in the water, so she adds another term, and now she has –

$$\text{No. of blocks seen} + \frac{\text{Weight of box} - 16\text{ oz.}}{3\text{ oz.}} + \frac{\text{Ht. of Water} - 6\text{ in.}}{\frac{1}{4}\text{ in.}}$$

and once again it adds up to 28. As the boy becomes more ingenious, and the mother continues to be equally ingenious, more and more terms must be added, all of which represent blocks, but from the mathematical standpoint are abstract calculations, because the blocks are not seen.

Now I would like to draw my analogy, and tell you what is common between this and the conservation of energy, and what is different. First suppose that in all of the situations you never saw any blocks. The term 'No. of blocks seen' is never included. Then the mother would always be calculating a whole lot of terms like 'blocks in the box', 'blocks in the water', and so on. With energy there is this difference, that there are no blocks, so far as we can tell. Also, unlike the case of the blocks, for energy the numbers that come out are not integers. I suppose it might happen to the poor mother that when she calculates one term it comes out $6\frac{1}{8}$ blocks, and when she calculates another it comes out $\frac{7}{8}$ of a block, and the others give 21, which still totals 28. That is how it looks with energy.

What we have discovered about energy is that we have a scheme with a sequence of rules. From each different set of rules we can calculate a number for each different kind of energy. When we add all the numbers together, from all the different forms of energy, it always gives the same total. But as far as we know there are no real units, no little ball-bearings. It is abstract, purely mathematical, that there is a number such that whenever you calculate it it does not change. I cannot interpret it any better than that.

This energy has all kinds of forms, analogous to the blocks in the box, blocks in the water, and so on. There is energy due to motion called kinetic energy, energy due to gravitational interaction (gravitational potential energy, it

is called), thermal energy, electrical energy, light energy, elastic energy in 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 directly on its mass. The last is the contribution of Einstein, as you undoubtedly know. $E = mc^2$ is the famous equation of the law I am talking about.

Although I have mentioned a large number of energies, I would like to explain that we are not completely ignorant about this, and we do understand the relationship of some of them to others. For instance, what we call thermal energy is to a large extent merely the kinetic energy of the motion of the particles inside an object. Elastic energy and chemical energy both have the same origin, namely the forces between the atoms. When the atoms rearrange themselves in a new pattern some energy is changed, and if that quantity changes it means that some other quantity also has to change. For example, if you are burning something the chemical energy changes, and you find heat where you did not have heat before, because it all has to add up right. Elastic energy and chemical energy are both interactions of atoms, and we now understand these interactions to be a combination of two things, one electrical energy and the other kinetic energy again, only this time the formula for it is quantum mechanical. Light energy is nothing but electrical energy, because light has now been interpreted as an electric and magnetic wave. Nuclear energy is not represented in terms of the others; at the moment I cannot say more than that it is the result of nuclear forces. I am not just talking here about the energy released. In the uranium nucleus there is a certain amount of energy, and when the thing disintegrates the amount of energy remaining in the nucleus changes, but the total amount of energy in the world does not change, so a lot of heat and stuff is generated in the process, in order to balance up.

This conservation law is very useful in many technical ways. I will give you some very simple examples to show how, knowing the law of conservation of energy and the formulae for calculating energy, we can understand other laws. In other words many other laws are not independent, but are simply secret ways of talking about the conservation of energy. The simplest is the law of the lever (fig. 16).

