Lecture 3: The Great Conservation Principles

[BBC TV Film Leader]
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The Great Conservation Principles

When learning about the laws of physics, you find that there are a large number of complicated and detailed laws—the laws of gravitation, of electricity and magnetism, nuclear interactions, and so on, and so on. But across the variety of these detailed laws, there sweep great general principles, which all the laws seem to follow.

Now, these principles are, for instance, the principles of conservation, certain qualities of symmetry, the general form of quantum mechanical principles, and—unhappily, or happily, as we spoke about last time—the fact that all the laws are mathematical.

Tonight I want to talk about the conservation principle.

Now, the physicist uses all the ordinary words in a peculiar manner, which is unfortunate. For example, "conservation" (the conservation law) means this—the way he uses the word: that there is a number, which you can calculate, at one moment-and as nature undergoes its multitude of changes, this number doesn’t change. That is, if you calculate, again, this quantity, it’ll be the same as it was before.

An example is the conservation of energy: there’s a quantity that you can calculate according to a certain rule, and it comes out the same answer after, no matter what happens, happens. Now you could see that such a thing is possibly useful. It’s analogous to this: suppose that the physics, or nature, is made analogous to a great chess game that we are watching, with millions of pieces on it, and we’re trying to discover the laws or the rules by which the pieces move—and the great gods who play the chess play it very rapidly; it’s hard to watch, and it’s difficult to see, and we’re catching on to some of the rules.

But there are some rules which we could work out, which do not require that we watch every move. For instance, if there’s one bishop only on the board, since the bishop moves diagonally, it never changes its color. So if there’s a red bishop on the board, and we look away for a moment while the gods play for a few, if we look again, we can expect that there’s a red bishop on the board—maybe in a different place, but the same red bishop—I mean, the same color square. This is in the nature of a conservation law: we don’t need to watch the insides, but we at least know something about the game, anyway.

It’s true that in chess this particular law is not necessarily perfectly valid. If we watch long enough it could happen that the bishop is captured while we weren’t looking; a pawn went down to queen, and the god decided that it was better to put a bishop

instead of a queen in the place of that pawn—and it was on a black square. And so, unfortunately, it may well turn out that some of the laws which we see today may not be exactly perfect, but I'll tell you how it looks now.
I said that we use words in a technical fashion, and another word in this title is the great conservation principles. This is not a technical word; it was merely put in to make the title sound more dramatic—you could just as well call them the conservation laws. If you wish, there are a few conservation laws that don't work-that are only approximately right, that are kind of useful—and we might call those the "little" conservation laws; I'll mention one or two of those.
But the other ones that I'm going to mention are, as far as we can tell today, absolutely accurate.
The easiest one to understand is the one I'll start with, and that's the conservation of electric charge: there's a number—the total electric charge on a thing—which, no matter what happens, doesn't change—the total electric charge in the world, rather, is what doesn't change: the charge may go from one place to another, but if you lose it here, you'll find it over there—so the conservation is of a total of the electric charge.
This was discovered experimentally, or demonstrated experimentally, by—I am embarrassed to say, I don't remember whether it was—I think it's Faraday (but it might have been Franklin); anyway, it's somebody whose name begins with F—and I know at least this much: that it isn't Feynman, anyway.
At any rate, the experiment consisted of getting inside of a great globe of metal, on the outside of which was a very delicate galvanometer to look for charge on the globe, because small amounts of charge would make a big effect. Then, inside the globe, this experiment—that was named again with F—built all kinds of weird electrical equipment of every kind: he made charges by rubbing glass rods with cat's fur; he made big electrostatic machines run inside, and so on, so that the inside looked like those horror movies laboratories. And during all these experiments, no charge developed on the surface; there was no net charge made.
When a glass rod was charged up with the cat's fur, the cats fur-although the rod may have been (I forget, say) positive, then the cat's fur would be the same amount of charge negative, because the total charge was never anything. If there were any charge developed on the inside, it would have appeared as an effect in the galvanometer on the outside—so the total charge is conserved.
Now, this one is an easy one to understand, because a very simple model that's not mathematical at all will explain it. Suppose that the world is only made of two kinds of particles: electrons, and protons (there was a time when it looked like it was going to be as easy as that), and that the electrons carry a negative charge, and the protons a positive charge, so we can separate them-we can take a piece of matter, and put more electrons on, or less electrons. But suppose that electrons are permanent: they do not disintegrate; they never disappear. That's all-that's not even mathematical; that's a

