ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed, and the laws will turn out to be simple, like the chequer board with all its apparent complexities. But this speculation is of the same nature as those other people make – 'I like it', 'I don't like it', – and it is not good to be too prejudiced about these things.

To summarize, I would use the words of Jeans, who said that 'the Great Architect seems to be a mathematician'. To those who do not know mathematics it is difficult to get across a real feeling as to the beauty, the deepest beauty, of nature. C. P. Snow talked about two cultures. I really think that those two cultures separate people who have and people who have not had this experience of understanding mathematics well enough to appreciate nature once.

It is too bad that it has to be mathematics, and that mathematics is hard for some people. It is reputed – I do not know if it is true – that when one of the kings was trying to learn geometry from Euclid he complained that it was difficult. And Euclid said, 'There is no royal road to geometry'. And there *is* no royal road. Physicists cannot make a conversion to any other language. If you want to learn about nature, to appreciate nature, it is necessary to understand the language that she speaks in. She offers her information only in one form; we are not so unhumble as to demand that she change before we pay any attention.

All the intellectual arguments that you can make will not communicate to deaf ears what the experience of music really is. In the same way all the intellectual arguments in the world will not convey an understanding of nature to those of 'the other culture'. Philosophers may try to teach you by telling you qualitatively about nature. I am trying to describe her. But it is not getting across because it is impossible. Perhaps it is because their horizons are limited in this way that some people are able to imagine that the centre of the universe is man.

3

The Great Conservation Principles

When learning about the laws of physics you find that there are a large number of complicated and detailed laws, laws of gravitation, of electricity and magnetism, nuclear interactions, and so on, but across the variety of these detailed laws there sweep great general principles which all the laws seem to follow. Examples of these are the principles of conservation, certain qualities of symmetry, the general form of quantum mechanical principles, and unhappily, or happily, as we considered last time, the fact that all the laws are mathematical. In this lecture I want to talk about the conservation principles.

The physicist uses ordinary words in a peculiar manner. To him a conservation law means that there is a number which you can calculate at one moment, then as nature undergoes its multitude of changes, if you calculate this quantity again at a later time it will be the same as it was before, the number does not change. An example is the conservation of energy. There is a quantity that you can calculate according to a certain rule, and it comes out the same answer always, no matter what happens.

Now you can see that such a thing is possibly useful. Suppose that physics, or rather nature, is considered analogous to a great chess game with millions of pieces in it, and we are trying to discover the laws by which the pieces move. The great gods who play this chess play it very rapidly, and it is hard to watch and difficult to see. However, we are catching on to some of the rules, and there are some rules which we can work out which do not require that we watch every move. For instance, suppose there is one bishop only, a red bishop, on the board, then since the bishop moves diagonally and therefore never changes the colour of its square, if we look away for a moment while the gods play and then look back again, we can expect that there will be still a red bishop on the board, maybe in a different place, but on the same colour square. This is in the nature of a conservation law. We do not need to watch the insides to know at least something about the game.

It is true that in chess this particular law is not necessarily perfectly valid. If we looked away long enough it could happen that the bishop was captured, a pawn went down to queen, and the god decided that it was better to hold a bishop instead of a queen in the place of that pawn, which happened to be on a black square. Unfortunately it may well turn out that some of the laws which we see today may not be exactly perfect, but I will tell you about them as we see them at present.

I have said that we use ordinary words in a technical fashion, and another word in the title of this lecture is 'great', 'The Great Conservation Principles'. This is not a technical word: it was merely put in to make the title sound more dramatic, and I could just as well have called it 'The Conservation Laws'. There are a few conservation laws that do not work; they are only approximately right, but are sometimes useful, and we might call those the 'little' conservation laws. I will mention later one or two of those that do not work, but the principal ones that I am going to discuss are, as far as we can tell today, absolutely accurate.

I will start with the easiest one to understand, and that is the conservation of electric charge. There is a number, the total electric charge in the world, which, no matter what happens, does not change. If you lose it in one place you will find it in another. The conservation is of the total of all electric charge. This was discovered experimentally by Faraday.* The experiment consisted of getting inside a great globe of metal, on the outside of which was a very delicate galvanometer, to look for the charge on the globe,

*Michael Faraday, 1791–1867, English physicist.

because a small amount of charge would make a big effect. Inside the globe Faraday built all kinds of weird electrical equipment. He made charges by rubbing glass rods with cat's fur, and he made big electrostatic machines so that the inside of this globe looked like those horror movie laboratories. But during all these experiments no charge developed on the surface; there was no net charge made. Although the glass rod may have been positive after it was charged up by rubbing on the cat's fur, then the fur would be the same amount negative, and the total charge was always nothing, because if there were any charge developed on the inside of the globe it would have appeared as an effect in the galvanometer on the outside. So the total charge is conserved.

