, Newtonian mechanics is an effective model in a certain regime are of parameters of length, mass, time, velocities, angular momentums and so on; so is quantum mechanics as far as we know, it is possible that one day it is subsumed into larger theory or a larger framework. But the difference between physical laws and mathematical laws is precisely this - whereas, mathematical laws, once you lay the axioms down would appear to be applicable in some absolute sense; physical laws are always applicable in some range of physical parameters. You go beyond the range, the law may or may not extrapolate in a smooth way, and this is also something which one should bear in mind, because this is very often lost sight of, that is what leads to questions of the kind - is the electron a wave or a particle? As we go along, I will convince you that the question itself is meaningless. An electron is what it is, and what properties it displays; in fact, that is going to be your attitude.

If I ask you what this piece of chalk is, every description, every definition that you think you give for what this piece of chalk is, will be a statement of one of its properties. So, I am not going to worry about what this chalk really is and use the word - the piece of chalk - for a pre agreed upon collection of properties of this object. So that is going to be shorthand for a collection of properties, which we have agreed upon. And then, of course, you see there is no difficulty with defining any object.

An electron is shorthand for the collection of its properties; it might turn out, that these properties would depend on how you probe these properties, and it does in this bigger range that I talked about; and therefore, I have no conflict at all. And then the question whether things like electrons are waves or particles, becomes question of semantics, it becomes a question of failure of the words - wave and particle - to apply in that regime, in an unambiguous manner

I need another language, but I have one it is called quantum mechanics. So I do not regard this wave particle duality as a mystery, I just think it is a failure of ordinary language, and of course, it will be a very unhappy situation if I did not have a language, instead of ordinary language, but fortunately for us we have discovered there is such a language and we will use that language when the time comes.

So I hope you got our philosophy, right? The rest of it is not going to be so descriptive; it is going to get considerably more quantitative. Let me stop once again, and pause and ask you - is there any comment or question that you would like to ask now?

Sir, why is that the combination of h, c, and g gives the lower limits of the Planck's length and Planck time?

It is a wonderful question - why is it - it is a deep question, why is it that the combination of these three, gives the lower limits of what we know and not the upper limits and so on. This is not a very, it is not a serious problem, in the sense that I do not know the upper limits; I do not know, for example, if the universe is finite or not, it is unbounded, but what I do know is that there is a fundamental velocity - the speed of light, there is a fundamental quantum of action - Planck's constant and there is g.

Now, in the case of Planck's constant, it turns out that this thing here actually describes certain fluctuations, certain indeterminacy, which you are familiar with in the guise of the uncertainty principle, and its numerical value is such that it happens to give you a applicable in the range of small, a very small; this is where fluctuations would play a role; very rough answer, very rough answer, but we will get more precise answers as we go along.

Now, of course, it is not always true that it gives a lower bound, if I look at mass, for example, I was careful not to use this, I did not use the Planck mass. The Planck mass, if I calculate, turns out to be of the order of 10 to the minus 5 grams; it is enormous compared to elementary particles, it is huge. So we believe the Planck's constant has something to do with fundamental at the lowest, at the reduction is ultimate level, it has to do with fluctuations, and some microscopic level, sub microscopic level, and you would expect the mass also to do this, but the actual masses of the elementary particles that we know are often much, much smaller.

So in a sense the Planck mass is a very large mass, it is a huge mass, of course, we put objects together, you get much larger masses like people, and galaxies, collections of galaxies and so on, and it could be infinite, on the other hand. So it is not always true that it does give the lower limit, but in the case of a length and time, it does because of a deeper reason, we believe that the Planck length and the Planck mass, are in fact the length and time scales on which… that the Planck length and Planck time are the length and time scales on which the concept of space time as a continuum itself breaks off.

So believe, we believe that below this, below the Planck length, and below the Planck time, thinking of time and length as continuous objects itself is suspect; we think the structure of space-time itself, could be very different from what we know of it on much longer time scales and length scales; this is where quantum fluctuations in space and time themselves, would start playing a role, and therefore, the meaning of space, and the meaning of length, the meaning of time is not very clear.

So, that is the reason why it is, it is not a reason, that happened, that is why on the lower, lower end, simply because below that it is fluctuation dominated, and after that in some sense these fluctuations are smoothed out, and more much larger scales you do not see, these fluctuations at all. It is like saying that if I give you a piece of paper and tear it the edge is jagged, but then, of course, you could look at it from sufficiently far away, it looks quite like a straight line, but I go closer and closer, I start seeing the fluctuations more and more. So it is in the lower level that you start seeing fluctuations, rather than on a close resolution; that is a very crude answer, but that is roughly what it is.

Any other thoughts? So as you can see, these are not….

This is precisely the point. I gave this example of water going into ice or steam or liquid water; it is quite clear that you need a sufficiently large number of molecules for this to happen, for you to be able to distinguish these phases, it is equally clear that the phase of water, of the, you know, whether it is ice, solid, liquid or gas, is not a property of a single molecule; that is obvious that is not. It is a same molecules; even interaction between the molecules is exactly the same, and yet, when you put aggregate together it exists in these three phases.

The interesting question is - how many should I put together before I can tell whether it is liquid or gas so on? Can I have an ice crystal which has only 10 water molecules or 50 or a 100 and so on? That is a much, much harder question. It turns out that there is no clear boundary, in this sense, you could go on subdividing matter and then there comes a stage when you to lose the concept of this phase. It happens fairly smoothly in most cases. So, this is not a… we will talk a lot more about this when I discuss short range order and long range order and liquids also. A very rough answer would be if you take, for example, water at low temperatures, but before it freezes, you discover the system is trying to become crystalline. So neighboring molecules are arranging themselves in a regular array, but then its perturbed by thermal fluctuations and it dissipates.

But as you lower the temperature, the thing becomes more sluggish and eventually clicks in to place, as a crystal, but you do need a collection for this. And the study of emergent property is, of course, is very, very vibrant, its phase transition is just one example of it and many, many other such properties, which are very interesting; it is also called collective behavior, it is got many, many other terms coherent structures and so on and so forth.

Another example, for instance, is if you took individual photons, nothing much happens, but if you put them all together in the right conditions, they could get coherent and produce a laser beam; that is not a property of a single photon. So, many delicate things happen simply because you have these collections, and the collections could be extremely weakly interacting, but still produce order. A very crude example would be, if there is a distraction at the other end of the room and just a few people in that corner start looking there, only their neighbors are influenced, they start looking there and pretty soon that propagates. So even if you do only what your neighbors do, you can have very long range coherence even though the interaction is short range - that is an emergent property.