Mechanics, Heat, Oscillations and Waves
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Lecture – 05
The Fundamental Forces of Nature

In this lecture, we will discuss the so called fundamental forces of nature, the forces which are responsible for all the phenomena that we see in the universe. Now, you would have come across in elementary science with various different kinds of forces. You would certainly heared of a fictional force which enables us to walk. You would have heared of a force which are centripetal force which is an invert force for a particle or an object which is in circular motion. You would have heared of mechanical forces, electrical forces, magnetic forces and so on.

Now, all these forces have large variety of these forces turns out, can all we brought into the broad, under the broad umbrella of just four fundamental forces of nature. In fact, the actual number that we come across in daily life is even smaller, it is generally just one or two as I will explain as we go along. But, what Physics has been I mean able to do is over the years, it is being able to identify four fundamental forces in nature which are responsible for all the phenomena that we see around us. And let me list those forces and after that, I will explain one by one what these four forces actually imply and what their effects are.

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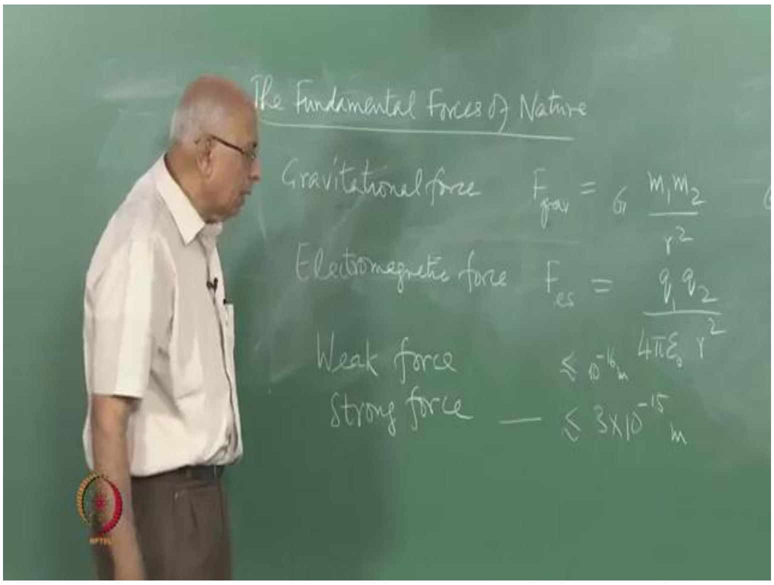

The first of these forces is the gravitational force and in the most elementary instance, this force has been known to human beings have a sense there were on this planet. Because, it is the force which operates here when you throw an object, when you fall down, you claim down from a tree and so on and so forth. So, the gravitational force was first mathematically quantitatively emphasis the stated by Newton's universal law of gravitation.

It says that if you have two masses m 1 and m 2, the gravitational force between them F gravitational is equal to the product of the masses divided by the square of the distance between them multiplied by universal gravitational constant G and this G is approximately equal to 6 times say 6 point something or rather 6.7 may be times 10 to the power minus 11 Newton's meter square over kilogram square.

Because, I did, bring these two downstairs and take this up here in the physical dimensions. The units of Newton meter square of a kilogram square and these time standard international units capital G is of orders 10 to the power minus 11. So, this is Newton's famous inverse square law of gravitation. It is also implied by this law that when the two objects, the two masses are separated by an arbitrarily large distance.

No matter how large r is, there is still a force between them. So, even if these two objects were many, many millions of light years apart, there is still a force between them which of course, decreases very rapidly, because of those like 1 over r square. Now, I am able to say how fast it decreases, decreases like 1 over r square, reciprocal the inverse square of the distance between them, so that is the first force the gravitational force.