This is easy to understand, because a very simple model, which is not mathematical at all, will explain it. Suppose the world is made of only two kinds of particles, electrons and protons – there was a time when it looked as if it was going to be as easy as that – and suppose that the electrons carry a negative charge and the protons a positive charge, so that we can separate them. We can take a piece of matter and put on more electrons, or take some off; but supposing that electrons are permanent and never disintegrate or disappear – that is a simple proposition, not even mathematical – then the total number of protons, less the total number of electrons, will not change. In fact in this particular model the total number of protons will not change, nor the number of electrons. But we are concentrating now on the charge. The contribution of the protons is positive and that of the electrons negative, and if these objects are never created or destroyed alone then the total charge will be conserved. I want to list as I go on the number of properties that conserve quantities, and I will start with charge (fig. 14). Against the question whether charge is conserved I write 'yes'.

This theoretical interpretation is very simple, but it was later discovered that electrons and protons are not permanent; for example, a particle called the neutron can disintegrate into a proton and an electron – plus something else

	Charge	Baryon No.	Strangeness	Energy	Angular Momentum
Conserved (locally)	Yes	Yes	Nearly	Yes	Yes
Comes in Units	Yes	Yes	Yes	No	Yes
Source of a Field	Yes	?	?	Yes	

NB This is the completed table which Professor Feynman added to throughout his lecture.

Figure 14

which we will 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; starting before, we had zero charge, and afterwards we had plus one and minus one which when added together become zero charge.

An example of a similar fact is that there exists another particle, besides the proton, which is positively charged. It is called a positron, which is a kind of image of an electron. It is just like the electron in most respects, except that it has the opposite sign of charge, and, more important, it is called an anti-particle because when it meets with an electron the two of them can annihilate each other and disintegrate, and nothing but light comes out. So electrons are not permanent even by themselves. An electron plus a positron will just make light. Actually the 'light' is invisible to the eye; it is gamma rays; but this is the same thing for a physicist, only the wavelength is different. So a particle and its anti-particle can annihilate. The light has no electric

charge, but we remove one positive and one negative charge, so we have not changed the total charge. The theory of conservation of charge is therefore slightly more complicated but still very unmathematical. You simply add together the number of positrons you have and the number of protons, take away the number of electrons – there are additional particles you have to check, for example anti-protons which contribute negatively, pi-plus mesons which are positive, in fact each fundamental particle in nature has a charge (possibly zero). All we have to do is add up the total number, and whatever happens in any reaction the total amount of charge on one side has to balance with the amount on the other side.

That is one aspect of the conservation of charge. Now comes an interesting question. Is it sufficient to say only that charge is conserved, or 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 another within the box. But another possibility is that the charge in one place disappears, and simultaneously charge arises in another place, instantaneously related, and in such a manner that the total charge is never changing. This second possibility for the conservation is of a different kind from the first, in which if a charge disappears in one place and turns up in another something has to travel through the space in between. The second form of charge conservation is called local charge conservation, and is far more detailed than the simple remark that the total charge does not change. So you see we are improving our law, if it is true that charge is locally conserved. In fact it is true. I have tried to show you from time to time some of the possibilities of reasoning, of interconnecting one idea with another, and I would now like to describe to you an argument, fundamentally due to Einstein, which indicates that if anything is conserved – and in this case I apply it to charge – it must be conserved locally. This argument relies on one thing, that if two fellows are passing each other in space ships, the question of which guy is doing the moving and which one standing still cannot be resolved by any experiment. That is called the principle of relativity, that uniform motion in a straight line is relative, and that we can look at any phenomenon from either point of view and cannot say which one is standing still and which one is moving.

