Lecture 1: The Law of Gravitation: an example of physical law

[BBC TV Film Leader]

Credits: Cornell University U.S.A., The Character of Physical Law, Professor Richard Feynman gives the Messenger Lectures

Introduction by Provost Dale R. Corson

Ladies and gentlemen, it's my privilege to introduce the Messenger Lecturer, Professor Richard P. Feynman of the California Institute of Technology.

Professor Feynman is a distinguished theoretical physicist, and he's done much to bring order out of the confusion which has marked much of the spectacular development in physics during the post-war period. Among his honors and awards I will mention only the Albert Einstein award, in 1954. This is an award which is made every third year, and which includes a gold medal and a substantial sum of money.

Professor Feynman did his undergraduate work at MIT and his graduate work at Princeton. He worked on the Manhattan Project at Princeton and later at Los Alamos. He was appointed an assistant professor here at Cornell in 1944, although he did not assume residence until the end of the war.

I thought it might be interesting to see what was said about him when he was appointed at Cornell, so I searched the minutes of our board of trustees—and there's absolutely no record of his appointment. There are, however, some twenty references to leaves of absence, salary, and promotions. One reference interested me especially: on July 31, 1945 the chairman of the physics department wrote the dean of the Arts College, stating that "Dr. Feynman is an outstanding teacher and investigator, the equal of whom develops infrequently." The chairman suggested that an annual salary of $3,000 was a bit too low for a distinguished faculty member, and recommended that Professor Feynman's salary be increased $900. The dean, in an act of unusual generosity and with complete disregard for the solvency of the university, crossed out the $900 and made it an even $1,000. You can see that we thought highly of Professor Feynman, even then.

Feynman took up residence here at the end of 1945 and spent five highly productive years on our faculty. He left Cornell in 1950 and went to Caltech, where he has been ever since.

Before I let him talk, I want to tell you just a little bit more about him. Three or four years ago he started teaching a beginning physics course at Caltech, and the result has added a new dimension to his fame. His lectures are now published in two volumes, and they represent a refreshing approach to the subject. In the preface of the published lectures, there's a picture of Feynman performing happily on the bongo drums. My

Caltech friends tell me that he sometimes drops in on the Los Angeles nightspots and takes over the work of the drummer, but Professor Feynman tells me that that's not so. Another of his specialties is safecracking. One legend says that he once opened a locked safe in a secret establishment, removed a secret document, and left a note saying GUESS WHO. I could tell you about the time that he learned Spanish before he went to give a series of lectures in Brazil, but I won't.

This gives you enough background, I think, so let me say that I'm delighted to welcome Professor Feynman back to Cornell; his general topic is the nature of physical law, and his topic for tonight is The Law of Gravitation— an example of physical law. Professor Feynman.

The Law of Gravitation: an example of physical law

It's odd, but in the infrequent occasions when I've been called upon in a formal place to play the bongo drums, the introducer never seems to find it necessary to mention that I also do theoretical physics. I believe that's probably that we respect the arts more than the sciences. The artists of the Renaissance said that man's main concern should be for man. And yet there are some other things of interest in the world: even the artist appreciates sunsets, and the ocean waves, and the march of the stars across the heavens. And there is some reason, then, to talk of other things sometimes.

As we look into these things, we get an aesthetic pleasure from them directly on observation, but there's also a rhythm and a pattern between the phenomena of nature, which isn't apparent to the eye, but only to the eye of analysis. And it's these rhythms and patterns which we call physical laws.

What I want to talk about in this series of lectures is the general characteristics of these physical laws. That's even another level, if you will, of higher generality over the laws themselves. And it's really (all I am talking about is) nature as seen as a result of detailed analysis—but only the most overall general qualities of nature is what I mainly wish to speak about.

Now, such a topic has a tendency to become too philosophical, because it becomes so general—that a person talks in such generalities that everybody can understand him—and it's considered to be some deep philosophy, if you will. However, I would like to be rather more special, and I would like to be understood in an honest way rather than in a vague way to some extent; and so, if you don't mind, I am going to try to give—instead of only generalities in this first lecture—an example of physical law, so that you have at least one example of the things about which I am speaking generally. In this way, I can use this example again and again to give an instance to make a reality out of something which would otherwise be too abstract.