The other next force is the electromagnetic force which is quite complicated, but in it is simplest form it is almost analogous, it is almost exactly the analog of Newton's law of gravitation. It is Coulomb's law between two static charges and that is the electrostatic between in force between them. The electromagnetic force magnifies in many, many other ways as well as we will see, but the most elementary way is when you have two static charges, there is a force between them which is a force either of attraction or of repulsion.

Unlike, the case of gravity which is again proportional to the inverse square of the distance between the charges and this force and let me call it electrostatic e s for electrostatic. This between two charges q 1 and q 2 is again proportional to q 1 times q 2 divided by the analog of this constant, which in the units we chosen is written as 4 pi Epsilon naught and r square. This Epsilon naught is called the electric constant of the vacuum or more popularly, the permittivity of the vacuum.

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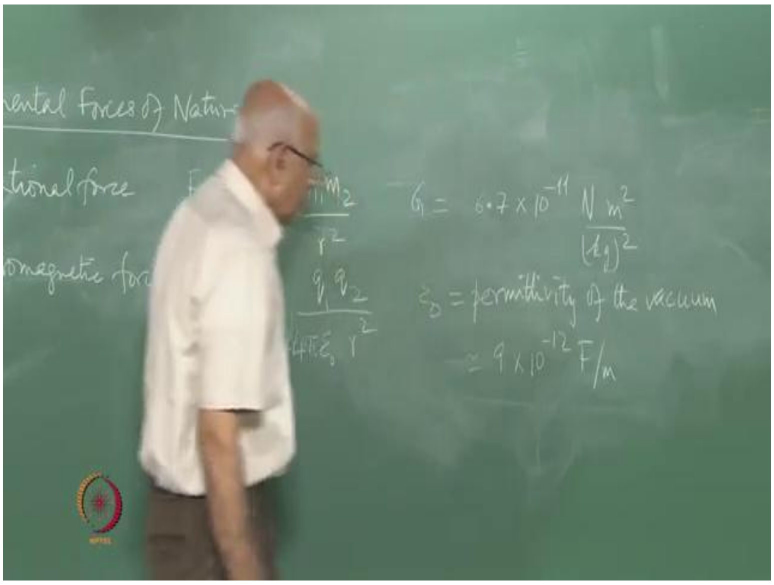

Epsilon naught is the permittivity and it has a certain value in the standard international units that we used, this is of the order of 9 times 10 to the minus 12 farad's per meter. When we come to electromagnetism I will explain what the unit farad means, but it since standard international units, this quantity has these physical dimensions here. So, we know it is value, numerical value in certain units in these units here, q is now measured in Coulomb's here.

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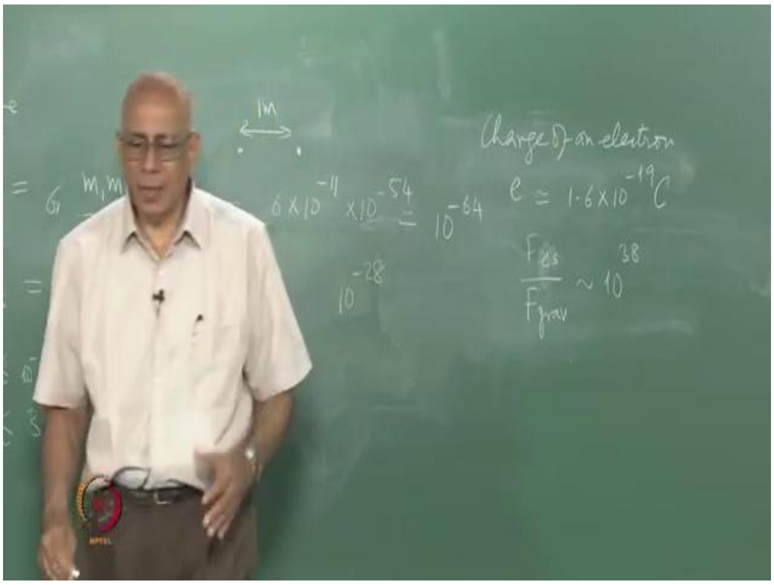

And just for reference, let me point out that the q for an electron, charge of an electron e denoted by e, not to be confused with the base of natural logarithms. This charge here is about 1.6 times 10 to the minus 19 Coulomb’s. So, ((Refer Time: 06:13)) these where the two forces that have been known since ancient times in one way or another and I might as well say, right away that the gravitational force is extremely weak compared to the electrostatic force, the electromagnetic force in general in a very specific quantitative sense, which I will come and explain in a very short while.

