The Universe and the Laws of Physics*

Lecture I

Mr. Vice Chancellor, Ladies and Gentlemen,

I consider it a great honour to be invited to give the Lokamanya Tilak Memorial Lectures. Tilak was not only a great political leader, but also a scholar interested in ancient literature and modern science. His most important astronomical work is contained in his monograph "Orion or Researches into the Antiquity of the Vedas". There he used astronomical methods to determine the antiquity of the Vedas. In India even today we tend to confuse between astrology and astronomy, laying more emphasis on the former than on the latter. It is all the more remarkable therefore that such astronomical work of high order should have come out of India more than sixty years ago.

From the time of the Vedas, or even earlier, man has made attempts to understand this universe he finds himself in. The basic problem has always been the same, but the approach to it and the methods adopted to tackle it have changed from time to time. Today we try to solve it through science. Science has different branches and physics claims to be the most fundamental of them. The aim of physics is to explain all phenomena observed in the universe in terms of as few basic laws as possible. This is an ambitious project by any standards, and perhaps it will never achieve complete success. In these lectures I wish to describe broadly the present state of affairs.

Before I do so, I want to clarify one of my earlier statements, namely, that physics is the most fundamental of all sciences. You may ask, what about mathematics? Is it not the queen of sciences? The answer to that question is that it is largely a matter of terminology. Since that famous remark was made, the

* Lokamanya Tilak Memorial Lectures (1967) at the University of Poona, India.

meaning of mathematics has changed. As we know it today, mathematics is not a science at all; it is an art. The mathematician is no longer concerned with whether what he says is applicable to the real universe. He starts with a set of axioms and develops the subject by following those axioms in a logically self-consistent manner. Many interesting new branches of mathematics have sprung up in this way in the last few decades. To ask whether they have any use is like asking whether a beautiful painting has any practical use — apart from aesthetic enjoyment.

The situation is different when we come to physics, however. The physicist also starts with some axioms when he builds a theory of the universe. But the theory must satisfy one important criterion. The results predicted by the theory must agree with the observations. This severely restricts the type of mathematics that a physicist can use to describe his theory. This restriction may not appeal to the aesthetic sense of the mathematician, but is absolutely necessary to the physicist. The situation was aptly described by the celebrated mathematician G. H. Hardy when he said "Pure mathematics is useless and applied mathematics trivial!"

When we survey the universe as described by physics, the most striking result that appears is the success, although modest, achieved by the mathematical laws of physics. As Whitehead put it, "The fact that changes in our material universe can be predicted — that they are subject to mathematical law — is the most significant thing about it; for a mathematical law is a concept of the mind and from the existence of the mathematical law we infer that our minds have access to something akin to themselves that is in or behind the universe". Take for example, the law of gravitation. The motion of planets in the sky had been carefully observed by astronomers for several centuries. The Greeks tried to describe it by a complicated theory of epicycles, but got nowhere near the true picture. With the work of Copernicus, Tycho Brahe, Kepler, Galileo, it became clear that planets moved round the sun in orbits of elliptical shape. Then came Newton with his inverse square law of gravitation which gave a mathematical description of planetary motion. Today, a college student of mathematics can solve this problem as an exercise in dynamics. But imagine the thrill it must have

given to the astronomers three hundred years ago, to see all planetary motions described by such a simple mathematical law! Seeing some abstract mathematical concept translated into reality is the greatest fun that can be enjoyed in this game of "hunt the universe".

To go into details about different laws of physics will take much longer time than these lectures would permit. Let me describe some general features that these laws have, which also seem to fit the universe.

The most striking feature is symmetry. We are all familiar with symmetry in one form or another. We see symmetric objects in everyday life. Thus we talk of a tennis ball being symmetric, a garden being laid out symmetrically with flowers and lawns, a pattern being symmetric about a central line and so on. What exactly is symmetry? Of course if you go to a mathematician he will give you a precise definition in a mathematical language. The definition can be translated into a less precise language of the layman. The mathematician Herman Weyl put it thus: "A thing is symmetrical if there is something that you can do to it so that after you have finished doing it, it looks exactly the same as it did before". Thus a circle has a symmetry of rotation: if we rotate it about the centre it still looks the same as before. A thing that looks the same when reflected in the mirror has the symmetry of reflection or the symmetry between left and right.

Now, the laws of physics show symmetries. That is, if we consider the mathematical expression of these laws, they remain unchanged when we make certain changes — as expressed by the above definition of Weyl. In many cases these symmetries can be described in the layman's language. Take for example, Newton's law of gravitation. It tells us that two particles of given masses attract each other with a force in proportion to their masses and in inverse proportion to the square of their distance apart. Now this law would be the same in a universe which is the mirror image of our universe. Suppose we now make a difference in the law. We put particle 1 on the left and particle 2 on the right, and say that only the particle on the left attracts the particle on the right. Thus particle 1 attracts particle 2, but 2 does not attract 1. When we reflect the system in the mirror we see 2 on the left and 1 on the right. So in the

mirror, only the particle on the right attracts the particle on the left! Such a law is not symmetric under reflection, as Newton's law is. The remarkable thing is that the actual universe seems to observe the symmetric law rather than the asymmetric one!