Now, I've chosen for my special example of physical law to tell you about the theory of gravitation, or the phenomena of gravity. Why I chose gravity, I don't know—whatever I chose, you would have asked the same question. Actually, it was one of the first great laws to be discovered, and it has an interesting history. You might say, "Yes, but then it's old hat—I would like to hear something about more modern science." More recent perhaps, but not more modern: modern science is exactly in the same tradition as the discoveries of the law of gravitation. It is only more recent discoveries that we would be talking about. And so I do not feel at all bad about telling you of the law of gravitation, because I am—in describing its history and the methods, the character of its discovery and its quality—talking about modern science, completely modern.

This law has been called the greatest generalization achieved by the human mind. And you can get already, from my introduction, that I'm interested not so much in the human mind as in the marvel of nature, who can obey such an elegant and simple law as this law of gravitation. So our main concentration will not be on how clever we are to have found it all out, but on how clever she is to pay attention to it!

Now, what is this law of gravitation that we're going to talk about? The law is that two bodies—or bodies—exert a force upon each other which is inversely as the square of the distance between them, and varies directly as the product of their masses. Mathematically, we can write that great law down in a formula: some kind of a constant, times the product of the two masses, divided by the square of the distance. Now, if I add the remark that a body reacts to a force by accelerating, or by changing its velocity every second to an extent inversely as its mass—it changes velocity more if the mass is lower, and so on, inversely as the mass—then I have said everything about the law of gravitation that needs to be said: everything else is a consequence, a mathematical consequence of those two things that I said. That's a remarkable enough phenomenon in itself, that the next lecture will consider this in more detail.

Now, I know you're not all—I know some of you are, but you're not all—mathematicians, so you cannot all immediately see all of the consequences of these two remarks. And so what I would like to do in this lecture is to briefly tell you the story of the discovery, tell you what some of the consequences are, what the effect this discovery had on the history of science, what kinds of mystery such a law entails, something about the refinements made by Einstein, and possibly the relation to other laws of physics.

The history of the thing, briefly, is this: that the ancients first observed the way the planets seemed to move about in the sky, and concluded that they all—along with the earth—went around the sun. This discovery was later made independently by Copernicus, after they had forgotten—people had forgotten—that it had already been made.

Now, the next question that came up to study was: exactly how do they go around the sun—that is, exactly what kind of motion: do they go with the sun at the center of a circle, or do they go in some other kind of a curve? How fast do they move?—and so on. And this discovery took longer to make. The times after Copernicus were times in which there were great debates—about whether the planets in fact went around the sun along with the earth, or whether the earth was at the center of the universe, and so on; and there were considerable arguments about this—when a man named Tycho Brahe got an idea of a way of answering the question: he thought that it might perhaps be a good idea to look very, very carefully, and to record where the planets actually appear in the sky—and then the alternative theories might be distinguished from one another. This is the key of modern science, and is the beginning of the true understanding of nature: this idea to look at the thing, to record the details, and to hope that in the information thus obtained may lie a clue to one or another of a possible theoretical interpretation. So Tycho—who was a rich man and owned, I believe, an island near Copenhagen—outfitted his island with great brass circles and special observing positions (situating chairs that you could look through a little hole) and recorded night after night the position of the planets.

It's only through such hard work that we can find out anything. When all these data were collected they came into the hands of Kepler, who then tried to analyze what kinds of motions the planets made around the sun. He did this by a method of trial and error. At one stage he thought he had it: he figured out that they went around the sun in circles, with the sun off center, and noticed that one planet—I think it was Mars, but I don't know—was eight minutes of arc off. He decided that this was too big for Tycho Brahe to have made an error, and that this was not the right answer.

So because of the precision of experiments, he was able to proceed and go onto another trial and found, in fact, ultimately this—three things: first, that the planets went in ellipses around the sun, with the sun at a focus. An ellipse is a curve all artists know about, because it's a foreshortened circle; children know about it because somebody told them that if you take a string and tie it to two tacks and put a pencil in there, it'll make an ellipse. These two tacks are the foci, and if the sun is here, the shape of the orbit of a planet around the sun is one of these curves.

The next question is, in going around the ellipse, how does it go: does it go faster when it's near the sun, and slower when it's further from the sun?—and so on. If we take away the other focus, we have the sun, then, and the planet going around.