But, this is known to you, it is known to all of us. For instance, if I take a bar magnet and apply it to the top of … Then, I place a pin on the top of the table and place a bar magnet over it, the pin can been attracted to the bar magnet and if we moves of the table and stretch to the bar magnet and what this little magnet is doing is out pulling the entire gravitational force of the earth.

So, in that sense you can see that this enormous mass of the earth is still not able to produce the gravitational force acting on the pin, which can overcome the attractive force due to the magnet only. So, in that sense, electromagnetism out pulls gravity in the suitable conditions and you need a huge mass before you have a sufficient, only large gravitational field which will keep the pin down. If you did the same experiment on the surface of a neutron star that is have to be very, very different all together.

We will see quantitatively how this works here. Now, these forces have been known for a long time, because of this fact that they drop very slowly to zero, they are long range forces. As I said, two masses will attract each other; however, free being no matter how far apart they are. Similarly, two charges will either attract or repel each other depending on whether these two charges have opposite signs or the same sign and no matter how far apart they are.

There is one fundamental difference between these two laws ((Refer Time: 08:01)), both of them are in r square, but we have no knowledge of any negative masses. All the masses we know of are positive, and therefore the gravitational force is always an attractive force between two like masses, like charges in the sense that they are positive masses. In contrast, we know of the existence of both positive and negative charges, so these q's can have either sign and it so happens that, when they have unlike signs, the force is attractive, and then they have like signs the force is repulsive.

On the other hand, you might say here too I can regard the masses as the analog of charges, yes indeed that will be true. We have only positive masses, so they would be like, like charges, but instead of repelling they attract each other. This is a fundamental difference between gravity and electrostatic magnetism and the reason is buried in quantum field theory. We are not going to get into that now, but it is a fact of nature.

This profound difference between electromagnetism and a gravitational theory, there is another thing that happens because of the fact that you do not have negative masses. The fact that you have both signs of charges allowed shows that forces can cancel. It can actually cancels each other whereas, if you take gravitational masses here, you know gravitational force here it is clear that this force, if you add more mass, the force is just going to increase all the time.

On the other hand, there is a possibility of having a plus charge here and a minus charge here and putting a test charge in the middle, in such a way that the force on it, the net force on it actually gets canceled out. So, these things are possible because of the difference in signs that is possible here ((Refer Time: 09:48)), but not possible here on this side. Now, what are the other two forces? Two more have been discovered and this discovery was made in the 20th century and these forces are called the weak force and the strong force ((Refer Time: 10:00)).

And start contrast to these two forces, these forces have only observable at extremely short distances. The range of these forces is very, very short and like the case of these two forces, but the range is actually theoretically infinite. Because, this r can go all the way up to infinity, the force becomes zero only as r tends to infinity. Now, what about the ranges of these forces? Let me write these down, so you can see.

There is no simple formula of this kind available in the case of these forces, but they are very, very important all the same. This force, ((Refer Time: 10:49)) the strong force is responsible for the force between nucleoli, the force that keeps an atomic nucleus stable, the force between different protons and neutrons in a nucleus, atomic nucleus. And in fact, for the force that keeps a proton stable and which has coax inside a proton and these coax bind together to form a proton or bind together in a different way to form a neutron.

