Lecture 4: Symmetry in Physical Law

[BBC TV Film Leader]
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Symmetry in Physical Law

Symmetry seems to be absolutely fascinating to the human mind. We like to look at symmetrical things in nature such as balls, which are perfectly symmetrical, spheres—like planets and the sun, and so on—or symmetrical crystals, snowflakes, flowers (which are nearly symmetrical), and so on. But it's not the objects in nature—the symmetry of the objects in nature—that I want to talk about tonight, it's rather the symmetry of the physical laws themselves.

Now, how can a physical law have a symmetry? It's easy to understand how an object has a symmetry; of course, it can't. But physicists delight themselves by using ordinary words for something else, and so, in this case, they have a thing about the physical laws which is very close to symmetry of objects, and they call it the "symmetry of the laws"-and that's what I'm going to talk about.

To show how close it is, I asked for a definition of symmetrical: what is symmetry? If you look at me, I'm symmetrical right and left—apparently, at least. A vase can be symmetrical that particular way, or in other ways. How can you define it? Well, Professor Weyl, a mathematician, gave an excellent definition of symmetry; it is this: as I am left and right symmetric, that means that if you put everything that's on this side on this side—and vice versa, if you just exchange the two sides—it'll look exactly the same. Or, for instance, a square has a symmetry—a special kind: if I turn it around to 90 degrees, it still looks exactly the same. So, Weyl said, a thing is symmetrical if there's something that you can do to it, so that after you're finished doing it, it looks the same as it did before. That is the sense in which we say that the laws of physics are symmetrical: that there are things that we can do to the physical laws, or to our way of representing the physical laws, which make no difference and leave everything unchanged in its effects.

This aspect of physical laws are what's going to concern us tonight. We will take a number of examples.

The simplest example of all, of a kind of symmetry (as you'll see, it's not the same as you would have thought—left and right symmetric, or anything like that), is a symmetry called translation in space. That has the following meaning: if you build any kind of apparatus, or do any kind of experiment with some things, and then go and build the same apparatus with the same—do the same kind of experiment with similar things, but put them here instead of there (merely translate it from one place to the other in space),

then the same thing will happen in the translated thing that would have happened in the original thing.
(It’s not really true, actually: if I actually built such an apparatus, and then displaced it 20 feet in that direction, it would get into the wall, and there would be difficulties.) It’s necessary, in defining this idea, to take into account everything that might affect the situation—so that when you move the thing, you move everything. For example, if the system involved a pendulum, and I moved it 20,000 miles to the right, it wouldn’t work right any more, because the pendulum involves the attraction of the earth-but if I imagine I move the earth and the equipment, then it will behave the same way. So the problem-the situation is, that you must translate everything which may have any influence on the situation.
Now, that sounds a little dopey, because it sounds like, "Well, uh just translate it, and if it doesn’t work, then you didn’t translate enough stuff!"—you’re bound to win. Actually, not: you see, it’s not self—evident that you’re bound to win. The remarkable thing about nature is that it is possible to translate enough stuff so that it does behave the same way—that’s a positive statement.
Now, I would like to illustrate that such a thing is true from the statement of the law of gravitation, for example, which said that the forces between the objects was inversely as the square of the distance between them—and I remind you that a thing responds to a force by changing its velocity, as time goes on, in the direction of the force. Now, if I move something from here to here—a pair of objects like a planet going around the sun-and move the whole pair over, then the distance between the objects, of course, doesn’t change, and so the forces don’t change. And further, when they moved over a situation at the same speed, then all the changes will remain in proportion; everything will go around in the two systems exactly the same way. Because the law said, the distance between the objects—rather than some absolute distance from the central eye of the universe, but it talked about distance between the objects—then it means that the laws are translatable in space.
I give another example of symmetry. That first symmetry is translates in space; the next one could be called translation in time, if you like, but better just to say, "A delay in time makes no difference": if we start a planet going around the sun in a certain direction (this goes around), and if we start it all over again two hours later—or, say, two years later, with another beginning, starting the planet and the sun going in the same way—it’ll behave in exactly the same way. Because, again, the law of gravitation, as stated, talks about the velocity, and never talks about the absolute time, and when you were supposed to start measuring things.
In this particular example, we are really not sure: when we discussed gravitation, we talked about the possibility that the force of the gravity changed with time. Now this would mean that the translation in time was not a valid proposition, because if the constant of gravitation is weaker a billion years hence than now, then it isn’t true that the

motion will be exactly the same for an experimental sun and planet a billion years from now, as it is now. But as far as we know today—I discuss only the laws as we know them today (I wish I could discuss the laws as we will know them tomorrow, but I cannot.) but as far as we know—a delay in time makes no difference. Actually, we know that isn't really true. That's true for what we now call a physical law, but one of the facts of the world, which is very different-well, which just may be very different, and may be not different than a physical law—is the fact that it looks like the universe had a definite time of beginning, that everything is exploding apart.