Kepler found the answer to this, too. He found this: that if you put the position of the planet down at two times separated by some definite time—let's say three weeks—and then at another place in the orbit, put the positions of the planets—again separated by three weeks—and draw lines from the sun to the planet (technically called radius vectors, but anyway lines from the sun to the planet)—then the area that's enclosed in the orbit of the planet and the two lines that are separated by the planet's position three weeks apart is the same no matter what part of the orbit the thing is on. So that it has to go faster when it's closer—in order to get the same area as it goes slower when it's further away—and in this precise manner. Some several years later, he found the third rule: that had not to do exactly with the motion of a single planet around the sun, but related the various planets to each other. It said that the time that it took the planet to go all the way around was related to the size of the orbit—that the time went as the square root of the cube of the size of the orbit—and the size of the orbit is the diameter all the way across the biggest distance on the ellipse.

So he has these three laws, which I'll summarize by saying: it's an ellipse; that equal areas are swept in equal times; and that the time to go around varies as the three-half power of the size—the square root of a cube of the size. So that's three laws of Kepler, which is a very complete description of the motion of the planets around the sun.

The next question was, what makes them go around? Or how can we understand this in more detail? Or is there anything else to say? In the meantime, Galileo was investigating the laws of motion.

Incidentally, at the time of Kepler, the problem of what drove the planets around the sun was answered by some people by saying that there were angels behind here beating their wings and pushing the planet along around the orbit.

As we'll see, that answer is not very far from the truth: the only difference is that the angels sit in a different direction, and their wings go this way. But the point that the angels sit in a different direction is the one that I must now come to. Galileo—in studying the laws of motion, and doing a number of experiments such as seeing how balls rolled down incline planes, and how pendulums swung, and so on—discovered an idealization, a great principle called the principle of inertia, which is this: that if a thing has nothing acting on it—if an object has nothing acting on it—and it's going along at a certain velocity in a straight line, it will go at the same velocity at exactly the same straight line forever. Unbelievable though that may sound to anybody who has tried to make a ball roll forever, the idealization is correct: that if there were no influences acting (such as friction on the floor, and so on), the thing would go at a uniform speed forever.

The next point was made by Newton, who discussed the next question, which is: when it doesn't go in a straight line, then what? He answered this way: that a force is needed to change the velocity in any manner. For instance, if you're pushing it in a direction that it moves, it will speed up; if you find that it changes direction, then the force must have been sideways. And that the force can be measured by the product of two effects: first, how much does the velocity change in a small interval of time? How fast is the velocity changing? How much is it accelerating in this direction, or how much is the velocity changing when it changes direction? That's called the acceleration. When that's multiplied by a coefficient called the mass of an object (or its inertia coefficient), then that together is the force.

For instance, if one has a stone on the end of a string, and swings it in a circle over one's head, then one finds that one has to pull; the reason is, that the speed is not changing as it goes around the circle, but it's changing its direction so there must be perpetually an in-pulling force, and this is proportional to the mass. So that if we were to take two different objects—first swing one, and then swing another one at the same speed around the head, and measure the force in the second one—that second one, the new force, is bigger than the other force in the proportion that the masses are different. This is a way of measuring the masses, by how hard it is to change the speed. Now, then, Newton saw from this that—for instance, to take a simple example—if a planet is going in a circle around the sun, no force is needed to make it go sideways, tangentially: if there were no force at all on it, it would just keep coasting this way. But actually, the planet doesn't keep coasting this way, but finds itself later not out here, where it would go if there were no force at all, but further down toward the sun. In other words, its velocity, its motion, has been deflected toward the sun. So what the angels have to do is to beat their wings in toward the sun all the time; that the motion to keep it going in a straight line has no known reason.

The reason why things coast forever has never been found out—the law of inertia has no known origin. So the angels don't exist, but the continuation of the motion does. But in order to obtain the falling operation we do need a force. So it became apparent that the force was toward the sun. As a matter of fact, Newton was able to demonstrate that the statement that equal areas are swept in equal times was a direct consequence of the simple idea that all of the changes in velocity are directed exactly to the sun, even in the elliptical case. Maybe I'll have time next time to show you how that works in detail. So from this law, he would confirm the idea that the force is toward the sun—and from knowing how the periods of the different planets vary with the distance away from the sun, it's possible to determine how that force must weaken at different distances—and he was able to determine that the force must vary inversely as the square of the distance. Now, so far he hasn't said anything new, because he only said the two things which Kepler said, in different language: one is exactly equivalent to the statement that the force is toward the sun; the other is exactly equivalent to the statement that the law is inversely as a square of the distance.

But: people had seen in telescopes that Jupiter's satellites are going around Jupiter; it looked like a little solar system—so the satellites were attracted to Jupiter. And the moon is attracted to the earth, and goes around the earth—it's attracted in the same way. So it looks like everything's attracted to everything else.