simple proposition-and there you see that the total number of electrons (or the protons, rather) take away the number of electrons, won't change.
(As a matter of fact, the total number of protons won't change, and the total number of electrons won't change, in this particular model, but we're concentrating now on the charge.)
The difference-the contribution of the protons is positive, and the electrons is negative, and if these objects are never created or destroyed alone, then the total charge will be conserved.
I want to list, later on, the number of properties of conserved quantities, and I start with the one about charge that we're talking about—and we mark down here that it is conserved. That's the beginning; this goes yes. So that's the first. The chart will expand as we go along.
This theoretical interpretation is very simple. But it was later discovered that electrons and protons are not permanent: for example, a particle called a neutron disintegrates—can disintegrate—into a proton and an electron, plus something else (which we'll come to). But the neutron, it turns out, is electrically neutral. So although protons are not permanent, nor are electrons permanent (in the sense that they can be created from a neutron), the charge still checks out, because starting before we had zero charge, and afterward we have plus 1 and minus 1—so when added together, we get zero charge.
Now, another example of a similar trouble—not trouble, but fact—is this: there exists another particle which is positively charged—besides the proton—called the positron, which is a kind of an image of an electron. It's just like the electron in most respects, except it has the opposite sign of charge—and, more important, it's called an antiparticle because when it meets with an electron, the two of them can disintegrate—they can annihilate each other—and nothing but light comes out.
So electrons are not permanent—even them, by themselves: an electron plus a positron will just make light (well, actually, the light is invisible; it's gamma rays, but it's the same thing for a physicist, just the wave length is different). So a particle and the antiparticle can annihilate; the light has no electrical charge, but we remove one positive and one negative charge, so we haven't changed the total charge. Therefore, the charge—the theory of this conservation of charge—is a little, slightly, more complicated, but still very unmathematical; it's simply this: how many positrons do you have, how many protons, take away the number of electrons-and there are other particles, it turns out, in the world, that you have to check.
For instance, there are antiprotons; they contribute negatively. There are positive pi mesons; they contribute positively. Each particle in nature has—fundamental particles have—charges, and all we have to do is add the total number; whatever happens in any reaction, the total amount of charges on one side has to balance on the other side.
That's one aspect of the conservation of charge.

Now comes an interesting question: is it sufficient to say only that charge is conserved, or could we say—do we have to say—more? If charge were conserved because it was a real particle which moved around, it would have a very special property. The total amount of charge in a box might stay the same in two ways: it may be that the charge moves from one place to the other in the box, and just stays in the box. But another possibility is this: charge here disappears, and simultaneously over here, charge arrives-in such a manner, instantaneously related, so that the total charge is never changing.

This possibility for the conservation is a different kind than the other one, in which if anything happens that the charge goes away here, something has got to go through the—in between, something goes past you—if you stood there and watched, something would go by.

The second form of charge conservation is called local charge conservation, and is far more detailed than the simple remark that the total charge doesn't change.

So you see, we've been proving our law (if in fact, it's true), that charge is locally conserved. (It is true.) Then, it must be true—of course, nothing can be proved without some other things, but as I desire to show you from time to time as much as possible some of the possibilities of reasoning interconnecting one idea with another, I would like to show you an argument, which is fundamentally due to Einstein, which indicates that if anything is conserved (in this case I apply it to charge), it must be conserved locally, provided one thing: provided that if two fellows are passing each other in a spaceship, the argument about which guy is doing the moving and which one is standing still cannot be resolved by any experiment.

That's called the principle of relativity—that the motion is relative, and that we can look at any phenomenon from either point of view, either from the point of view that the one is moving, and that this—say this one is standing still, and this one is moving, or the other way around.

Now, suppose I take this point of view that this one is the one that's moving past him. (Don't forget, that's just temporary; you can also look at it the other way, and you must get the same phenomena of nature.) Now suppose that this man, who's standing still, wants to argue whether or not he sees a charge over here disappear and a charge over here appear at the same time. In order to make sure that it's at the same time, he can't sit in the front of the ship, because he'll see one before he sees the other on account of light—so let's suppose that he's very careful; he sits dead center in the middle of the ship, right here, and looks-he's right in the middle, halfway in between.

Incidentally, I'm going to have another man doing the same kind of observation in the other ship. And now: a lightning bolt strikes, and charge at this point A is created, at a certain instant. And at the same instant, back over here at this place B on the other side, on the back of this—at the other end of the spaceship (funny—looking spaceship), the charge is annihilated—disappears—at the same time, which is perfectly consistent