Now, that, you might call a condition of geography, analogous to the situation that if I say "I translate," [and] I don't translate everything—I mean, I have to move that wall, if it's going to make any difference. And in the same sense, you would say, "Oh, I see; he means the laws are the same—the universe expanded, and everything else—but we could have made another analysis in which we start the universe later."

But we don't start the universe, and we have no control on the situation. And we have no way to define that idea experimentally. Therefore, as far as the science is concerned, there really is no way to tell. The fact of the matter is, that the conditions of the world are changing in time (as we know, apparently); at least the galaxies are all separating from one another—so if you were to awake in some science fiction story, at an unknown time, [then] by measuring the distances (the average distances to the galaxies), you could tell when it was—and that means that the world will not look the same, if delayed in time. Now, it is conventional today to separate the physical laws which tell how things will move, if you start them at a given condition, from the statement of how the world actually began—because we know so little about that, and it is usually considered that astronomical history (or cosmological history, or whatever you want) is a little different than physical laws—but if put to a test of how would you define the difference, I would be hard pressed.

The best characteristic of physical law is its universality, and if there's anything universal about the thing, it's the universal expansion of all the nebulae-so I have no way of defining that. But if I restrict myself to disregard that matter, then as far as the other physical laws are known—(and the law that determines how the thing expands, or, I mean, the cause of it, and so on, is not known)—if you take only the physical laws that are known, a delay in time makes no difference.

Now, we take some other examples. Another is a rotation in space, a fixed rotation: if I build a piece of equipment, and do some experiment with a piece of equipment built here and then take another one (better translate it so it doesn't get in the way) here—but turn it so that all the axes are a different direction, it'll work the same way. Again, we have to turn everything that's relevant: if the thing is a grandfather clock, and you turn it this way, well, the pendulum would just sit up against the wall of the can; it won't work-but if you turn the earth too, as is going on all the time, it still keeps working all right.

The mathematical description of this possibility of turning is a rather interesting one, because to describe what goes on in this situation, we like to use numbers to tell where something is—they're called the coordinates of a point. We use, for instance, sometimes, three numbers to do it: how high it is above some plane, how far it is in front of me, say (and back is the negative numbers), and how far to the left. Suppose I did that. (I'm not going to worry about up and down because for rotations, I just have to use two of these three.) Let's call the distance this way X, in front of me, and Y is how much to the left; then I can locate anybody by telling how far he is in front, how far to the left. (Those who come from New York City will know that the street numbers work that way very neatly—until they began to change the name of 6th Avenue!)
Now, the mathematical idea about the turning is this: that if I sit at a somewhat different angle, and make my calculations, then what's directly in front of me at distance X is a mixture. Let's say there's a man over here (you), who's standing this way, and making his analysis, and me, standing this way, and making my analysis. When I measure distance X, if I go straight out on X and don't change to the right or to the left, you'll see that that line is a mixture of some of your X-ish business, and some of the Y. So that the connection, the transformation, is that X gets mixed into X and Y, and Y gets mixed into Y and X—and the laws of nature shall be so written that if you make such a mixture and resubstitute it in the equations, the equations will not change their form—that's the mathematical way in which the symmetry appears. If you write, in mathematical form, the symmetry appears this way: you write the equations with certain letters, then there's a way of changing the letters from X and Y to a different X (X'), and a different Y (Y'), which is some formula in terms of the old X and Y, and the equations look the same—only you have "primes" (') all over them. That just means that the man will see the thing behaving in his apparatus the same way as I see it in mine, which is turned the other way.
I give another example. This example is very interesting; it's a question of uniform velocity in a straight line: it is believed that the laws of physics are unchanged under the symmetry—under the operation—of making a uniform velocity in a straight line. This is called the principle of relativity. If we have, for instance, a spaceship, and we have a little equipment in it that's doing something, and we have another equipment down here on the ground-and the spaceship is going along at a uniform speed-then inside the spaceship, somebody watching what's going on can see nothing different than the man that's standing still in his apparatus in there. Of course, if he looks outside, or he bumps into an outside wall, or something like that, that's another matter, but insofar as he is moving at a uniform velocity in a straight line, the laws of physics look the same to him as they do to me, who is not moving. Since that's the case, I cannot say who's moving.
Now, I insist and emphasize here something before we go any further: that in all of these transformations and all of these symmetries, we are not talking about moving the whole universe. Just like the case of the time, I could imagine I moved all the times in

the whole universe- but that doesn’t make any difference: there’d be no content in the statement that if I took everything in the whole universe and moved it over, it would all behave the same way.

The very remarkable thing is, if I take a piece of apparatus and move it over, then if I make sure about a lot of conditions, and can include enough apparatus, I can get a piece of the world, and move it relative to the average of all the rest of the stars-and it still doesn’t make any difference. And in this case, it means that someone coasting at a uniform velocity in a straight line relative to the average of the rest of the nebulae sees no effect: it is impossible to determine by experiments inside a car without looking out, by any effects, that you’re moving relative to all the stars, if you want.