The next statement was to generalize this—to say that every object attracts every other object. If so, the earth must be pulling on the moon, just as the sun pulls on the planets. But it's known that the earth pulls on things, because you're all sitting tightly in your seats in spite of your desires to float out of the hall at this time. The pull for objects on the earth was well known in the phenomenon of gravitation; it was Newton's idea, then, that maybe the gravitation which held the moon in its orbit was the same gravitation that pulled objects toward the earth.

Now, it is easy to figure out how far the moon falls in one second, because if it went in a straight line—you know the size of the orbit; you know it takes a month to go around—and if you figure out how far it goes in one second, you can figure out how far the circle of the moon's orbit has fallen below the straight line that it would have been in if it didn't go the way it does go. This distance is 1/20th of an inch.

Now, the moon is 60 times as far away from the earth's center than we are: we're 4,000 miles away from the center, and the moon is 240,000 miles away from the center. So if the law of inverse square is right, an object at the earth's surface should fall in one second by 1/20th of an inch times 3600 (being the square of 60, because the force has been weakened by 60 x 60 for the inverse square law, in getting out there to the moon). If you multiply a 20th of an inch by 3600, you get about 16 feet—and lo, it is known already from Galileo's measurements that things fell in one second on the earth's surface by 16 feet. So this meant, you see, that he was on the right track—there was no going back now! Because a new fact that was completely independent previously—the period of the moon's orbit and its distance from the earth—was connected to another fact—how long it takes something to fall in one second. This was a dramatic test that everything's all right.

Further, he had a lot of other predictions. He was able to calculate what the shape of the orbit should be with the law of the inverse square, and found, indeed, that it was an ellipse. So he got three for two, as it were.

In addition, a number of new phenomena now had obvious explanations. One was the tides: the tides were due to the pull of the moon on the earth. This had sometimes been thought of before, with the difficulty that if it was the pull of the moon on the earth—the earth being here and the water is being pulled up to the moon—then there would only be one tide a day where that bump of water is under the moon. But actually, you know, there are tides every 12 hours, roughly; that's two tides a day.

There was another school of thought that had a different conclusion: their theory was that it was the earth that was pulled by the moon, away from the water! Newton was the first one to realize what actually was going on: that the force of the moon on the earth, and on the water, is the same at the same distance—and that the water here is closer to the moon, and the water here is further from the moon than the earth—than the rigid earth—so that the water is pulled more toward the moon here, and here is less toward the moon than the earth, so there's a combination of those two pictures that makes a double tide.

Actually, the earth does the same trick as the moon: it goes around a circle, really. I mean, the force of the moon on the earth is balanced, but by what? By the fact that—just like the moon goes in a circle to balance the earth's force—the earth is also going in a circle. Actually, the center of that circle is somewhere inside the earth; it's also going in a circle to balance the moon. So the two of them go around a common center here—and, if you wish, this water is thrown off by centrifugal force more than the earth is, and this water's attracted more than this average of the earth. At any rate, the tides were then explained, and the fact that there were two a day.

A lot of other things became quite clear: why the earth is round (because everything gets pulled in) and why it isn't exactly round (because it's spinning, so the outside gets thrown out a little bit and it balances), and why the sun and moon are round, and so on.
Now, as science developed and measurements were made ever more accurately, the tests of Newton's law became much more stringent. The first careful tests involved the moons of Jupiter: by careful observations of the way they went around over a long period of time, one could be very careful to check that everything was according to Hoyle... —Newton; it turned out not to be the case. The moons of Jupiter appeared to get sometimes eight minutes ahead of time, and sometimes eight minutes behind schedule, where "schedule" is the calculated values according to Newton's laws—it was noticed that they were ahead of schedule when they were close, when Jupiter was close to the earth, and behind schedule when it was far away—a rather odd circumstance.
Ole Romer [in 1676], having confidence in the law of gravitation, came to an interesting conclusion: that it takes light some time to travel from the moons to the earth, and that what we're looking at when we see the moons is not how they are now, but how they were the time ago that it took the light to get here. Now, when Jupiter is near us, it takes less time for the light to come, and when Jupiter is further, it takes longer time. So he had to correct the observations for the differences in time. And by the fact that they were this too much early or that much too late, was able to determine the velocity of light.
This was the first demonstration that light is not an instantaneously propagating material. I bring this particular matter to your attention because it illustrates something: when a law is right, it can be used to find another one. By having confidence in this law, if something is the matter it suggests, perhaps, some other phenomenon. If we had not known the law of gravitation, we would have taken much longer to find the speed of light, because we would not have known what to expect of Jupiter's satellites. This process has developed into an avalanche of discoveries: each new discovery permits the tools for much more discovery, and this is the beginning of that avalanche which has gone on, now, for 400 years in a continuous process—and we're still avalanching along at high speed at this time.
Another problem came up: the planets shouldn't really go in ellipses, because according to Newton's laws, they're not attracted only by the sun, but also they pull on each other—a little bit, only a little bit. But a little bit is something, and will alter the motion a little bit. So Jupiter, Saturn, and Uranus were big planets that were known, and calculations were made as to how slightly different than the perfect ellipses of Kepler the planets ought to be going—Jupiter, Saturn, and Uranus—by the pull of one on each other. When they were finished (the calculations, I mean, and the observations), it was noticed that Jupiter and Saturn went according to the calculations, but that Uranus was doing something funny—another opportunity for Newton's laws to be found wanting.