with our idea that charge is conserved, because if we lose one electron—we get one electron here, and lose one here, but nothing went in between.
He says it's the same time—he watches; he sees it's exactly the same time—because the light which comes from the bolt which created the [charge at] A reaches him at the same time as the light which comes from the flash of disappearance—we suppose that when it disappears there's the flash, and when it's created there's a flash (so we can see what happened), and then we see the two flash at the same time—and since he knows he's in the middle of the ship, he says, "Yes, when one disappeared, the other was created."
But: what happens to our friend in the other ship? He says, "No, you're wrong, my friend; I saw A was created before B, because the light is coming out of A, but the man is moving toward it, because he's moving, and the light hits him from the front before the light can reach him from the back, because he's moving away from the light [at B]. So by the time the light gets to here he's got—moved over.
So he says, "No; A, you see, was created first, and then B disappeared—so for a short time after A, after I saw A was created, B hadn't yet disappeared, and I got some charge.
That's not the conservation of charge, it's against the laws."
So the other fellow says, "Yeah, but you're moving." He says, "How do you know?"—and so on—"I think you're moving." So if we are unable by any experiment to see a difference in the physical laws whether we're moving or not, if the conservation of charge were not local, we could tell when were—you see, if it were not local, only a certain kind of man would see it work right, namely, the guy who's standing still in an absolute sense, but such a thing shall be impossible according to Einstein, and, therefore, it's impossible, according to the relativity principle, to have non-local conservation of charge.
This conversation—the locality of the conservation of charge—is consonant with the theory of relativity, and it turns out that this is true of all the conservation laws—not just the charge, as you can appreciate; if anything is conserved, it's the same principle.
Now, another interesting thing about charge, which has nothing to do with the conservation law and is independent of that, is a very strange one for which we have no real explanation today—and that is: that the charge always comes in units.
When we have a particle that's charged, it's got 1 charge, or 2 charge, or -1, or -2. It's a nice little lumpy unit, and has nothing to do with the conservation of charge, but I can't help writing down that it comes in units, the thing that's conserved. It's very nice that it comes in units, because that makes the theory of conservation of charge very easy to understand: it's just a thing, which we count, which goes from place to place.
Finally, it turns out, technically, that the total charge of a thing is very easy to determine electrically, because the charge has a very important characteristic: it's the source of the

electric and magnetic field—charge is a measure of the interaction of an object with electricity, with electric fields.
And so the other item that we should put here on the list is that this is a source of a field. In other words, the electricity is related to the charge. So the particular quantity which is conserved here has two other aspects which are not connected with the conservation directly, but are interesting anyway: one is that it comes in units, and the other that it's the source of a field.
Are there other examples?
There are many conservation laws.
I give some more examples of conservation laws of the same type as the charge in the sense that it's merely a matter of counting. There is a conservation law called a conservation of baryons. A neutron can go into a proton. If we count each of those as one "p-en", then we don't lose the number of "p-en"s. The word "p-en" is actually substituted by baryon, which is equally mysterious and meaningless. The neutron carries one baryonic charge unit, or represents one baryon; then a proton represents one baryon—all we're doing is counting and making big words. So the total number—if this reaction occurs, the total number of baryons doesn't change.
It does turn out, however, that there are other reactions in nature. For example, a proton plus a proton can produce rather a great variety of strange objects:—a lambda, a proton, and a K+, for instance. These lambda and K+ are names for peculiar particles. Now from this one, you know you put two baryons in; you see one come out, so possibly one or the other is one [baryon]. But if you'll study the lambda later, you'll discover that it very slowly—this is easy for it, and this is hard for it to do; it disintegrates into a proton and a pi, and ultimately the pi disintegrates into electrons and whatnot-but what you've got here is the baryon coming out again. So we think that the lambda has a baryon number, but the K does not, [it] has zero.
So in counting these other numbers, we have a similar situation with baryons-so we have charge, and then we have baryon number, with a special rule that the baryon number is the number of protons, plus the number of neutrons, plus the number of lambdas, minus the number of antiprotons, minus the number of antineutrons, and so on-it's just a counting proposition; it's conserved. It comes in units, and nobody knows, but everybody wants to think by analogy that it's the source of a field.
We are trying to guess at the laws of nuclear interaction, and the reason we make these kinds of tables is, this is one of the trick ways of guessing at nature. If this is a source of a field, and this does the same thing, it ought to be a source of a field, too-too bad; so far it doesn't seem to be, or for sure it isn't anyway—we don't know. Sometimes people think it is, sometimes not. We don't know enough to be sure about that question.
Now, it turns out that there is a very peculiar thing—[but first] I would like to mention there are one or two more of these counting propositions, called lepton numbers, and so on, but you learn nothing new; it's the same idea, just counting.

There is one, however, which is slightly different; [it] is that there are, in nature, characteristic rates, apparently, with these strange particles: there are rates of reactions which are very fast, and very easy reactions to do—and others that are very slow. (I don't mean easy and hard in a technical sense, in actually doing the experiment; it's got to do with the rates at which these reactions occur, when the particles are present.) Anyway, there's a clear distinction between this kind of a reaction, and this.

It turns out that if you take only faster, easy, reactions, that there's one more counting law, in which the lambda gets a minus one, and the K+ gets a plus one, and it's called the strangeness number—or hyperon charge, rather—and the proton gets zero. And that particular rule is right for every easy reaction, but it's wrong for the slow reaction. Then, we have a conservation law called the conservation of strangeness or the conservation of hyperon number, which is nearly right, which is very peculiar-it's why the stuff has been called strangeness, the number: it's nearly true—nearly true. But in trying to understand the strong interactions, which are involved in nuclear forces (since, as far as the strong interactions are involved, the thing is conserved), that has made people propose that for the strong interactions, it's again a source of a field—but we don't know.