This proposition was first stated by Newton. Let’s take his law of gravitation, for instance. It said that the forces are inversely as a square (so, let’s see, what else, yes), and that the force produces changes in velocity. Now, suppose that I watch a moving thing—for instance, I have worked out what happens when a planet goes around a fixed sun—and now I want to work out what happens when a planet’s going around a drifting sun. Well, then, all of the velocities that I had in the first case are different than in the second case; I just add a constant velocity on. But the laws are stated in terms of changes in velocity, so that what happens is that the pull of this planet for this changes this one’s speed—and for the other case, changes its speed by the same amount.

So anything that I started with—any initial speed that I started with—it just keeps on going, and all the changes are accumulated on top of that. That’s not a very good description, but the net result of the mathematics is that if you add a constant speed, the laws will be exactly the same—so that we cannot, by studying the solar system and the way the planets go around the sun, figure out whether the sun is itself drifting through space: there’s no effect of such a drift through space on the motion of the planets around the sun according to Newton’s laws. So that Newton said, "The motion of bodies among themselves is the same in a space, whether that space is itself at rest relative to fixed stars, or is moving at a uniform velocity in a straight line."

Now, it turns out that as time went on, that new laws were discovered after Newton; those were the laws of electricity by Maxwell. One of the consequences of the laws of electricity was that there should be waves—electromagnetic waves (light, in fact, is an example)—which should go at 186,000 miles a second—flat. I mean, by that, 186,000 miles a second come what may. So then it was easy to tell where rest was, because a law like "light goes 186,000 miles a second" is certainly not one (or at first sight is certainly not one) which is quite right, which will permit one to move and get the same law.

It’s evident, is it not, that if you’re in a spaceship going 100,000 miles a second in that direction, and I’m standing still and shoot a light beam at 186,000 miles a second, you look out the window-or if I shoot the beam through a little hole through your ship, as it goes through your ship, since you're going 100,000, and the light's going 186,000—light is only going to look like it's passing you at 86,000 miles a second.

But if you do the experiment, it looks like it's going 186,000 miles past you, and past me! The facts of nature are not so easy to understand, and the fact of the experiment was so obviously counter to common sense, that there are some people who still don't believe the result. But experimentally, time after time, experiments indicated that the speed is 186,000 miles a second, no matter how fast you're moving.

And now the question, how could that be? Poincaré proposed that one take as one of the principles of nature that the principles of Maxwell's equations are right, and that the mathematical changes needed to compare a system moving and a system standing still that come in that case should be—well, that's—I'm making it sound too complicated; I'll come back and change the way of stating it:

Einstein realized, and Poincaré, too (and it's hard to get the history right while you're trying to explain the idea at the same time), that the only possible way in which a person moving and a person standing still could measure the speed to be the same was that their sense of time and their sense of space are not the same—that the ticking clocks inside the spaceship are ticking at a different speed than they are on the ground, and so forth. Of course, you say, "Yeah, but if the clock is ticking, I look at the clock in the spaceship, but I see it's going slow." "No, no: your brain is going slow too!"

So by making sure that everything went just so inside the spaceship, it was possible to cook up a system by which in the spaceship it would look like 186,000 spaceship miles per spaceship second—whereas it looks like 186,000 my miles in my seconds at the same thing.

It was a very ingenious thing to be able to do; it turns out, remarkably enough, to be possible. I mentioned already one of the consequences of this principle of relativity-that you cannot tell how fast you're moving in a straight line: in which we had two cars, and there was an event that happened at each end of this car-a man was standing in the middle of the car, and there was an event that happened at each end of this car at a certain instant—which this man claimed was the same time (because, standing in the middle of the car, he saw the light from both of these things at the same time), whereas a man in another car, who happened to be moving this way with a velocity, saw these same two events not at the same time, but in fact saw the one here first, because the light reached him before the light from here, because he was moving forward. So, you see, that one of the consequences of the principle of symmetry for uniform velocity in a straight line (that symmetry means you can't tell who's right), is that when someone talks about something—like, when I talk about everything that's happening in the world now-that doesn't mean anything. If you're moving along at a uniform velocity in a straight line, everything that happens at now—simultaneous—is not the same events as my now, even though we're passing each other, and our instant here is the same, but somewhere else—we cannot agree what now means at a distance.

So this means a profound transformation of our ideas of space and time, in order to maintain this principle that uniform velocity in a straight line cannot be detected. Actually, what's happening here is that the time—from one point of view, two things that are simultaneous, seem, from another point of view, to be not at the same time, provided they're not at the same place—that they're far apart in distance. That's very much like my X and Y: two things which seem to me to be at the same horizontal—well, let's say the same distance in front—zero distance in front, will, from somebody this way—he'll say, "One of them is in front of me, and one is in back." See, consider, from my point of view, they're both even with me—that wall and that wall—is even with me. But if I stand and turn like this, and look at the same pair of walls but from a different point of view, that one's in front of me, and that one's behind. And so it is that the two events, which from one point of view seem to be at the same time, from the other point of view seem to be at different times. And the generalization of the two—dimensional rotation that I'm talking about into space and time was made, so that the time was added to the space to make a four—dimensional world.