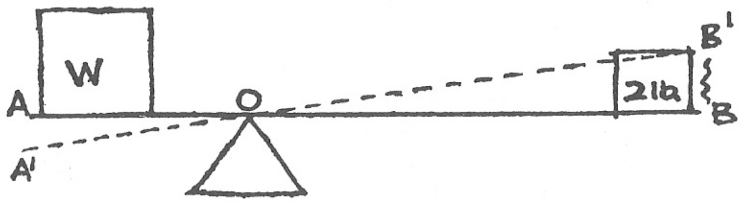

Figure 16

We have a lever on a pivot. The length of one arm is 1 foot and the other 4 feet. First I must give the law for gravity energy, which is that if you have a number of weights, you take the weight of each and multiply it by its height above the ground, add this together for all the weights, and that gives the total of gravity energy. Suppose I have a 2 lb weight on the long arm, and an unknown mystic weight on the other side – X is always the unknown, so let us call it W to make it seem that we have advanced above the usual! Now the question is, how much must W be so that it just balances and swings quietly back and forth without any trouble? If it swings quietly back and forth, that means that the energy is the same whether the balance is parallel to the ground or tilted so that the 2 lb weight is, say, 1 inch above the ground. If the energy is the same then it does not care much which way, and it does not fall over. If the 2 lb weight goes up 1 inch how far down does W go? From the diagram you can see (fig. 3) that if AO is 1 foot and OB is 4 feet, then when BB′ is 1 inch AA′ will be $\frac{1}{4}$ inch. Now apply the law for gravity energy. Before anything happened all the heights were zero, so the total energy was zero. After the move has happened to get the gravity energy we multiply the weight 2 lb by the height 1 inch and add it to the

unknown weight W times the height – $\frac{1}{4}$ inch. The sum of this must give the same energy as before – zero. So –

$$2 - \frac{W}{4} = 0, \text{ so } W \text{ must be } 8$$

This is one way we can understand the easy law, which you already knew of course, the law of the lever. But it is interesting that not only this but hundreds of other physical laws can be closely related to various forms of energy. I showed you this example only to illustrate how useful it is.

The only trouble is, of course, that in practice it does not really work because of friction in the fulcrum. If I have something moving, for example a ball rolling along at a constant height, then it will stop on account of friction. What happened to the kinetic energy of the ball? The answer is that the energy of the motion 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 like a nice round ball when we polish it, but it is really quite complicated when looked at on a little scale; billions of tiny atoms, with all kinds of irregular shapes. It is like a very rough boulder when looked at finely enough, because it is made out of these little balls. The floor is the same, a bumpy business made out of balls. When you roll this monster boulder over the magnified floor you can see that the little atoms are going to go snap-jiggle, snap-jiggle. After the thing has rolled across, the ones that are left behind are still shaking a little from the pushing and snapping that they went through; so there is left in the floor a jiggling motion, or thermal energy. At first it appears as if the law of conservation is false, but energy has the tendency to hide from us and we need thermometers and other instruments to make sure that it is still there. We find that energy is conserved no matter how complex the process, even when we do not know the detailed laws.

The first demonstration of the law of conservation of energy was not by a physicist but by a medical man. He demonstrated with rats. If you burn food you can find out how much heat is generated. If you then feed the same amount of food to rats it is converted, with oxygen, into carbon dioxide, in the same way as in burning. When you measure the energy in each case you find out that living creatures do exactly the same as non-living creatures. The law for conservation of energy is as true for life as for other phenomena. Incidentally, it is interesting that every law or principle that we know for 'dead' things, and that we can test on the great phenomenon of life, works just as well there. There is no evidence yet that what goes on in living creatures is necessarily different, so far as the physical laws are concerned, from what goes on in non-living things, although the living things may be much more complicated.

The amount of energy in food, which will tell you how much heat, mechanical work, etc., it can generate, is measured in calories. When you hear of calories you are not eating something called calories, that is simply the measure of the amount of heat energy that is in the food. Physicists sometimes feel so superior and smart that other people would like to catch them out once on something. I will give you something to get them on. They should be utterly ashamed of the way they take energy and measure it in a host of different ways, with different names. It is absurd that energy can be measured in calories, in ergs, in electron volts, in foot pounds, in B.T.U.s, in horsepower hours, in kilowatt hours – all measuring exactly the same thing. It is like having money in dollars, pounds, and so on; but unlike the economic situation where the ratio can change, these dopey things are in absolutely guaranteed proportion. If anything is analogous, it is like shillings and pounds – there are always 20 shillings to a pound. But one complication that the physicist allows is that instead of having a number like 20 he has irrational ratios like 1·6183178 shillings to a pound. You would think that at least the more modern high-class theoretical physicists would use a common unit, but you find papers with degrees Kelvin for measuring energy, mega-

cycles, and now inverse Fermis, the latest invention. For those who want some proof that physicists are human, the proof is in the idiocy of all the different units which they use for measuring energy.