I bring these matters up to show you how the conservation laws are used to guess new laws.

Now, there are other conservation laws that have been proposed from time to time of the same nature as counting. For example, chemists once thought that no matter what happened, the number of sodium atoms stayed the same. But sodium atoms are not permanent; it's possible to transmute atoms from one to another, so that one has disappeared.

Another law, which was for a while believed to be true, was that the total mass of an object stays the same. It depends on how you define mass, and whether you get mixed up with the energy, nowadays, and I will disregard this mass law until we come to the conservation of energy. But the mass conservation law has been contained in the next one, which I'm going to discuss now, which is the law of conservation of energy.

The law of conservation of energy is the most difficult, abstract one—and the most useful, as a matter of fact, of all the conservation laws. It's more difficult to understand than the charge (and these other ones), because in the charge, (and these other ones), it's obviously, merely—the mechanism is perfectly clear—it's a conservation of the object (sort of). I mean not quite, because of this problem that we get some new things from old things, but it's really a matter of counting. But the conservation of energy is a little more difficult: here, we have a number which is not changed in time, but the number doesn't represent the number of any particular thing. I would like to make a kind of silly analogy to explain a little bit about it.

I want you to imagine that a mother has a very difficult child—well, not necessarily difficult, but she has a child—who she leaves alone in a room with 28 blocks—they're indestructible, absolutely indestructible blocks, like the charges. The child plays with the blocks all during the day, and when the mother comes back she discovers indeed there are 28 blocks. She checks all the time the conservation of blocks. Well, this goes on for a few days until one day when she comes in, there are only 27 blocks: one block she finds later outside the window; he threw one out the window.

So first we must appreciate the conservation laws involved that you watch out that the stuff that you're trying to check doesn't go out through some wall.

The same thing could happen the other way—if a boy came to play with him and brought in some blocks; of course, those are obvious technical matters that you have to be careful of when you talk about a conservation law.

Now suppose, however, that when the mother comes to count the blocks, she finds there are only 25 blocks, but suspects that in a little toy box, in a box that the boy has, he has hidden the blocks. So she says, "I'm going to open the box." He says, "No, you cannot open the box." How can she tell? She says, "I am a very clever mother, unlike most," she would say; "the box weighs, I know, when it's empty, 16 ounces, and each block weighs 3 ounces, so what I'm going to do is, I'm going to weigh the box." So she would have another thing: number of blocks seen, plus weight of box minus 16 ounces, divided by 3 ounces, and that adds always the same, for 28. Goes on for a while until it doesn't check, but she notices that the dirty water in the sink is changing its level—so, we add the water level: height of water in sink minus 6 inches (which it is when there's no block in it), divided by a quarter of an inch (which is the height that the water rises when a block is in the dirty water).

Now, as the boy becomes more ingenious, and the mother continues to be ingenious, more and more terms must be added on here—which all really represent blocks, but from a mathematical standpoint are abstract calculations—which are blocks not seen.

Now I would like to draw my analogy, and tell you what is in common for this and the conservation of energy, and what is different. Suppose that you never saw the blocks at all—that in any one of the situations, there were never any blocks. Then the mother would be always calculating a whole lot of terms, which she could call blocks in the box, blocks in the water, blocks in—and so on. But there are other differences: there aren't any blocks, as far as we can tell, and the numbers that come out here are not integers, unlike the case of the blocks with the child. Suppose— I mean it could happen to the poor lady that when she calculates this number, it comes out 6 1/8 blocks, and when she calculates this number, it comes out 7/8 of a block, and the rest of them give 21; still 28—that's the way it looks.

So, what we discover is, that we have a scheme in which we can find a sequence of rules—and from the rules, each one of the different kinds of calculations we call calculating the same "thing" (number of blocks, or energy) by different rules. Then we add all the numbers together, from all the different forms of energy; it always adds up to the same total.

But as far as we know, there are not real units—it's not made out of little ball bearings—so it's abstract; it's purely mathematical: there exists a number such that you can calculate it, and it doesn't change—I cannot interpret it any better than that.

This energy has all kinds of forms analogous to the blocks in the box, and blocks in the sinkwater, and so on. There's energy due to motion; it's called kinetic energy. There's energy due to gravitational interaction; the gravitational potential energy, it's called. There's a thing called thermal energy, electrical energy, light energy, elastic energy, and springs, and so on; chemical energy, nuclear energy—and there is also an energy that a particle has from its mere existence, an energy that depends on its mass directly; that's the contribution of Einstein, as you undoubtedly know.

(E=MC-squared is what I was talking about, which is the famous equation of this mystic law.)