And it's not merely an artificial addition to say, "Well, we add time to space, because, as is seen in most of the popular books, you cannot only locate a point, but you have to say when." That's all true, but that doesn't make it real space; that just puts two things together. Real space has, in a sense, the characteristic that ... it's possible to look at it from a different point of view, that it has an existence that's independent of the particular point of view. There's a commonness—there's a certain amount of time that can get mixed up with a certain amount of space, so that space and time must be completely interlocked.

After this discovery, Minkowski said, "Space of itself, and time of itself, shall sink into mere shadows, and only a kind of union of the two shall survive." I bring this particular example up in such detail because it is really the beginning of the study of symmetries and physical laws. It was Poincaré's suggestion to make this analysis of what you can do to the equations and leave them alone. It was Poincaré's attitude to pay attention to the symmetries of physical laws: the symmetries of translation in space, delay in time, and so on, were not very deep, but the symmetry of uniform velocity in a straight line is very interesting, and has all kinds of consequences.

Furthermore, these consequences were extendable into laws that we did not know: by guessing that this principle is true with the disintegration of a mu meson (we don't know why the mu meson disintegrates in the first place), we can tell a lot about it by the proposition that we can't use mu mesons to tell how fast we're going in the spaceship either—and that tells us something, at least, about the mu meson disintegrations.

There are many other symmetries of somewhat—some of are of different kinds.

I just mentioned a—another one is that you can replace one atom by another of the same kind, and it makes no difference to any phenomenon. Now you say, "Yeah, what do you mean by the same kind?"—"I mean one where you replace it by the other it doesn't make any difference."

It looks like physicists are always talking nonsense in a way, doesn't it? Because there are many different kinds, and if you replace one [atom] by one of the different kind, it makes a difference, but if you replace one by the same kind, it doesn't make any difference—and that just seems like a circular definition. But the meaning of the thing is, that there are atoms of the same kind, that it is possible to find groups, classes of atoms, that you can replace one by another of the same kind, and it doesn't make any difference—there are such things.

Since the number of atoms in any little tiny piece of material is one followed by 23 naughts [zeros] or so, it's very important that they are the same—that they're not all different kinds. It's really very interesting that we can classify them into a limited number of a few hundred atoms, so that the statement that we can replace one atom by another of the same kind has a very great amount of content. It has the greatest amount of content in quantum mechanics, and it is impossible for me to explain how, partly. But only partly, because this is an audience that is mathematically untrained. It's quite subtle, anyhow. But in quantum mechanics the proposition that you can replace one atom by the same kind has marvelous consequences that produces peculiar phenomena—in liquid helium, the liquid that flows through pipes without any resistance, just coasts on forever; it has all kinds of consequences—in fact, it's the origin of the whole periodic table of the elements, and the force that keeps me from going through the floor. But I can't go into that particular thing, but I want to emphasize the importance of looking at these principles.

By this time, you're probably convinced that all the laws of physics are symmetric under any kind of change whatsoever, so I have to give a few ones that don't work. First one, change of scale: it is not true that if you build an apparatus, and come over here and build one twice as big—every part made exactly the same, same kind of stuff but twice as big-that it will work exactly the same way. You who are familiar with atoms are aware of this fact, because if I made it 10 billion times smaller, I would only have five atoms in it-and I can't make a machine tool, which this thing is, with screw threads, and so on, out of five atoms.

So it's perfectly obvious, if we go far enough, that we can't change the scale. But even before the complete awareness of the atomic picture was developed, it became apparent that this law isn't right. You've probably seen in the newspapers from time to time somebody who's made a cathedral with matchsticks-several floors, and beautifully delicate, and everything just-more Gothic than any Gothic cathedral has ever been, more delicate. Why don't we build big ones like that, with great logs, with the same degree of ginger cake, the same enormous degree of detail? The answer is, if we did, it would be so high, and so heavy, it would collapse. You say, "Yeah, but you forgot when you're comparing two things, you must change everything that's in the system: the little cathedral made with matchsticks is attracted to the earth, so to make the comparison, I should make the big cathedral, like, attract it to an even bigger earth!" Too bad: a bigger earth would attract it even more, and the sticks would break even more surely."

This fact, that the laws of physics were [not] unchanged under scale was first discovered by Galileo. He argued, in discussing the strength of rods and bones—he argued that if you need a bone for a bigger animal (say, an animal is twice as high, wide, and thick), you need eight times the weight—so you need a bone that can hold the strength eight times. But what a bone can hold depends on its cross section, and if you made the bone twice as big, it would only have four times the cross section, and would only be able to support four times the weight.