There are a number of interesting phenomena in nature which present us with curious problems concerning energy. There has been a recent discovery of things called quasars, which are enormously far away, and they radiate so much energy in the form of light and radio waves that the question is where does it come from? If the conservation of energy is right, the condition of the quasar after it has radiated this enormous amount of energy must be different from its condition before. The question is, is it coming from gravitation energy – is the thing collapsed gravitationally, in a different condition gravitationally? Or is this big emission coming from nuclear energy? Nobody knows. You might propose that perhaps the law of conservation of energy is not right. Well, when a thing is investigated as incompletely as the quasar – quasars are so distant that the astronomers cannot see them too easily – then if such a thing seems to conflict with the fundamental laws, it very rarely is that the fundamental laws are wrong, it usually is just that the details are unknown.

Another interesting example of the use of the law of conservation of energy is in the reaction when a neutron disintegrates into a proton, an electron, and an anti-neutrino. It was first thought that a neutron turned into a proton plus an electron. But the energy of all the particles could be measured, and a proton and an electron together did not add up to a neutron. Two possibilities existed. It might have been that the law of energy conservation was not right; in fact it was proposed by Bohr* for a while that perhaps the conservation law worked only statistically, on the average. But it turns out now that the other possibility is the correct one, that the fact that the energy does not check out is because there is something else coming out, something

*Niels Bohr, Danish physicist.

which we now call an anti-neutrino. The anti-neutrino which comes out takes up the energy. You might say that the only reason for the anti-neutrino is to make the conservation of energy right. But it makes a lot of other things right, like the conservation of momentum and other conservation laws, and very recently it has been directly demonstrated that such neutrinos do indeed exist.

This example illustrates a point. How is it possible that we can extend our laws into regions we are not sure about? Why are we so confident that, because we have checked the energy conservation here, when we get a new phenomenon we can say it has to satisfy the law of conservation of energy? Every once in a while you read in the paper that physicists have discovered that one of their favourite laws is wrong. Is it then a mistake to say that a law is true in a region where you have not yet looked? If you will never say that a law is true in a region where you have not already looked you do not know anything. If the only laws that you find are those which you have just finished observing then you can never make any predictions. Yet the only utility of science is to go on and to try to make guesses. So what we always do is to stick our necks out, and in the case of energy the most likely thing is that it is conserved in other places.

Of course this means that science is uncertain; the moment that you make a proposition about a region of experience that you have not directly seen then you must be uncertain. But we always must make statements about the regions that we have not seen, or the whole business is no use. For instance, the mass of an object changes when it moves, because of the conservation of energy. Because of the relation of mass and energy the energy associated with the motion appears as an extra mass, so things get heavier when they move. Newton believed that this was not the case, and that the masses stayed constant. When it was discovered that the Newtonian idea was false everyone kept saying what a terrible thing it was that physicists had found out that they were wrong. Why did they think they were right? The effect is very small, and only shows when you get

near the speed of light. If you spin a top it weighs the same as if you do not spin it, to within a very very fine fraction. Should they then have said, 'If you do not move any faster than so-and-so, then the mass does not change'? That would then be certain. No, because if the experiment happened to have been done only with tops of wood, copper and steel, they would have had to say 'Tops made out of copper, wood and steel, when not moving any faster than so and so . . .'. 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 is conserved. So we have to make guesses in order to give any utility at all to science. In order to avoid simply describing experiments that have been done, we have to propose laws beyond their observed range. There is nothing wrong with that, despite the fact that it makes science uncertain. If you thought before that science was certain – well, that is just an error on your part.

To return then, to our list of conservation laws (fig. 14), we can add energy. It is conserved perfectly, as far as we know. It does not come in units. Now the question is, is it the source of a field? The answer is yes. Einstein understood gravitation as being generated by energy. Energy and mass are equivalent, and so Newton's interpretation that the mass is what produces gravity has been modified to the statement that the energy produces the gravity.