Suppose I have two space ships, A and B (fig. 15). I am

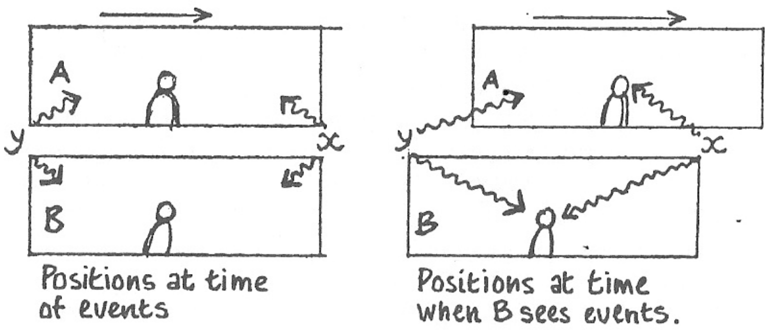

Figure 15

going to take the point of view that A is the one that is moving past B. Remember that is just an opinion, you can also look it at the other way and you will get the same phenomena of nature. Now suppose that the man who is standing still wants to argue whether or not he has seen a charge at one end of his ship disappear and a charge at the other end appear at the same time. In order to make sure it is the same time he cannot sit in the front of the ship, because he will see one before he sees the other because of the travel time of light; so let us suppose that he is very careful and sits dead centre in the middle of the ship. We have another man doing the same kind of observation in the other ship. Now a lightning bolt strikes, and charge is created at point x, and at the same instant at point y at the

other end of the ship the charge is annihilated, it disappears. At the same instant, note, and perfectly consistent with our idea that charge is conserved. If we lose one electron in one place we get another elsewhere, but nothing passes in between. Let us suppose that when the charge disappears there is a flash, and when it is created there is a flash, so that we can see what happens. B says they both happen at the same time, since he knows he is in the middle of the ship and the light from the bolt which creates x reaches him at the same time as the light from the flash of disappearance at y. Then B will say, 'Yes, when one disappeared the other was created'. But what happens to our friend in the other ship? He says, 'No, you are wrong my friend. I saw x created before y'. This is because he is moving towards x, so the light from x will have a shorter distance to travel than the light from y, since he is moving away from y. He could say, 'No, x was created first and then y disappeared, so for a short time after x was created and before y disappeared I got some charge. That is not the conservation of charge. It is against the law'. But the first fellow says, 'Yes, but you are moving'. Then he says, 'How do you know? I think you are moving', and so on. If we are unable, by any experiment, to see a difference in the physical laws whether we are moving or not, then if the conservation of charge were not local only a certain kind of man would see it work right, namely the guy who is standing still, in an absolute sense. But such a thing is impossible according to Einstein's relativity principle, and therefore it is impossible to have non-local conservation of charge. 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. You can appreciate that if anything is conserved the same principle applies.

There is another interesting thing about charge, a very strange thing for which we have no real explanation today. It has nothing to do with the conservation law and is independent of it. Charge always comes in units. When we have a charged particle it has one charge or two charges, or minus one or minus two. Returning to our table, although this has nothing to do with the conservation of charge, I must write down that the thing that is conserved comes in units. It is very nice that it comes in units, because that makes the theory of conservation of charge very easy to understand. It is just a *thing* we can count, which goes from place to place. Finally it turns out technically that the total charge of a thing is easy to determine electrically because the charge has a very important characteristic; it is the source of the electric and magnetic field. Charge is a measure of the interaction of an object with electricity, with an electric field. So another item which we should add to the list is that charge is the source of a field; in other words, electricity is related to charge. Thus 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 is the source of a field.

There are many conservation laws, and I will give some more examples of laws of the same type as the conservation of charge, in the sense that it is merely a matter of counting. There is a conservation law called the conservation of baryons. A neutron can go into a proton. If we count each of these as one unit, or baryon, then we do not lose the number of baryons. The neutron carries one baryonic charge unit, or represents one baryon, a proton represents one baryon – all we are doing is counting and making big words! – so if the reaction I am speaking of occurs, in which a neutron decays into a proton, an electron and an anti-neutrino, the total number of baryons does not change. However there are other reactions in nature. A proton plus a proton can produce a great variety of strange objects, for example a lambda, a proton and a K plus. Lambda and K plus are names for peculiar particles.

$$\text{(easy)}\ P + P \rightarrow \lambda + P + K^{+}$$

In this reaction we know we put two baryons in, but we see only one come out, so possibly either lambda or K^{+} has a baryon. If we study the lambda later we discover that very slowly it disintegrates into a proton and a pi, and ultimately the pi disintegrates into electrons and what-not.

$$\text{(slow)}\ \lambda \rightarrow P + \pi$$

What we have here is the baryon coming out again in the proton, so we think the lambda has a baryon number of 1, but the K^{+} does not, the K^{+} has zero.