In Galileo’s book called Two New Sciences, you’ll see pictures of imaginary bones of enormous dogs, way out of proportion. Galileo felt that the discovery—I suppose he felt, I don’t know, but the discovery-of the fact that the laws of nature are not unchanged on the change of scale was as important as his laws of motion, because they’re both put together in a tome called Two New Sciences.

Now, I go on to another example of something that is not a symmetry law, and that is, it is not true that if you’re spinning at a uniform angular speed in a spaceship, you can’t tell if you’re going around; you can: everything gets thrown to the walls. I was going to say you get dizzy, but that soon passes. There are a lot of effects, however: things do get thrown to the walls from the centrifugal force, or however you wish to describe it. (I hope that there’s no teachers of freshman physics here to correct me!) But it is possible to tell that the earth is rotating by a pendulum, or by a gyroscope, and you’re probably aware, in various observatories and museums, and so on, of these Foucault pendulums that prove the earth is rotating, without looking at the stars. So it is possible to tell that we are going around at a uniform angular velocity on the earth without looking outside, because the laws of physics are not unchanged by that. Many people have proposed that really you’re rotating relative to the galaxies, see, and if you would turn the galaxies, too, it wouldn’t make any difference.

Well, I don’t know what would happen if you would turn the whole universe, and we have, at the moment, no way to tell—nor, at the moment, do we have a theory which describes the influence of a galaxy on things here so that it comes out of this theory in a straightforward way (not by cheating, or forcing, or anything like that, [but] in a straightforward way) that the inertia for rotation—that the effects of rotation, the fact that a spinning bucket of water has a shape into a surface like this-that this is a result of a force from the objects around. That’s not known to be the case. That this should be the case was called Mach’s principle—but that it is the case has not yet been demonstrated.

But the real question is—I mean, the more direct, experimental question is—that if we’re rotating at a uniform velocity relative to the nebulae, do we see an effect? The answer is yes. If we’re moving in a spaceship at a uniform velocity in a straight line relative to the nebulae, do we see an effect? The answer is no—two different things. So, don't say all motion is relative; that's not the content of relativity. Relativity says that uniform velocity in a straight line, relative to the nebulae, is undetectable.

Now the next symmetry law that I would like to discuss is an interesting one, because it has an interesting history, and that's the question of reflection in space. If I build a piece of apparatus, let's say a clock, and then I come over here, and I build another clock exactly the same way, but like this one looks in the mirror. I don't mean I look at this one in a mirror only; I mean I build another clock which is exact built, to be a "Chinese copy" of what the other one looks like in a mirror. In other words, I have the number 2 painted neatly on the dial here; then I paint the number 2 the other way around over here. (I got an opportunity to make a drawing: 2 on one part, [backwards] 2 on the other part.) Each spring which is wound one way in one part, is wound in the corresponding opposite way in the other clock; they match each other like two gloves, right and left. Now we wind up the two clocks; we set them in corresponding positions (I was going to say the same, but we set them to the mirrored positions) and we let them tick.

Question: will they always agree with each other? Will all the machinery of the clock go in the mirror image of the other one? I don't know what you would guess about that; you'd probably guess it's true, and most people did guess it was true. Of course, we're not talking about geography; we can distinguish right and left by geography: we can say if we stand in Florida and look at New York, the ocean is on the right-and that distinguishes right and left ... and if the clock involved the water of the sea, and New York and so on, then it wouldn't work if you built it the other way because its ticker wouldn't get in the water.

But what we have to imagine, of course, is that the geography of the earth is turned around, too, on the other clock—anything that's involved must be turned around. Nor are we interested in history: for example, if you pick up a screw in a machine shop, the chances are it's right—hand thread, and you might argue the other clock isn't going to be the same as this one, because it's harder to get the screws—but that's just a question of what kind of things we make. So that altogether, the first guess is, that it doesn't make any difference.

It turns out that the laws of gravitation are such that it wouldn't make any difference, if it worked by gravity. The laws of electricity and magnetism are such that if, in addition, it had electric and magnetic guts (currents and wires and whatnot), it would still-the corresponding clock would run the same. And if the clock involved nuclear reactions—ordinary nuclear reactions—to make it run, it wouldn't make any difference either, but it does make a little bit of difference; I'll come to what makes a difference in a minute.

But the first possibility (it might suggest itself if you know anything much), you may have heard that it's possible to measure the concentration of sugar in water by putting polarized light through the water. If you put the piece of Polaroid that lets light through in a certain axis through the water, then you'll find ... when you watch the light as it goes through deeper and deeper sugarwater, you have to turn the Polaroid—another piece of Polaroid at the other end of the water—more and more to the right, as the stuff goes through. (Maybe it's to the left; I can't remember, but let's say to the right, as you go through deeper, deeper solution.) And if you make the light go the other way through the solution, it's still to the right—so there's a right—hand way; there's a difference for right or left.

So if we put sugarwater in the clocks, and light, then if we put, say, in one tank of [sugar] water and make the light go through, and turn, and put the Polaroid so it can just get through, and make the corresponding image on the other side, hoping the light will turn this way, it won't-it'll turn the other way, and it won't go through right. So by using sugarwater, our two clocks can be made differently. So it's a very remarkable fact.