So, even the constituency of the nucleoli are kept in place by the strong force, as we will see in what sense this is an extremely strong force here. But, the range of this force is of the order of less than or of the order of a few fermi's ((Refer Time: 11:32)). So, about 3 times 10 to the minus 15 meters, so a few simple meters. Because, as I said it manifest itself in atomic nucleoli in the nucleoli and the atoms and beyond that, this force is essentially zero, it does not exist beyond that.

Similarly, the weak force is also extremely short range and the range here is of the order of ((Refer Time: 12:04)) or less than or of the order of 10 to the minus 16 meters. What is it responsible for? It is responsible for radioactive decay, for fission reaction, it is for radioactive decay of unstable nucleoli and so on. So, this force here and this force here really are very closely related to each other, although they are quite distinct from each other.

They both operate at sub atomic scales at nuclear scales and sub nuclear scales. So, that is the reason why it took so long to discover these forces. Because, we really needed to get atoms measures, we needed to get particle accelerators, before you could probe distances short enough where these forces manifest themselves, these two fundamental forces of nature here. Now, what is the other significant difference between these forces and what is the reason why the range is very short?

Again the reason is varied in quantum field theory which we will not get into; obviously, here. But, the significant point about these forces is that the relative strengths compared to these two forces are very dramatic and that is what I would like to illustrate now with a little calculation. I would like to show you how strong are these forces with some common reference point.

So, let us take two protons ((Refer Time: 13:24)), here is a proton and here is another proton and the distance between them is 1 meter. And I ask what is the gravitational force and what is the electrostatic force between these two protons at this distance, kept at this distance? Well, this force here is of the order of, this is G is 6 into 10 to the power of minus 11 is I said, and then the two protons and each proton has a mass which is of the order of 10 to the minus 27 kilograms.

So, this multiplied by 10 to the minus 54 divided by the distance between them, the square of the distance between them that is 1. So, this is clearly, this is equal to of the order of 10 to the minus 64. ((Refer Time: 14:21)) 5 on to this and give another 10 for this, so that into the minus 64. This on the other hand is of the order of, if the charge of a proton is 1.6 times 10 to the minus 19 Coulomb's, so this is 1.6 square into 10 to the minus 38 Coulomb's square divided by 4 pi that is approximately 10, and then there is Epsilon naught which is 9 times 10 to the minus 12, so that is another 10.

So, 10 square into 10 to the minus 12, now then and then r was again 1. So, this give us 10 to the minus 10, so this thing here moves up when becomes minus 28, approximately 10 to the power minus 28, so that is 36 orders of magnitude difference. So, it tells you that the ratio of the gravitational force or rather say the electrostatic force to the gravitational force, under these conditions when the two protons repel or attract from each other is of the order of 10 to the power 38.

So, this shows you how much stronger electromagnetic forces are qualitative with gravitational force. For the gravitational force to become significant, you need a very large mass. You need astronomical masses and that is why gravitation controls what happens in the universe, the motion of galaxies, the behavior of galaxies, the goods of galaxies and so on or you in the motion of planets. On the other hand, what happens in daily life all around us is controlled largely by electromagnetic forces, not just the electrostatic force, but electromagnetic forces.

A little settled here, you might say where is these electromagnetic forces come from, if all the atoms are neutral. The point is slight charge imbalances are enough to cause these forces and that is exactly what happens when you have two different signs possible. For instants, here is a famous question. Once you have two atoms, let suppose both these are spherical atoms, hydrogen atoms in the simplest picture.