There are other laws similar to the conservation of energy, in the sense that they are numbers. One of them is momentum. If you take all the masses of an object, multiply them by the velocities, and add them all together, the sum is the momentum of the particles; and the total amount of momentum is conserved. Energy and momentum are now understood to be very closely related, so I have put them in the same column of our table.

Another example of a conserved quantity is angular momentum, an item which we discussed before. The angular momentum is the area generated per second by objects moving about. For example, if we have a moving object, and we take any centre whatsoever, then the speed at which the area (fig. 17) swept out by a line from centre to object,

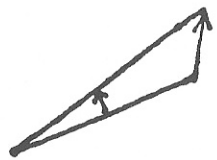

Figure 17

increases, multiplied by the mass of the object, and added together for all the objects, is called the angular momentum. And that quantity does not change. 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 in different forms. Although most people think it only appears in motion it does appear in other forms, as I will illustrate. If you have a wire, and move a magnet up into it, increasing the magnetic field through the flux through the wire, there will be an electric current – that is how electric generators work. Imagine that instead of a wire I have a disc, on which there are electric charges analogous to the electrons in the wire (fig. 18). Now I bring a magnet dead centre along the

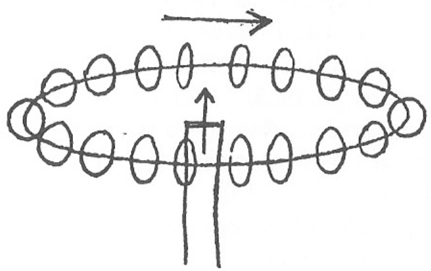

Figure 18

axis from far away, very rapidly up to the disc, so that now there is a flux change. Then, just as in the wire, the charges will start to go around, and if the disc were on a wheel it would be spinning by the time I had brought the magnet up. That does not look like conservation of angular momentum, because when the magnet is away from the disc nothing is turning, and when they are close together it is spinning. We have got turning for nothing, and that is against the rules. 'Oh yes,' you say, 'I know, there must be some other kind of interaction that makes the magnet spin the opposite way.' That is 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. There is angular momentum in the field around the magnet, although it does not appear as motion, and this has the opposite sign to the spin. If we take the opposite case it is even clearer (fig. 19).

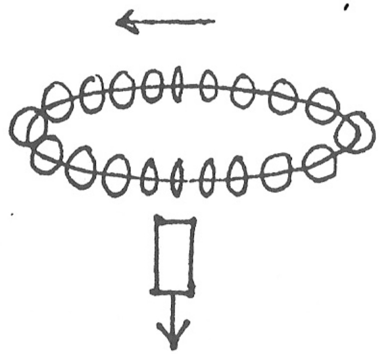

Figure 19

If we have just the particles, and the magnet, close together, and everything is standing still, I say there is angular momentum in the field, a hidden form of angular momentum which does not appear as actual rotation. When you pull the magnet down and take the instrument apart, then all the fields separate and the angular momentum now has to appear and the disc will start to spin. The law that makes it spin is the law of induction of electricity.

Whether angular momentum comes in units is very difficult for me to answer. At first sight it appears that it is absolutely impossible that angular momentum comes in units, because angular momentum depends upon the direction at which you project the picture. You are looking at an area change, and obviously this will be different depending on whether it is looked at from an angle, or straight on. If angular momentum came in units, and say you looked at something and it showed 8 units, then if you looked at it from a very slightly different angle, the number of units would be very slightly different, perhaps a tiny bit less than 8. But 7 is not a little bit less than 8; it is a definite amount less than eight. So it cannot possibly come in units. However this proof is evaded by the subtleties and peculiarities of quantum mechanics, and if we measure the angular momentum about any axis, amazingly enough it is always a number of units. It is not the kind of unit, like an electric charge, that you can count. The angular momentum does come in units in the mathematical sense that the number we get in any measurement is a definite integer times a unit. But we cannot interpret this in the same way as with units of electric charge, imaginable units that we can count – one, then another, then another. In the case of angular momentum we cannot imagine them as separate units, but it comes out always as an integer . . . which is very peculiar.