It isn't true, therefore, at first [glance], that the two clocks will be—that the physical laws are symmetric for reflections. However, it's possible to make sugar in the laboratory. The sugar that we got that time might have been from sugar beets, but sugar isn't a complicated molecule, and it's possible to make sugar in the laboratory (out of carbon dioxide and water, and going through lots and lots of stages in between), and make artificial sugar. When you put the artificial sugar in there, which is chemically (and we measure it) every way it seems to be the same, it doesn't turn the light.

Then if you put bacteria in the sugarwater, bacteria eat the sugar—and when you let the bacteria eat the sugar, and then try with what's left, it turns out: first, they only eat half the sugar—[half of] the artificial sugar; second, when you're all done, it's turned to the left, the stuff that's left.

Now, you find the explanation to all this is the following: that sugar is a complicated molecule—a set of balls (atoms) in some complicated arrangement. If you make exactly the same arrangement, but left as right (like, if the arrangement is complicated like this, then you make one the same way), then every distance between every pair of atoms is the same in one as in the other; the energy of the molecules is exactly the same—for all chemical phenomena not involving light, they're the same. But living creatures find a difference: the bacteria eat one kind, and not the other. The sugar that comes from sugar beets is only one kind, all left—hand molecules—or right—hand, [I should say]—so it turns the light one way. The bacteria can only eat that kind of molecule. When we manufacture the sugar from substances which themselves are not asymmetrical (simple gasses), we make both kinds, in equal number. Then, if we let the bacteria eat, they'll eat the kind they can eat, and the other is left—and that's why it comes out the other way. It's possible to separate the two by looking through magnifying glasses at the crystals, and separating them, ... as Pasteur discovered, ... so that I can definitely show that all this makes sense. And even our artificial sugar, then, we can separate ourselves; we don't have to wait for the bacteria.

But the interesting thing is that the bacteria can do this. Does that mean that the living processes don't obey the same laws of chemistry, and so on? Apparently not. It seems that in the living creatures there are many, many complicated molecules, and they all have a kind of thread to them. One of the most characteristic molecules in living creatures are proteins, and it takes a little while to explain the details, but let's put it very simply, they have a corkscrew property and they go, let's say, to the right.

Now, as far as we can tell, chemically, we could make this, chemically, the same thing to the left. It would not function biologically, because it wouldn't, when it met the other proteins, fit the same way. That is, a left—hand thread'll fit a left—hand thread but a left and right don't fit very well the same way. So the bacteria having a left—hand thread in the chemical inside can distinguish the left and right sugar.

How did they get that way? Physics and chemistry cannot distinguish the molecules; it can only make both kinds—but biology can. It's easy to believe that the explanation is, that long, long ago, when the life processes first began, some accidental molecule got started and propagated itself by reproducing itself, and so on, until, after many, many years, these funny-looking blobs with the prongs sticking out yak at each other-but they are nothing but the offspring of the first few molecules, and it's an accident of the first few molecules that it happened to form one way instead of the other.

It has to be one or the other, so the thing that reproduces itself is either left or right, and then it goes on and propagates this on and on. It's much like the screws in the machine shop: we use right—hand thread screws to make new right—hand thread screws, and so on. So this is probably one of the deepest demonstrations—the fact that the protein molecules are exactly the same in all life, they all have exactly the same kind of thread-is probably one of the deepest demonstrations of the uniformity of the ancestry of life, the common ancestry of all life—back, in fact, to the completely molecular level.

Now, in order to test better this question about whether the laws of physics are same right and left, we can put the problem to ourselves this way.

Suppose that we were in telephone conversation with a Martian or an Arcturian, or something. We don't know where he is and we would like to describe things to him. We want to tell him about things. You say, so how's he going to understand the words, well, that's been studied very much by Professor Morrison here. He has pointed out that one way would be to start out and say tick tick two, tick tick tick three, and so on, and pretty soon the guy'd catch onto the numbers. Then—as he understands your number system, then—you can write lots of numbers and you could, for example, write a whole sequence of numbers that represents the weights, the proportional weights, of the different atoms, in succession.

Then say, hydrogen: 1.008, deuterium, and so on and so on. And he would-after he sat down with all those numbers and piddled around a while, would-discover that the mathematical ratios were the same as the ratios of the weights of the elements and, therefore, those names must be for the elements—and so gradually, you could, in talking to him, have a common language, in many ways, common. There are many-now comes the problem.

Suppose that he says, you fellas—after we get familiar with him, he says, "You're very nice; now I'd like to know what you look like." And you start out, "Well, we're about six feet tall." He says, "Six feet, how big is a foot?" "It's very easy," you say; "six feet tall is 170 thousand million hydrogen atoms high." Well, it's not a joke; it's a possible way of describing six feet to someone that has no measure, assuming that we cannot send him any samples, nor can we both look at the same object.