But, courage: two men—both who made these calculations, Adams and Le Verrier, independently and at almost exactly the same time—proposed that the motions of Uranus were due to an unseen-as-yet new planet. They wrote letters to their respective observatories telling them to look: turn your telescope, and look there, and you'll find a planet. How absurd!—said one of the observatories—that some guy sitting with pieces of paper and pencils can tell us where we look to find some new planet! The other observatory was more—well, less—well, the administration was different—and they found Neptune.

More recently, in the beginning of the 20th century, it became apparent that the motion of the planet Mercury was not exactly right, and this caused a lot of trouble and had no explanation, until a modification of Newton's—this did show, ultimately, that Newton's laws were slightly off, and that they had to be modified. I will not discuss the modification in detail; it was made by Einstein.

Now the question is, how far does this law extend? Does it extent outside the solar system? And so I show, on the first slide, evidence that the law of gravitation is on a wider scale than just the solar system. Here is a series of three pictures of a so—called double star. There's a third star, fortunately, in the picture, so you can see that they're really turning around [each other], and that nobody just simply turned the frames of the pictures around, which is easy to do on astronomical pictures. But the stars are actually going around [each other]. By watching these things and plotting the orbit, you see the orbit that they make on the next slide. It's evident that they're attracting each other, and that they're going around in an ellipse according to the way expected: these are a succession of pictures going for all these different periods of time, I think—yes, it goes around this way—and they didn't see it well when it was too close, and here it is in 1905—my slide is very old; It's gone around maybe once more since.

You'll be happy, except when you notice, if you haven't noticed already, that the center is not a focus of the ellipse, but it's quite a bit off. So something's the matter with the law? No: god hasn't presented us with this orbit face on; it's tilted at a funny angle. If you take an ellipse and mark its focus, and then hold the paper at an odd angle and look at it in projection, the focus doesn't have to be at the focus of the projected image. So it's because its orbit is tilted in space that it looks that way. It looks like it's not the right pattern, but it's all right, and you can figure everything out satisfactorily for that.

How about a bigger distance? There's forces between the stars: does it go any further than these distances, which are not more than two or three times the solar system's diameter?

Here's something, in the next slide, that's 100,000 times as big as a solar system in diameter. This is a large number of stars, a tremendous number of stars: this white spot is not a solid white spot; it's just because of the failure of our instruments to resolve it, but these are very, very tiny dots just like the other stars, well separated from one another, not hitting each other, each one falling through and back and forth through this great globular cluster.

It's one of the most beautiful things in the sky—as good as sea waves and sunsets. And the distribution of this material—it's perfectly clear that the thing that holds this together is the gravitational attraction of the stars for each other. The distribution of the material—in the sense of how the stars peter out as you go out in distance—permits one to find out, roughly, what the law is of force between the stars—and, of course, it comes out right; it is, roughly, the inverse square. (The accuracy of these calculations and measurements is not anywhere near as careful as in the solar system.)

Onward! Does gravity extend still further? This is a little pinpoint inside of a big galaxy, and the next slide shows a typical galaxy: it's clear that this thing, again, is held together somehow, and the only candidate that's reasonable is gravitation. But when we get to this size, we haven't any way any longer to check the inverse square law, but there seems to be no doubt that these great agglomerations of stars—these galaxies, which are 50,000 to 100,000 light years across (the solar system is, well, from the earth to the sun is only eight light minutes); this is 100,000 light years—that gravity is extending even over these distances.