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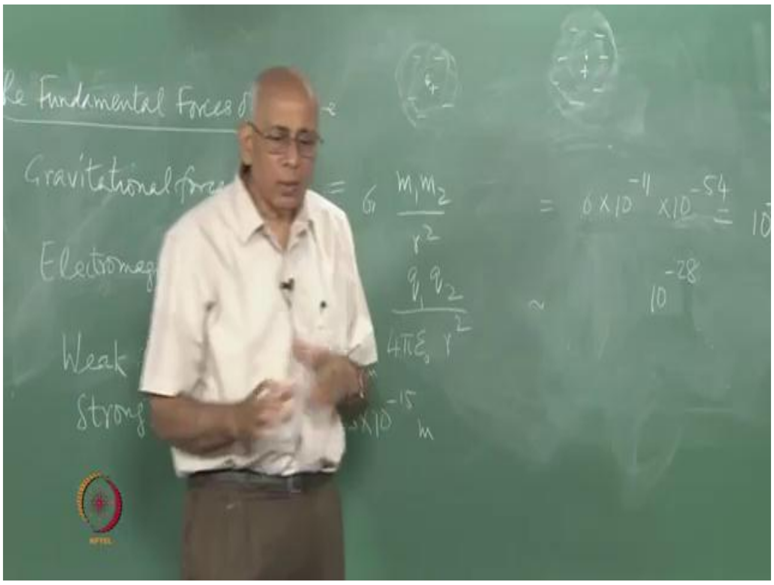

So, you have a spherical cloud around 1 hydrogen atom, another hydrogen atom here, a spherical negative charge electron cloud. So, there is a plus charge here and there is many minus charges in the spherically symmetrical cloud, this object is electrically neutral and there is no electric field due to this object outside, because it is completely spherically symmetrical, the positive charge is balanced completely by the negative charge.

So, is the other atom, how then would see a random force between them, any force at all. The point is, this is not static these are dynamic, the moving entities the electron cloud is not static or anything like that. So, moments tell me, if there is a displacement of the center of the charge negative charge, so that you have… Moment tell me, you have a net positive charge here, and then a net negative charge here, this forms what is called an electric dipole.

This electric dipole in this says immediately a field at this point, an electric field at that point which causes also a separation of the charge. And because you have two dipoles, it is like two bar magnets as you know, if you have two bar magnets with north poles pointing the same direction, when you bring them closer they repel and when you bring them in the opposite directions they attract.

A similar thing happens here and there is a net force between these two objects, whose distance dependence can be calculated in threads out. In this case, in the simplest picture that the forces between these two objects decreases like the reciprocal like 1 over r to the power 7 and it is called a Van der waals force. So, there is actually an induced electromagnetic force even if the atoms are neutral and this is what is governing all the behavior of objects are found us.

So, various kinds of electromagnetic forces, friction for example is ultimately due to electromagnetic forces. A lot of a chemical, all of chemical binding and so on are all ultimately due to electromagnetic forces with the added complication that want to make an exclusive, very significant role things like that. All the exclusive principle play a very significant role, but finally, in the final analysis they are not strong forces, they are not weak forces, they are not gravitational forces, but they are electromagnetic forces which control the behavior of most objects around us. So, these two forces in that sense are extremely crucial.

Now, ((Refer Time: 19:05)) why is the range of these forces so small and what are the peculiarities of these forces? That requires us to understand, it is not understandable in very elementary terms or simple terms at all. Because, as I said there is no simple analog of either Newton's law of gravitation or Coulomb's law of attraction or repulsion between charges in the case of these two forces here. But, the origin of these forces comes about in more or less a same way as the origin of these forces, when understood at the level of quantum field theory.

And today, the belief today is that all fundamental forces are transmitted with the help of certain quantum fields called the edge fields which have associated particles with it. And in the case of electromagnetic force, the particle is the familiar proton. In the case of the weak force and the strong force, there are corresponding particles. In the case of the strong force they are called bluons, in the case of the weak force there are other particles called the w and the G particles which are responsible for mediating respectively, the strong force and the weak force here.

But, the peculiarities of these particles, their properties will dictate what the behavior of these forces in each case ((Refer Time: 20:20)). However, these forces are responsible for a lot of Physics, this force here the strong force as I said, when it operates within a Fermi, distance of a femtometer. It is responsible for the behavior for creating particles like a proton and the neutron, nucleons. Now, we know that the proton is made up of three quarks of a certain kind, the neutron is made up three quarks slightly different kind and these objects here, I kept in place by the forces between the mediated by bluons, the force is between the quarks.