If we have to tell him how big we are; we can do it. That's because the laws of physics are not unchanged under a scale change. We can use that factor, use the properties of the scale to determine—I mean, you can use that fact to determine the scale.

Well, here we've described ourselves after telling six feet tall, and we're so-and-so bilateral on the outside, and we look like this, and there are these prongs sticking out, and all this. And he says, "That's very interesting; what do you look like on the inside?" So we describe the heart and so on, and we say, "Now, put the heart in on the left side." Now the question is, how can we tell him which side is the left side? By what possible-you say, "Aw, you take beet sugar, see, and you put it in water, and it turns." Only trouble is, he has no beets up there. Or, we have no way of knowing whether the evolution, if it was even corresponding to the same proteins on Mars as here, whether the accidents of the evolution would have started with maybe the wrong—handed threads—there's no way to tell. After much thought, you see you can't do it, so you conclude it's impossible.

However, about five or six years ago, certain experiments ... produced all kinds of puzzles (I won't go into details); we got into tighter and tighter difficulties, more and more paradoxical situations, until ... Lee and Yang proposed [that] maybe the principle that right and left symmetry—that nature's the same for right and left—is not right, and that would help to explain a number of mysteries.

Lee and Yang proposed some more direct experiments to demonstrate this. I'll just mention the most direct of all the experiments, the easiest way to tell ... (well, there were several "first" experiments which were quite clear, but the one that's easiest to explain) is this: that when we have a radioactive disintegration ... in which an electron and a neutrino are emitted (for example, this is one that we talked about before, electron and antineutrino); this is a neutron disintegrating into a proton, an electron, and an antineutrino, or this corresponding thing can happen to a neutron in a nucleus. Anyway, there are many radioactivities in which the charge of the nucleus increases by one, and an electron comes out.

The thing that's interesting is that if you measure the spin—electrons are spinning as they come out; if you measure the spin—you find out that they're spinning to the left. That is a definite significance: that the electron, when it comes out of disintegration, is turning this way; that helical description is a left—hand thread. It's as though, in the beta decay, the gun that was shooting out the electron were a rifled gun, and there's two ways to rifle a gun, because there's a direction—out—and then there's a question: do you turn it this way, or that way, as you go out? The experiment is, that the electrons come from a rifled gun, rifled and twisted to the left. And so, using this fact, we can call up the Martian and say, "Listen: take radioactive stuff" (I ought to have prepared a particular example) "a neutron-and look at the electrons which come from such a beta decay."

Then you define "left" by this screw thread. Let's see ... it'll take me some while to figure out how to do it in detail: say the electron's going up in the direction of motion, and the way it's spinning is into the body [from the back] on the left side—and that's where the heart goes—something like that. I'd have to think a little bit more on it.

But anyway, it is possible to tell right from left, and thus, the law of this—that the world was symmetrical for left and right—has collapsed.

... The next thing I would like to talk about is the relationship of conservation laws to symmetry laws. We last time talked about conservation principles—conservation of energy, of momentum, angular momentum, and so on; now we're talking about symmetry laws. It's extremely interesting that there seems to be a deep connection between the conservation laws and the symmetry laws. This connection has its proper interpretation, at least as we understand it today, only in the knowledge of quantum mechanics.

Nevertheless, I will show you the following; I will try to explain the following: if we will assume that the laws of physics are describable by a minimum principle—that the paths are taken so that some quantity is least (an idea I described once before); if we add that the laws of nature come from a minimum principle—then we can show that if the law is such that you can move all the equipment to one side (in other words, if it's translatable in space), then there must be conservation of momentum, that there's a deep connection between the symmetry principles and the conservation laws, but that that connection requires that the minimum principle be assumed.

You remember at one time we discussed one way of describing physical laws, by saying that a particle goes from one place to another in a given length of time by trying different paths, and the actual path taken has this property: that there's a certain quantity, which unfortunately happens to be called the action (which is not to be taken to signify anything, because it's got nothing to do with action); anyway, there's a certain quantity called the action, which you calculate on this path, and if you will calculate it for any other path, the answer's bigger. It's least for the real path, and that one way of describing the laws of nature is to say that the action—a certain mathematical quantity—is least for the actual path, than for any other path.

Now, another way of saying the thing is least is to say this: that if you move the path a little bit, at first it doesn't make any difference. Suppose you were walking around ... on mountains, on hills—but smooth hills, please, smooth—the mathematical things that are involved here correspond to smooth things. We're walking around on hills and valleys, and we come to a place where we're lowest. Then I say, if you take a small step forward you won't change your height. When you're at the lowest (or at the highest) point, a step doesn't make any difference in the altitude, in first approximation, whereas, if you're on a slope, you can walk down the slope with a step—and then if you take the step in the opposite direction, you walk up. That's the key to the reason why, when you're at the lowest place, taking a step doesn't make much difference, because if it did make any difference you could put the step in the opposite direction, you'd go down-I mean, if it went up one way, it would go down another way, but since this is the lowest point and you can't go down, in first approximation the step doesn't make any difference. We therefore know that if we move this path a little bit, in first approximation it doesn't make any difference to the action.