In the next slide is evidence that it extends even further: here is what is called a cluster of galaxies. There's a galaxy here and here and here; there are galaxies here. They're all in one lump of galaxies—analogous to the cluster of stars, but this time what's clustered are those big babies that I showed you in this previous slide. Now, this is as far as about one tenth—well, 100th maybe—of the size of the universe, and as far as we have any direct evidence that gravitational forces extend. So the earth's gravitation, if we take the view, has no edge (as you may read in the newspapers, when the planet gets "outside the field of gravity"); it keeps on going, ever weaker and weaker, inversely as the square of the distance, dividing by four each time you're twice as far away, until it mingles with the strong fields and gets lost in the confusion of the strong fields of other stars—but all together, with the stars in its neighborhood, pulls the other stars to form the galaxy, and, all together, they pull on other galaxies to make a pattern. or cluster, of galaxies.

So the earth's gravitational field never ends, but peters out very slowly in a precise and careful law, probably to the edges of the universe. The law of gravitation is different than many of the other [laws]—well, it is very important in the economy, or in the machinery, of the universe; there are many places where gravity has its practical applications as far as the universe is concerned. But atypically among all the other laws of physics, gravitation has relatively few practical applications [for us]. I mean, the new knowledge of the law has a lot of applications—it keeps people in their seats and so on—but the knowledge of the law has few practical applications, relatively speaking, compared to the other laws.

This is one case in which I picked an atypical example. (It is impossible, by the way, by picking one example of anything, to avoid picking one which is atypical in some sense—that's the wonder of the world.) The only applications I could think of were, first, in some geophysical prospecting, in predicting the tides; nowadays, more modernly, in working out the motions of the satellites and the planet probes, and so on, that we send up—and also, modernly, to calculate the predictions of the planet's position, which have great utility for astrologers to publish their predictions and horoscopes in the magazines. That's the strange world we live in, that all the advances and understanding are used only to continue the nonsense which has existed for 2,000 years.

Now, that shows that gravitation extends to the great distances, but Newton said that everything attracted everything else. Do I attract you? Excuse me, I mean, do I attract you? I was going to say, excuse me, do I attract you physically? I didn't mean that. What I mean is, is it really true that two things attract each other directly? Can we make a direct test, and not just wait for the planets and look at the planets to see if they attract each other? This experiment—the direct test—was made by Cavendish on equipment which you see indicated on the next slide (if I got my slides right).

Well, I made a mistake: I was talking about the importance of gravitation, and I was overwhelmed by my clever remark about astrologers, and forgot to mention the important places where gravitation does have some real effect in the behavior of the universe. One of the interesting ones is the formation of new stars. In this picture, which is a gaseous nebula inside our own galaxy (and is not a lot of stars, but is gas), there are places where the gas has been compressed or attracted to itself here. It starts, perhaps, by some kind of shock waves to get collected, but the remainder of the phenomenon is gravitation pulls the cloud of gas closer and closer together. So big mobs of gas and dust collect and form balls, which, as they fall still further, the heat generated by the falling, lights them up and they become stars—and we have in the next slide some evidence of the creation of new stars. It is, unfortunately, harder to see than I thought it was when I looked at it before, but this is not exactly the same as this. This bump here is further out than here and that this also has a new dot here. There are- I have found better examples but were unable to produce a slide.

There is one example of a star patch—light—that grew in a place in 200 days so that —when—there—is— in the same kind of a condition of a gas cloud, when the gas collects too much together by gravitation, stars are born, and this is the beginning of new stars. The stars belch out dirt and gasses when they explode, sometimes, and the dirt and gasses then collect back again and make new stars—it sounds like perpetual motion.

I now turn to the subject I meant to introduce, which was the experiments on the small scale, to see whether things really attract each other. And I hope, now, that the next slide does indicate—this is the second try, Yeah! —Cavendish's experiment. The idea was to hang, by a very, very fine quartz fiber, a rod with two balls—and then put two large lead balls in the positions indicated here, next to it on the side. Then, because of the attraction of the balls, there would be a slight twist to the fiber. It had to be done so delicately because the gravitational force between ordinary things is very, very tiny indeed. And there it was. It was possible, then, to measure the force between these two balls. Cavendish called his experiment "weighing the earth".