There are other conservation laws. They are not as interesting as those I have described, and do not deal exactly with the conservation of numbers. Suppose we had some kind of device with particles moving with a certain definite symmetry, and suppose their movements were bilaterally symmetrical (fig. 20). Then, following the laws of physics, with all the movements and collisions, you could expect, and rightly, that if you look at the same picture later on it will still be bilaterally symmetrical. So there is a kind of conservation, the conservation of the symmetry character. This should be in the table, but it is not like a number that you

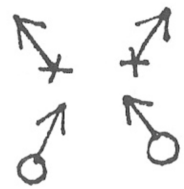

Figure 20

measure, and we will discuss it in much more detail in the next lecture. The reason this is not very interesting in classical physics is because the times when there are such nicely symmetrical initial conditions are very rare, and it is therefore a not very important or practical conservation law. But in quantum mechanics, when we deal with very simple systems like atoms, their internal constitution often has a kind of symmetry, like bilateral symmetry, and then the symmetry character is maintained. This is therefore an important law for understanding quantum phenomena.

One interesting question is whether there is a deeper basis for these conservation laws, or whether we have to take them as they are. I will discuss that question in the next lecture, but there is one point I should like to make now. In discussing these ideas on a popular level, there seem to be a lot of unrelated concepts; but with a more profound understanding of the various principles there appear deep interconnections between the concepts, each one implying others in some way. One example is the relation between relativity and the necessity for local conservation. If I had stated this without a demonstration, it might appear to be some kind of miracle that if you cannot tell how fast you are moving this implies that if something is conserved it must be done not by jumping from one place to another.

At this point I would like to indicate how the conservation of angular momentum, 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. If you have a lot of particles (fig. 21), and take your centre (x) very far away, then the distances are almost the same for every object. In this case the only thing that counts in the area sweeping, or in the conservation of angular momentum, is the component of motion, which in figure 21 is vertical. What we discover then

Figure 21

is that the total of the masses, each multiplied by its velocity vertically, must be a constant, because the angular momentum is a constant about any point, and if the chosen point is far enough away only the masses and velocities are relevant. In this way the conservation of angular momentum implies the conservation of momentum. This in turn implies something else, the conservation of another item which is so closely connected that I did not bother to put it in the table. This is a principle about the centre of gravity (fig. 22).

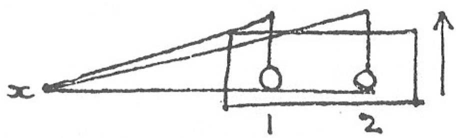

Figure 22

A mass, in a box, cannot just disappear from one position and move over to another position all by itself. That is nothing to do with conservation of the mass; you still have the mass, just moved from one place to another. Charge

could do this, but not a mass. Let me explain why. The laws of physics are not affected by motion, so we can suppose that this box is drifting slowly upwards. Now we take the angular momentum from a point not far away, x. As the box is drifting upwards, if the mass is lying quiet in the box, at position 1, it will be producing an area at a given rate. After the mass has moved over to position 2, the area will be increasing at a greater rate, because although the altitude will be the same because the box is still drifting upwards, the distance from x to the mass has increased. By the conservation of angular momentum you cannot change the rate at which the area is changing, and therefore you simply cannot move one mass from one place to another unless you push on something else to balance up the angular momentum. That is the reason why rockets in empty space cannot go . . . but they do go. If you figure it out with a lot of masses, then if you move one forward you must move others back, so that the total motion back and forward of all the masses is nothing. This is how a rocket works. At first it is standing still, say, in empty space, and then it shoots some gas out of the back, and the rocket goes forward. The point is that of all the stuff in the world, the centre of mass, the average of all the mass, is still right where it was before. The interesting part has moved on, and an uninteresting part that we do not care about has moved back. 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 together the pieces of a jigsaw puzzle. We have all these different pieces, and today they are proliferating rapidly. Many of them are lying about and cannot be fitted with the other ones. How do we know that they belong together? How do we know that they are really all part of one as yet incomplete picture? We are 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 are all made out of the same kind of wood. All the various physical laws obey the same conservation principles.