Now, actually, although I mentioned a large number of energies, I would like to explain that we're not completely ignorant about the thing, and that we understand the relationship of some of them. For example, what we call thermal energy is, to a large extent, merely the energy—the kinetic energy of motion—of the particles inside an object. What we call elastic energy and chemical energy both have about the same origin—namely, the forces between the atoms: when the atoms rearrange in a new pattern, some energy is changed—that quantity changes; that means that some other quantity has to change. So, for instance, if the chemical energy changes, then heat energy is changed—in burning something, the chemical energy changes, and you find heat where you didn't have the heat before—because it all has to add up right. But elastic energy and chemical energy are both interactions of atoms, and we now understand the interactions of the energies of the atom-or those chemical interactions, or those interactions of the atoms-to be a combination of two things: one is electrical energy, and the other is kinetic energy, again—only the formula for it is quantum mechanical, instead of the usual; it's a little different one.

Light energy is nothing but electrical energy, because light has now been interpreted as an electric and magnetic wave.

The nuclear energy has no—is not represented in terms of the others, but as a result of—what do we say—due to "nuclear forces"; well, we didn't say anything but [that] nuclear energy is not connected yet to the others. I'm not just talking about the energy released; in the uranium nucleus there's a certain amount of energy, and then when the thing disintegrates, it changes the amount of energy in the nucleus, but the total amount of energy in the world doesn't change—so a lot of heat and stuff is generated in the process, in order to balance that thing out.

Now, this conservation law is very useful in many technical ways, and I wish I could give you a number of them. I'll give you some very simple ones, to show you how—from the conservation of energy, and knowing the formulas for the energy (which are not those)—you can calculate (you can see what) some certain things have to happen. In other words, many laws are not independent laws, but are just secret ways of talking about the conservation of energy—or, better: knowing the conservation of energy, you can also understand a lot of [other] laws.

The simplest one is a lever. If this is a lever on a pivot, and let's say this distance is 1, and this distance 4 (one foot and four feet), then—but first, I must give you the law for gravity energy: the law for gravity energy is to take (if you have a lot of weight, you take) the weight of each weight, multiply it by the height above the ground, and add this together for all the weights; that gives all the gravity energy. Let's put the ground right here.

Now, the problem is this: suppose that I have a one—pound weight here, just to make it—to make it more complicated, a two—pound weight here, and I have an unknown mystic weight on the other side: X is always the unknown, so let's call it W—to make it look like we've advanced above the usual.

Now, the question is, how much must W be, so that it just balances—it swings quietly back and forth without any trouble? That means that the energy—if it swings quietly back and forth without any trouble when it's set this way-when it's tilted up a little bit (say for instance, that this has gone up one inch), the energy is the same. If it is the same, then it doesn't care much which way, and it doesn't fall over. So if this goes up one inch, how far down does this go? If you think about it quite a long time (this being one inch and that being four feet), you can figure out by proportion that this being one foot, this is a quarter of an inch. So that the rule says this: that before anything happened, all the heights were zero, so the total energy is zero. After the thing has happened, we multiply the weights unknown by the height—minus-a-quarter-of-an-inch, add the other weight—two by the height one—inch, and this should add up to the same energy as before. So that a quarter of W taken away from two is zero, and W must be eight.

So that's how we find the laws—I mean, that's one way we can understand the easy law that you know, of course, the law of the lever. But it's interesting that not only this one, but hundreds of others of the physical laws can all be closely related to the various forms of energy—so I illustrate that only to illustrate how useful it is.

The only trouble is, of course, it doesn't really work. I mean, if you did that, it wouldn't swing like this on account of friction in the fulcrum. If I had something moving, for instance—if it has kinetic energy, like a rolling ball, and it's on a constant height, and it rolls along—and then it stops, that's on account of friction. But what happened to the energy of the ball? The answer is that the energy of the ball has gone into the energy of the jiggling of the atoms in the floor and in the ball.

The world that we see on a large scale looks so nice when we polish a nice round ball, and so on-it's really quite complicated when you look at it on a little scale: billions of tiny atoms, with all kinds of irregular shapes, looked at in detail. It's like a very rough boulder, really, when looked at finely enough, because it's made out of these little balls [i.e. atoms]. The floor is the same way; it's a bumpy business made out of balls. You roll this monster thing over the other, you can see that the little atoms are going to go snap, jiggle, snap, jiggle—and after the thing has rolled across, the ones that are left behind are still shaking a little bit from the pushing and snapping that they went through.

So there is left in the floor a jiggling motion, or thermal energy. And although at first it looks like the law of conservation is false, energy has a tendency to hide from us, and we need thermometers and other instruments to make sure that it's still there.

The first demonstration of the conservation of energy (—oh: the energy is conserved no matter how complex the process, or no matter what, even when we don't know the detailed laws)

The first demonstration of the law of conservation of energy, in fact, was not by a physicist, but by a doctor—a medical man. He demonstrated with rats that the total energy of the food put in before, and their heat generated by the—well, you burn food, and you find out how much heat is generated, and then you feed the rats the food—and oxygen—and it's converted to carbon dioxide the same way as in burning, and measure the energy in that case, and you find out that living creatures do exactly the same thing as non—living creatures, that the law of conservation of energy is exactly as true for life, as not! As a matter of fact, it was discovered by this.