Over and above this, there is also a little residuals strong force which spells over outside the nucleon, outside the neutron and the proton which is what next nucleus stick together. So, nucleus stick together in spite of the fact that they have neutrons which are electrically neutral and the lot of protons which will repel each other, but that repulsion is overcome by the residual strong force and the nucleus stick together.

However, if you put two many protons in there, in the relatively smaller number of neutrons, then it is clear that the repulsion is going to take over and finally, the nucleus becomes unstable and this is what happens in real nucleoli. You might have noticed in the table of elements of nucleoids, that as you go up and the mass number increases the number of neutrons becomes are the larger than the number of protons, it is not as of few equal numbers.

In the case of hydrogen, you have a single proton. In nucleus, in the case of helium 4 you have 2 protons and 2 neutrons and so on. For a while, but gradually you realize that the number of neutrons becomes larger and this is needed, otherwise you would not have stable nucleoli, because you have two strong Coulomb repulsion between the protons to make it unstable here. As it is the radioactive decay of an elements or even if a single neutron happens, because the weak force takes over here.

This force is responsible for weak decay and today we understand the behavior of these forces at individual levels. This and this two are very large extend, this two are rather smaller extend although we understand principles on which it works. The gravitational force also is independently understood at the classical level, but not quite at the level of quantum field theory. So, this is still an unsolved problem. So, the statements you would have heard about the unification of all these forces that program is not complete.

These two forces have been unified in a very specific sense of the word, but not yet fully. So, unify with the strong force and certainly not yet the gravitational force at all. Now, one could ask is there such a unified theory at all, does it exist, do you know knowledge of it. We think it will exist, because the principles on which these forces arise, the fundamental principles appear to be common, they appear to somewhere. It give common principles which tell you, how these various forces arise and there is also good evidence to feel to believe that if you go to shorten short a distances, there we come a stage where this forces get unified in a very specific sense.

For instance, I said in, I am quite mentioned this, we found the ratio of the electrostatic to the gravitational force. What about these two forces? On the same scale, what would these looks like?

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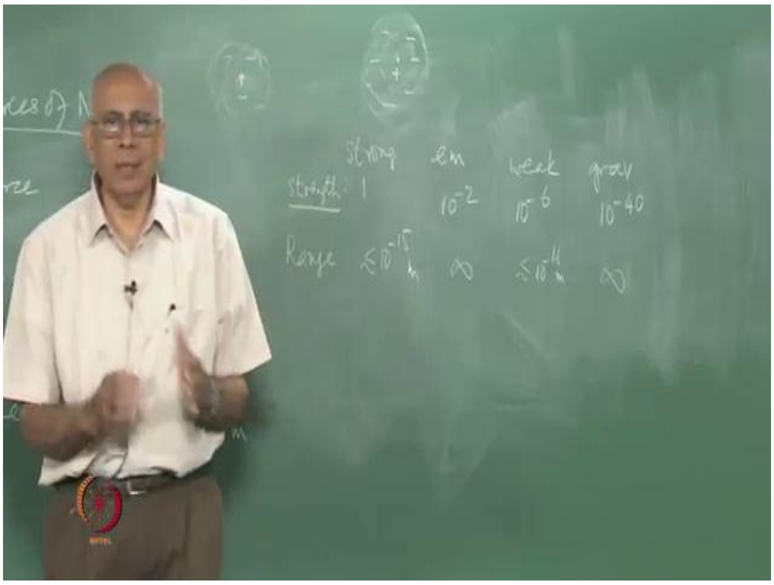

So, let say that the strong force, if I represented it is magnitude by 1 and that is for the strong force, then relative to this 1 for the strong force, the relative strength of the electromagnetic force under appropriate conditions of comparison is of the order of 10 to the minus 2. On the same scale, the weak force has a strength of about 10 to the minus 6 and the gravitational force on the same scale has a strength of about 10 to the minus 40.