On our chart of conservation laws (fig. 14), then, we have charge and now we have a similar situation with baryons, 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 anti-protons, minus the number of anti-neutrons, and so on; it is just a counting proposition. It is conserved, it comes in units, and nobody knows but everybody wants to think, by analogy, that it is the source of a field. The reason we make these tables is that we are trying to guess at the laws of nuclear interaction, and this is one of the quick ways of guessing at nature. If charge is the source of a field, and baryon does the same things in other respects it ought to be the source of a field too. Too bad that so far it does not seem to be, it is possible, but we do not know enough to be sure.

There are one or two more of these counting propositions, for example Lepton numbers, and so on, but the idea is the same as with baryons. There is one, however, which is slightly different. There are in nature among these strange particles characteristic rates of reaction, some of which are very fast and easy, and others which are very slow and hard. I do not mean easy and hard in a technical sense, in actually doing the experiment. It concerns the rates at which the reactions occur when the particles are present. There is a clear distinction between the two kinds of reaction which I have mentioned above, the decay of a pair of protons, and the much slower decay of the lambda. It turns out that if you take only the fast and easy reactions there is one more counting law, in which the lambda gets a minus 1, and the K plus gets a plus 1, and the proton gets zero. This is called the strangeness number, or hyperon charge, and it appears that the rule that it is conserved is right for every easy reaction, but wrong for the slow reactions. On our chart (fig. 14) we must therefore add the conservation law called the conservation of strangeness, or the conservation of hyperon number, which is nearly right. This is very peculiar; we see why this quantity has been called strangeness. It is nearly true that it is conserved, and true that it comes in units. In trying to understand the strong interactions which are involved in nuclear forces, the fact that in strong interactions the thing is conserved has made people propose that for strong interactions it is also the source of a field, but again we do not know. I bring these matters up to show you how conservation laws can be used to guess new laws.

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 is possible to transmute atoms from one element to another so that the original element has completely disappeared. Another law which was for a while believed to be true was that the total mass of an object stays the same. This depends on how you define mass, and whether you get mixed up with energy. The mass conservation law is contained in the next one which I am going to discuss, the law of conservation of energy. Of all the conservation laws, that dealing with energy is the most difficult and abstract, and yet the most useful. It is more difficult to understand than those I have described so far, because in the case of charge, and the others, the mechanism is clear, it is more or less the conservation of objects. This is not absolutely the case, because of the problem that we get new things from old things, but it is really a matter of simply counting.

The conservation of energy is a little more difficult, because this time we have a number which is not changed in time, but this number does not represent any particular thing. I would like to make a kind of silly analogy to explain a little about it.

I want you to imagine that a mother has a child whom she leaves alone in a room with 28 absolutely indestructible blocks. The child plays with the blocks all day, and when the mother comes back she discovers that there are indeed 28 blocks; she checks all the time the conservation of blocks! This goes on for a few days, and then one day when she comes in there are only 27 blocks. However, she finds one block lying outside the window, the child had thrown it out. The first thing you must appreciate about conservation laws is that you must watch that the stuff you are trying to check does not go out through the wall. The same thing could happen the other way, if a boy came in to play with the child, bringing some blocks with him. Obviously these are matters you have to consider when you talk about conservation laws. Suppose one day when the mother comes to count the blocks she finds that there are only 25 blocks, but suspects that the child has hidden the other three blocks in a little toy box. So she says, 'I am going to open the box'. 'No,' he says, 'you cannot open the box.' Being a very clever mother she would say, 'I know that when the box is empty it weighs 16 ounces, and each block weighs 3 ounces, so what I am going to do is to weigh the box'. So, totalling up the number of blocks, she would get –

$$\text{No. of blocks seen} + \frac{\text{Weight of box} - 16\text{ oz.}}{3\text{ oz.}}$$

and that adds up to 28. This works all right for a while, and then one day the sum does not check up properly. However, she notices that the dirty water in the sink is changing its level. She knows that the water is 6 inches deep when there is no block in it, and that it would rise $\frac{1}{4}$ inch if a block was