Incidentally, it's interesting, that every overall principle that we know, that we can test on the great phenomena of life, work just as well as for dead things. That is, there is no evidence yet that what goes on in living creatures is necessarily different (it may be more complicated, but [not] necessarily different) than what goes on in non—living things—I mean as far as the physical laws are concerned.

Incidentally, this amount of energy that's in the food—it'll tell you how much heat and mechanical work and everything that's generated, is what you read—when you read or hear about calories, you're not eating something called calories; you're eating that measure of the amount of heat energy that's in the food. For people who like to-physicists always feel so superior, and smart, and so on, that people would just like to get them once on something—and so I'll give you something to get them on.

They should be utterly ashamed of themselves, because they take the same thing—energy—and they measure it in a host of different ways, with different names, absolutely absurd: energy can be measured in calories, in ergs, in electron volts, in foot pounds, in BTU, in horsepower hours, in kilowatt hours-all exactly the same thing. It's like having money, you know, in dollars and in pounds, and so on, but unlike the economic situation, where the ratio can change, these dopey things are an absolutely guaranteed proportion. If anything could be analogous to it at all, the only hope would be to say that there are 20 shillings to a pound, and that you have shillings and pounds-with one complication that the physicist allows: instead of saying he has 20 shillings to a pound, he says he has irrational ratios, like 1.6183178 shillings to a pound. In addition to that, you'd think that the more modern or high-class theoretical physicists would at least use a common unit, but you can find papers with degrees Kelvin for measuring energy, megacycles—inverse Fermis is the latest invention. We don't need any more inventions; we should all measure the energy in exactly the same—we should measure the energy in one unit, and let it be done, instead of having all these different names.

It just shows that people are often also—they want to say, see, I should bring my little boy to show on the screen, so that the audience will understand that I'm human—well, the proof that physicists are human is the idiocy of all the different units which they use for measuring energy!

Now, we have a number of interesting phenomena in nature, which present us some curious problems with energy; [it] has recently been discovered some things called quasars, which are very far away, and they emit a lot of light—they're enormously far away, and emit a lot of light, and a lot of radio waves—and have radiating so much energy, that the question is, where does it come from? That is, after it's radiated this enormous amount of energy, the condition must be different than it was before, if the conservation of energy is right.

Question: does the thing collapse gravitationally? Is it a different condition gravitationally? Is it coming from gravity energy, this big emission, or is it coming from nuclear energy, and so on?

Nobody knows.

Would you like to propose that maybe the law of conservation of energy is not right? Well, when a thing is investigated as poorly—I mean, as incompletely-as is the quasars (because they can't see so easily at such a large distance), it very rarely is, when a thing looks difficult, that the fundamental laws are wrong; it's usually that the details are unknown. Another interesting example of the use of the conservation of energy is in this reaction: it was first thought that neutrons turned to protons plus electrons, but the energy of a neutron is fixed, and that of a proton could be measured, and the energy of an electron did not add up correctly to the energy of the neutron-the proton and electron together didn't add up to the neutron.

Two possibilities existed. One was the law of energy conservation is not right. In fact, it was proposed by Bohr for a while, that maybe the conservation law worked only statistically, on the average, for large scale. But it turns out that Fermi—I mean, Pauli—suggested, no, that the fact that the energy doesn't check out is because there's a something else coming out which we now call an antineutrino, and that this other thing coming out takes out the energy.

If you say, "The only reason for the antineutrino is to make the conservation of energy right," well, it makes a lot of other things right: conservation of momentum, and other conservation laws, are fixed up because a piece came out that we weren't worrying about—and very recently it has been directly demonstrated that such neutrinos indeed exist.

That illustrates a point. Why are we able to extend our laws to regions that we're not sure [about]? How is it possible—why are we so confident that because we check the energy conservation here, then—when we get a new phenomenon—we say, "It's got to satisfy the conservation of energy." Every once in a while you read in the paper that the physicists have discovered one of their favorite laws is wrong. It's not a mistake to say that it's true in a region where you don't look yet, where you haven't looked yet. If you will not say that it's true in a region that you haven't looked yet, you don't know anything. If the only laws that you find are those which you just finished observing, then you can't make any predictions.

The only utility of the science is to go on and to try to take guesses, you see; the most likely thing is that the energy is conserved in other places. So what we do, always, is to stick your neck out—and that, of course, means that the science is uncertain. The moment that you make a proposition about a region of experience that you haven't directly seen, then you must be uncertain. But we always must make statements about the regions that we haven't seen, or it's no use in the whole business.