Now, I want you to consider the following possible other path. First, we jump immediately over to another place here nearby. Then, we go along—(this sticks out too far to make the diagram clear, so if you'll permit me to just change the shape of the path)—we move on exactly the corresponding path to another point, here, which is displaced the same amount, of course; this is the corresponding path, to the side. Now we have just discovered that the laws of nature are such that the action—the total amount of action—going on this path is the same, in first approximation, to that path. That's from a minimum principle, when it's the real motion.

Now, I show you something else. That the action on this path is the same as the action from this little cross to that little cross if the world is the same when you move everything over, because the difference of these two is only that you moved everything over. If the symmetry principle of translation in space is right, if that's right, then the total action between the crosses is the same as between the dots. But for the true motion, the total action on this cockeyed path here is about—is very closely—the same as for the original one (subtracting equals from equals, and so on, and so on); anyway, you could probably see, therefore, that the contribution from this little section and from this little section are equal. But in making this little motion, we're going this way, and making this one, we're going the other way.

... So the contribution of this, taken as the effect of moving that way, and the contribution of this, thinking of it as an effect of moving that way, but making it the other sign (because it's the other way), we see that there is a quantity here which has to match the quantity here, to cancel out—which is the effect on the action of a little tiny step in the X direction: there is that quantity, the effect on the action of a small step in the X direction, [that] is the same at the beginning as at the end. There is a quantity, therefore, that doesn't change as time goes on, provided the minimum principle works, and the symmetry principle of displacement in space is right.

Now, this quantity which doesn't change is, in fact, exactly the momentum that we discussed last time. A corresponding argument for the displacement in time, the delay in time, comes out as a conservation of energy; the case that if we rotate in space doesn't make any difference, comes out as the conservation of angular momentum, and so on. That we can reflect and it makes no difference doesn't come out to be anything simple, in the classical sense; it hasn't, therefore, got a simple classical interpretation. People have called it parity, and they have a conservation law called the conservation of parity, but those are just complicated words in the case of the quantum mechanics; all we're saying is, that the right and left symmetry law is not valid.

I have to mention that conservation of parity, because you may have read in the papers that the law of conservation of parity has been proved wrong; it should have been written, because it's much easier to understand, [that] the principle that you can't distinguish right and left has been proved wrong.

Now, I would like to say, as we go on about other symmetries, that there are a few problems—new problems: for instance, for every particle, like an electron, there's an antiparticle (a positron). For a proton, there's an antiproton. We can make, in principle, what we call antimatter, in which every atom has its corresponding anti pieces put together. For example, a hydrogen atom is a proton and an electron. If we take an antiproton, which is electrically negative, and a positron, and put them together, they will also make a kind of hydrogen atom, an antihydrogen atom—in principle; it's never been made, in fact, but this is figured out, that we could make this—we could make all kinds of antimatter in the same manner.

Well, the question is, whether the matter works the same as the antimatter. As far as we know, it does. One of the laws of symmetry is that if we make stuff out of antimatter, it'll behave the same way as do when we make the corresponding stuff out of matter. (Of course if they come together they annihilate; there would be sparks and everything else.) It was believed that this is true: that matter and antimatter have the same laws.

Now, the next question is this: once it's found that the left and right is wrong (the left and right symmetry is wrong), an important question comes.

... If I look at this disintegration, but with antimatter—an antineutron goes into an antiproton plus an antielectron (that's a positron) plus a neutrino—the question is, does the antimatter behave like the matter in the sense that it comes out left-hand thread, or does it behave the other way? It turns out, we think (up until a few months ago), that it behaves the opposite way; that the antimatter behaves like it goes to the right, where matter goes to the left. And so there was another principle—and [therefore], in fact, we really can't tell a Martian which is right and left, because if he happens to be made out of antimatter, he'd get the thing the other way, because when he does his experiment, his positrons are coming out, puts the heart on the wrong side. And so you can see that if the Martian—if you telephone the Martian, and explain how to make a man, and suppose he makes one and it works, ... and you explain to him also all our social conventions, and so on.

Then when we go finally to meet this man (after he tells us how to build a sufficiently good spaceship), we go to meet this man, and you walk up to him and you put out your right hand to shake hands—if he puts out his right hand, okay, but if he puts out his left hand, watch out, because the two of you will annihilate with each other!

Now, these are all the symmetries that I have time to tell you about; I wish I could tell you about a few more, but they become more difficult technically to explain. ... There are some very remarkable things, which are the near symmetries, the remarkable feature of this effect (that we can distinguish right and left) is that we can distinguish right and left only with a very weak effect, with this beta disintegration.

What it means, that nature is 99.99 indistinguishable right from left, but that there's just one little piece, one little characteristic phenomenon, which is completely different in the sense that it's absolutely lopsided, is a mystery that no one has the slightest idea about yet.

Thank you.