This observed is very rough estimates, we sort of explains the terminology also. Why this is called weak compared to the strong and why the electromagnetic forces rather strong compared to the weak. But, as you go to sort a distances, I have already mentioned that ((Refer Time: 24:58)) the weak force has a range of about 6 to 10 to the minus 16 meters that is 0.1 for me femtometer There was a strong force has a range which is of the order of few approximately from meters here.

If you go to smaller distances like 10 to the minus 18 meters, then it turns out that the strength of the weak force and the strength of the electromagnetic force become comparable to each other. So, this suggest that as you go to higher energies, which means you go to smaller distances or you go to earlier part you know the history of the universe, they would have been a stage when these forces were unified. It has a same force in some sense and split into two distinct forces that we see today and that is indeed too, this is called electromagnetic unification.

And it happens at an energy scale which is of the order of a 100 times the proton mass. As you know, Einstein's special theory of relativity and we will take about that, he suggested to us, he informed us that mass and energy are equivalent to each other. So, we could measure energy in mass units and mass in energy units in a very specific precise sense and that scale, if I go to energies which are comparable to 100 times the s mass of the proton, then the weak and electromagnetic forces tend to get unified to each other, so they were unified at some stage in the past.

So, so much for the relative tense of these forces, you should also write down here the ranges of these forces. The strong force, as I said is at the order of less than or of the order of 10 to the minus 15 meters. The electromagnetic force is infinite range force, because the 1 over r square force goes on forever for all values if r goes to infinity. The gravitational force is infinite and the weak forces of the order of 10 to the minus 16 meters.

One second I emphasize, the short range is what made it impossible for these forces to be detected, until you are able to probe what is happening inside an atom. So, you need to go at least to those energies, ((Refer Time: 27:13)) nuclear energy is much greater than that in order to probe these forces here. But, today we know that these are the fundamental forces of nature and that all physical phenomena as far as we know can be now attributed to the operation of just these four fundamental forces of nature.

So, in that senses certain unification has been achieved. The first unification was already achieved earlier by Newton himself. When you wrote down the law of gravitation, he made a very important observation which is that the same gravitational force which cause the apple to fall. The apple to fall from the tree also held the movements of it is orbits around the earth. So, we actually unified terrestrial gravitation with celestial or astronomical gravitation, so that sense it is our assurance that the gravitational force is actually universal force operates everywhere.

The next unification came when Maxwell unified electricity and magnetism and incidentally also shown that light is a form of electromagnetic radiation. So, there was a unification of electricity, magnetism and optics and light and that is a second great unification. The third one came much later in the later half of the 20th century, when the weak force and the electromagnetic force were unified into one entity called the electro weak force here and the question is on for unification of the strong force with these three, with these other two forces in which case you would have what is called the grand unification.

And finally, that is still leaves probes in the problem of gravitation here. Now, the very difference in scales here is what makes the problem of unification extremely difficult, because you have phenomena appearing and different scales are together separated by large number of orders of magnitude and this makes it very non trivial in order to bring these things in to the same umbrella under the same umbrella.

So, that is one reason why this unification program is a very non trivial program in a difficult one and there is no guarantee that such a theory exist as of now. Although, theoretically you would like to derive that exist for esthetic reasons for various kinds. It would also be very unified picture, it would learn threatens to many of the theoretical conjunctions that have been made in nature so far.

So, so much for the fundamental forces of nature, then I take home lesson is that the forces that we see in daily life or the gravitational force and various manifestation of the electromagnetic force. All terrestrial phenomena other than those dictated; obviously, by gravity in various case mechanical, behavior and so on. All the other forces, all the chemistry and so on are all dictated by the electromagnetic force in it is very large number of different manifestations.