For instance, the mass of an object changes when it moves, because of the conservation of energy-the energy associated with the motion appears as an extra mass, because of the relation of mass and energy—so things get heavier when they move. It was first believed by Newton that this wasn't the case, [and] that the masses stayed constant. So when it was discovered that that was false, everybody'd say, "It was a terrible thing that physicists found out they were wrong—why did they think they were right?" The effect is very small—only when you get near the speed of light does it make any difference. If you spin a top, it weighs the same as if you don't spin it, within millions-a very, very fine fraction. So you could say, "Oh! They should have said—they should have said—that if you do not move any faster than so—and—so, then the mass doesn't change— that would then be certain."

No, the experiment [also] happens to be done only with tops made out of wood, copper, steel, and so on-so we [also] should have said that tops made out of copper, steel, wood, and so on, were not moving any faster. You see, we do not know all the conditions that we need for an experiment: it is not known whether a radioactive top would have a mass that's conserved, but we have to take a guess.

So in order to have any utility at all to the science, in order not simply to describe an experiment that's just been done, we have to propose laws beyond their range—and there's nothing wrong with that—that's the success; that's the point.

That makes the science uncertain. If you thought before that science was certain, well, that's just an error on your part.

Now there are other—so, we have here the energy, which we could put on our list, and it's conserved perfectly, as far as we know—but it does not come in units. Now the question is, is it the source of a field—and the answer is yes.

Einstein understood gravitation as being generated by energy. Energy and mass are equivalent, and Newton's interpretation that the mass is what produced the gravity has been modified to being the energy that produces the gravity. There are other laws that are similar to the conservation of energy in the sense that they are numbers. I haven't very much time to describe them, but I'll mention what they are.

One of them is the momentum. It means if you take all the masses in an object and multiply them by the velocities (for instance), and add it together, that's the momentum-of the particles in it, anyway; that total amount of momentum is conserved. The energy and the momentum are now understood to be very closely related, and so they should be in the same column in this conservation law [table].

Another example of a conserved quantity is angular momentum, an item which we discussed some time before. The angular momentum is the area generated per second by objects moving about. For example, if an object is here, and is moving, and we take any center whatsoever, then—the area, the rate of change—the speed at which this area increases, multiplied by the mass of the object, and added together for all the objects, is called the angular momentum—and that quantity doesn't change, either. So we have conservation of angular momentum.

Incidentally, at first sight, if you know too much physics, you might think that the angular momentum is not conserved: like the energy, it appears also in different forms, although most people think it only appears in motion-but it does appear in other forms, and I will illustrate that. You know that if you have a wire, and move a magnet up into it, increasing the magnetic field through the flux through the wires, there'll be an electric current—that's how electric generators work.

Now, imagine that I have instead of a wire, a disk on which there are electric charges analogous to the electrons in the wire. Then I bring up a magnet dead center along the axis from far away, very rapidly, up to here, so now there's a flux change through here. Then, just as in the wire, these will start to go around. If this were on a wheel, it would be spinning by the time I brought the magnet up. Well, that doesn't look like conservation of angular momentum, because when it's down here, nothing's turning, and when it's up here, it's spinning. So we got turning for nothing—and that's against the rules.

"Oh, yes," you say, "I know; there must be another kind of interaction that makes the magnets spin the opposite way." That's not the case: there is no electrical force on the magnet tending to twist it the opposite way. The explanation is, that angular momentum appears in two forms: one of them is angular momentum of motion, and the other is angular momentum in electric and magnetic fields—and there is angular momentum in the field here, although it doesn't appear as motion, and has the opposite sign to the spin.

If we take the opposite case it's even more clear: if we have just these particles and the magnet here—and everything standing still, I say there's angular momentum there.

There's a rotational effect; I mean, there's an angular momentum in the field-there's a hidden form of angular momentum; it doesn't appear as actual rotation. When you pull this magnet down, and take the instrument apart, and all the fields separate, then the angular momentum that's in the field has to appear now, and this thing will spin from the-the law that makes it spin is the law of induction of electricity.

Now the question as to whether it comes in units is very difficult for me to answer. At first sight, you'd say, it's absolutely impossible that angular momentum come in units, because angular momentum depends upon the direction in which you project the picture. I said in another lecture that you have to look at this thing, and see how the area changes. If you look at an angle—if you had something turning this way, and you looked at it sideways—you wouldn't see any area changing. If you looked at not—quite—vertical, but just a little bit off, you'll see that the area changes a little bit different—a little bit different, if you come at a small angle.

So if angular momentum came in units, 8 units, and then you looked not exactly down at the 8 but at a slight angle, it should look like a little bit less than 8. Now, 7 is not a little bit less than 8, it's a definite amount less than 8, so the darn thing can't possibly come in units. This "proof," however, is evaded by the subtleties and peculiarities of quantum mechanics: if we measure the angular momentum about any axis, amazingly enough it's always a number of units! So what to say about this is, yes—but it's not the kind of unit, like electric charge, that you can count them inside. The angular momentum, although it does come in units—in the mathematical sense that the number that we get in any measurement is a definite integer times a unit—we cannot interpret that in the same manner that we interpret this in the case of electricity, that there's this one, and I see another one; you see those little six little units in there. You can't see the units, you see, but it comes out always an integer anyway, which is very peculiar.