We're pedantic and careful today; we wouldn't let our students say that: we would have to say they're measuring the mass of the earth. But the reason he said that is the following: by a direct experiment he was able to measure the force, the two masses, and the distance, and thus determine the gravitational constant. You say, yes, but we have the same situation on the earth: we know what the pull is, and we know what the mass of the object pulled is, and we know how far away we are—but we don't know either the mass of the earth or the constant, but only the combination. So by measuring the constant, and knowing the facts about the pull of the earth, the mass of the earth could be determined.

So, indirectly, this experiment was the first determination of how heavy, or how massive, is the ball on which we stand. Like it's a kind of amazing achievement to find that out, and I think that's why Cavendish named his experiment that way, instead of determining the constant in the gravitation equation.

"Weighing the earth."

He, incidentally, was weighing the sun and everything else at the same time, because the pull of the sun is known in the same manner. Now, one other test of the law of gravitation is very interesting, and that is the question as to whether the pull is exactly proportional to the mass. If the pull is exactly proportional to the mass, and the reaction to forces—the motions induced by forces, the changes in velocity—are inversely proportional to the mass, that means that two objects of different mass will change their velocity in the same manner in a gravitational field. Or: two different things, no matter what their mass, in a vacuum will fall the same way toward the earth. That's Galileo's old experiment from the leaning tower.

I took my young son of two and a half to the Leaning Tower of Pisa, and now every time a guest comes he says, "Leaning Towah!" Anyhow, it means, for example, that in a satellite (I mean a man—made satellite), an object inside will go around the earth in the same kind of an orbit as the satellite on the outside, and thus float in the middle, apparently.

This fact—that the force is exactly proportional to the mass and that the reactions are inversely to proportional mass—has this very interesting consequence. The question is, how accurate is it? It has been measured by an experiment by a man named Eotvos in 1909, and very much more recently and more accurately by Dicke, and it was known that one part in ten thousand million the mass is exactly proportional—I mean, the forces are exactly proportional to the mass. How it's possible to measure with that accuracy, I wish I had the time to explain, but I'm afraid I cannot—it's remarkably clever.

I'll give a hint, however; I'll give one hint. Suppose that you wanted to measure whether it's true for the pull of the sun. You know the sun is pulling us all; it pulls the earth, too. But suppose you wanted to know whether, if you add a piece of lead here, and a piece of copper here (or polyethylene and lead—it was first done with sandalwood; now it's done with polyethylene)—whether the pull is exactly proportional to the inertia. The earth is going around the sun, so these things are thrown out by inertia. They're thrown out to the extent that these two objects have inertia. But they're attracted to the sun to the extent that they have mass in the attraction law. So if they're attracted to the sun in a different proportion than they're thrown out by inertia, one will be pulled toward the sun and the other away. And so, hanging on another one of those Cavendish quartz fibers, the thing will twist toward the sun. It doesn't twist at this accuracy, so we know that the sun's attraction for these two objects is exactly proportional to the centrifugal effect, which is inertia. So the force of attraction on an object is exactly proportional to its coefficient of inertia—in other words, its mass.

I should say something about the relation of gravitation to other forces—to other parts of nature, other phenomena in nature. I'll have more to say of a general quality later, but there is one thing that's particularly interesting, and that is that the inverse square law appears again: it appears in the electrical laws, for instance—that electricity also exerts forces inversely as the square of the distance, this time between charges.

And, one thinks perhaps that inverse square of the distance has some deep significance; maybe gravity and electricity are different aspects of the same thing. No one has ever succeeded in making gravity and electricity different aspects of the same thing; today, our theories of physics—the laws of physics—are a multitude of different parts and pieces that don't fit together very well.

We don't understand the one exactly in terms of the other. We don't have one structure from which all is deduced; we have several pieces that don't quite fit exactly, yet. That's the reason why, in these lectures, instead of having the ability to tell you what the law of physics is, I have to talk about the things that are common to the various laws, because we don't know—we don't understand the connection between them—but what's very strange is, that there are certain things that are the same in both.

But now let's look again at the law of electricity: the law goes inversely is the square of the distance, but the thing that is remarkable is the tremendous difference in the strength of the electrical and gravitational laws. People who want to make electricity and gravitation out of the same thing will find that electricity is so much more powerful than gravity, that it's hard to believe they could both have the same origin.