Now, there are a number of other conservation laws that I should include in the list, and I'll just illustrate the type. They're not as interesting as these; they're not numbers, exactly. If the laws of physics are nice, and if were to start some kind of device off, with particles moving, which had a certain definite symmetry—suppose that we had some objects that were like this, and that the exact way that they were moving was such that it was bilaterally symmetrical—then, as the laws of physics go on, and all the collisions, and so on, you would probably expect (and rightly so) that if you'd look at this same picture later, it will be bilaterally symmetrical.

So there is a kind of conservation, a conservation of the symmetry character, which is—should be—in the list there, but it's not like a number that you measure; it's just, well, a symmetry character.

I will discuss it in much more detail in the next lecture. The reason it's not interesting—it's not very interesting in classical physics, because the times in which you get such nicely symmetrical initial conditions is very rare, and it's not a very important or practical conservation law.

But in quantum mechanics, when we deal with very simple systems like atoms, and so on, their internal constitution often has this kind of symmetry (of some sort), like bilateral symmetry, or other, and then the symmetry character is maintained—it's an important law for understanding quantum phenomena.

I should include it in the list of all the important conservation laws, but I will discuss it next time.

An interesting question is, whether there's a deeper basis for these conservation laws, or whether we have to take them as they are. That, again, I will reserve for next time. I would like, however, to remind you that in making a popular speech on these subjects, there seem to be a lot of independent things.

But with a deeper understanding of the physics, of the various principles, there are deep interconnections between the things, so that one implies the other, in some way. For example, the relation between relativity and the necessity for local conservation, which, if I said that without the demonstration, would appear as some kind of a miracle-that the statement that you can't tell how fast you're moving implies that if something is conserved, it must be done not by jumping from one place to another-and here I would like to show you, or indicate, how the conservation of angular momentum, and the conservation of momentum (and a few other things) are, to some extent, related. The conservation of angular momentum has to do with the area swept by particles moving. Now, if you had a lot of little particles here, and you took the center very far away, then the distances are almost the same for every object, and it doesn't make much difference—so the only thing that counts in the area sweeping, or in the conservation of angular momentum, is the component of motion (vertically, say, in this case). What we would discover is that each mass, multiplied by its velocity vertically, added together, must be a constant—because the angular momentum is a constant about any point, and if that point is far enough away, then it must be only that the sum of the masses times the velocities is constant—and therefore the angular momentum implies the conservation of momentum. The conservation of angular momentum implies the conservation of momentum—and that, in turn, implies another thing, which is the conservation of another item, which is so closely connected that I don't put it on the list: the principle about the center of gravity, that a mass in a box cannot just move—disappear here, and move over here by itself—that's nothing to do with conservation: if you think, "Well, you still got the mass, and I moved it from here to here," charge could do that, but not a mass.

Let me explain why. Suppose, since the laws of physics are not affected by motions, that this box was drifting slowly upwards, and take a point not far away. Now, as it's drifting upwards, if the mass were here, quiet in a box, in the beginning it has a mass here going up, and producing an area at a certain rate. After the mass has moved over here, if it's going up at the same speed because the box is drifting, then the area would be increasing at a greater rate because there's a bigger length this way, although the altitudes are the same.

But by the conservation of angular momentum, you can't change the rate at which the area's changing, and therefore, you simply can't move one mass from one place to the other, if you don't push on something else and get rid of the momentum or angular momentum. That's the reason why the rockets in empty space can't go—but they do go: that's because we have—the rocket—the center of gravity—if you figured it out with a lot of masses, if you move one forward, you got to move others back, so that the total motion back and forth of all the masses is nothing.

Now, the way a rocket works is: here's a rocket, which shoots some gas out of the back. Here's the gas-you see, beforehand the rocket standing still, say, in empty space, and afterwards it shoots some stuff out the back—and then the rocket's going forward. The point is, that of all of the stuff in the world, the center of mass, the average of all the mass, is still right where it was before. But the interesting part has moved out here, and an uninteresting part, that we don't care about, has moved out here. There is no theorem that says that the interesting things in the world are conserved, only the total of everything.

Discovering the laws of physics is like trying to put the pieces together of a jigsaw puzzle: we have all these different pieces, and today they're proliferating rapidly; they're lying about—many of them can't be fitted with other ones. Now, how do we know that they belong together? How do we know that they really are parts of one picture, one at present incomplete picture? We're not sure, and it worries us to some extent, but we get encouragement from the common characteristics of several pieces: they all show blue sky, or they're all made out of the same kind of wood.

Thank you very much.