Now, how can I say one thing is more powerful than another? It depends on upon how much charge you have, and how much mass you have. You can't talk about how strong gravity is by saying, "I take a lump of such and such a size," because you chose the size. If we try to get something that nature produces—her own pure number that has nothing to do with inches or years or anything to do with our own dimensions—we can do it this way: if we take the fundamental particles, such as an electron—any different ones will give different numbers, but to get an idea of the number, take electrons. Two electrons, each a fundamental particle; it's an object. It's not something I can—I don't have to tell you what units I measure in. It's two particles that are fundamental particles; they repel each other inversely as a square of the distance due to electricity, and they attract each other inversely as a square of the distance due to gravitation.

Question: what is the ratio of the gravitational force to the electrical force? That is illustrated on the next slide. The ratio of the gravitational attraction to the electrical repulsion is given by a number with 42 digits, and goes off here: all this is written very carefully out, so that's 42 digits. Now, therein lies a very deep mystery: where could such a tremendous number come from? That means if you ever had a theory from which both of these things are to come, how could they come in such disproportion? From what equation has a solution which has for one, two kinds of forces, an attraction and a repulsion with that fantastic ratio? People have looked for such a large ratio in other places. They're looking for a large number. They hope, for example, that there's another large number. And if you want a large number why not take the diameter of the universe to the diameter of a proton. Amazingly enough, it also is a number with 42 digits.

So an interesting proposal is made that this ratio depends—is the same as—the ratio of the size of the universe to the diameter of a proton. But the universe is expanding with time, and that would mean the gravitational constant is changing with time. Although that's a possibility, there's no evidence to indicate that it's in fact true, and there are several difficulties—I mean, partial indications, that it doesn't, that the gravitational constant has not changed in that way.

So this tremendous number remains a mystery. I must say, to finish about the theory of gravitation, two more things. One is that Einstein had to modify the laws of gravitation in accordance with his principles of relativity. The first was—one of the principles was—that if x cannot occur instantaneously, while Newton's theory said that the force was instantaneous, he has to modify Newton's laws. They have very small effects, these modifications.

One of them is, all masses fall. Light has energy, and energy is equivalent to mass, so light should fall. That should mean that light going near the sun is deflected; it is. Also, the force of gravitation is slightly modified in his theory, so that the law is slightly changed—very, very slightly—and it is just the right amount to account for the slight discrepancy that was found in the movement of Mercury.

Finally, with connection to the laws of physics on a small scale: we have found that the behavior of matter on a small scale obeys laws so different, very different, than things on a large scale. And so the question is, how does gravity look on a small scale?

What is what is called a quantum theory of gravity? There is no quantum theory of gravity today: people have not succeeded completely in making a theory which is consistent with the uncertainty principles and the quantum mechanical principles.
I'll discuss these principles in another lecture.
Now, finally, you will say to me, "Yes, you told us what happens, but what is this gravity? Where does it come from and what is it? Do you mean to tell me that the planet looks at the sun, sees how far it is, takes the inverse of the square of the distance, and then decides to move in accordance with that law?" In other words, although I've stated a mathematical law, I have given you no clue as to the mechanism. I will discuss the possibility of doing this in the next lecture, which is the relation of mathematics to physics.
But finally, in this lecture I would like to remark, just at the end here, to emphasize some characteristics that gravity has in common with the other laws that we have mentioned as we passed along.
The first is that it's mathematical in its expression—the others are that way too; we'll discuss that next time.
Second, it's not exact—Einstein had to modify it. We know it isn't quite right yet, because they have to put the quantum theory in—that's the same with all our other laws; they're not exact.
There's always an edge of mystery; there's always a place that we have some fiddling around to do yet. That, of course, is not a property—probably not a property, it may or may not be a property—of nature, but it certainly is common with all the laws as we know them today—it may be only a lack of knowledge.
But the most impressive fact is that gravity is simple: it is simple to state the principle completely, and have not left any vagueness for anybody to change the ideas about. It's simple, and therefore it's beautiful. It's simple in its pattern. I don't mean it's simple in its action; the motions of the various planets and the perturbations of one on another can be quite complicated to work out, or to follow how all those stars in the globular cluster move, is quite beyond our ability. It's complicated in its actions, but not in the basic pattern, or the system underneath the whole thing; that's a simple thing.
That's common in all our laws; they all turn out to be simple things, although complex in their actual actions. Finally comes the universality of the gravitational law. The fact that it extends over such enormous distances. That Newton, in his mind worrying about the solar system, was able to predict what would happen in an experiment of Cavendish, where Cavendish's little model of the solar system—the two balls attracting—has to be expanded 10 million million times to become the solar system—and then 10 million million times expanded once again, and we find the galaxies attracting each other by exactly the same law.
Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry.

Thank you.