If you think further about this, you will realize the enormous implications of this from a practical point of view. Suppose you want to communicate what you mean by left and right to somebody on a distant planet. How will you do it? If you tell him to look for his heart and say that it is on the left you may be wrong! Even on the earth there are people with hearts on the right. Clearly you will need something more fundamental than this information. The law of gravitation is no use, because the law makes no distinction between left and right. If the universe had followed our modified asymetric law, we could have used it to convey the required information. The law of electricity and magnetism also does not help for the same reason. These are the only two laws known to pre-quantum physics. So if you were living at the turn of the century, you would not have been able to convey the information at all! Does the knowledge of quantum physics help? I will return to this problem later.

Another symmetry is that of rotation. A physical system behaves in the same way even after a rotation of the whole system by any angle. In other words we cannot tell one direction from another by looking at the physical system. But, you will say, this is absurd. We know our directions all right. We can distinguish between north and south! But this is not what the law implies! The directions north, south, etc. are determined in a somewhat arbitrary way — with reference to the earth and the solar system. If you are blindfolded and taken away from the sun and the stars out into the almost empty intergalactic space can you still point to a certain direction and say, it is north? You cannot, even if you took the whole laboratory with you to make experiments.

Just as there is symmetry in space, there is symmetry in time. The laws make no difference with regard to the past and future of a system. Again, you will point out that this is not what we observe of the real universe. In the real universe we do feel that there is a difference between the past and the future. How does this distinction come about? This is a more fundamental question than that about the directions in space I described above. In spite of the time-symmetry of physical laws there is a direction of time. Why? I shall discuss this question later in the lecture.

The arrival of the quantum theory brought further concepts of symmetry. The most important one is the symmetry between matter and antimatter. In the early thirties, theoretical investigations by Dirac into the quantum theory of electrons led him to the result that the theory could not be complete without particles of the same mass but opposite charge as the electron. These particles, he called positrons. Did positrons actually exist in the universe? Or did they just exist in the mathematical structure of Dirac's theory? The question was resolved soon after by Anderson's discovery of the positron. Electrons, together with protons and neutrons are the most important constituents of matter that we see around us. Dirac's result predicted the existence of antimatter formed by positrons, anti-protons and anti-neutrons. However, we do not see antimatter around us because it is annihilated by matter in an extremely short time. It so happens that we live in a matter-dominated region, and so we do not see antimatter except by careful laboratory experiments.

Quantum mechanical laws appear to follow an important symmetry rule, known as the CPT rule.* This states that the behaviour of a physical system is unchanged if we replace matter by antimatter, left by right and *vice versa,* and interchange past and present. As Feynman described it once, if you go near a distant planet which looks very much like the earth with inhabitants like the human beings, and if one of them comes out to welcome you with his left hand outstretched to shake yours, run away as fast as you can! Because you are near the anti-earth, where the predominance of antimatter will destroy you in no time!

One of the most important results in the last few years was the discovery of a quantum mechanical law which is *not* symmetric with respect to the left and right. This is the law of weak interactions. It hinges round the fundamental particle called the neutrino. It has no charge and no mass. It always moves with the speed of light. What is peculiar about it is, how-

* Short for "charge conjugation, parity and time reversal".

ever, that it always spins in a clockwise sense in the direction of its motion. Now such a particle when reflected in a mirror would spin anti-clockwise. Neutrinos of this type are not, however, observed in the actual universe. Thus the law of weak interaction does tell you the difference between left and right. So if we return to our problem of explaining what we mean by left and right to somebody on a distant planet, we can now solve the problem in the following way. We tell him to perform an experiment which gives out neutrinos. When he examines the neutrinos he will understand the meaning of clockwise and anti-clockwise and therefore of left and right.

There is a possibility that this experiment will still not succeed. For, if that somebody lives in an antimatter region, what he will observe will be the anti-neutrinos which spin in the opposite sense to the neutrinos! So again he will get the whole thing wrong. But we can guard against this by sending first a spaceship to him. If the spaceship is annihilated the planet is of anti-matter. Needless to say, the spaceship should be unmanned!

I have so far talked about symmetries of physical laws describing the universe. These symmetries are of a local nature — they describe the situation at a given point. We observe symmetries in a global way also. When we look at the large-scale structure of the universe we find a great deal of regularity. First, we notice that the distant galaxies show the phenomenon of red shift. The light from these galaxies undergoes an increase of wavelength when it reaches us. Further, this increase is correlated with distance. The larger the distance the greater the red shift. This phenomenon was first noted by Hubble, who also found a linear law connecting the red shift with distance. This is known as Hubble's law. If we interpret the red shift as a Doppler effect, we would say that the galaxies are all receding from us at speeds proportional to their distances from us. Why should we be in such a special position? Clearly such a statement would take us back to the Greeks who regarded the earth as the centre of the universe.

However, a closer examination of the situation shows that we are in no privileged position. Indeed, if we observe the universe from another galaxy we would get the same large-scale view of the universe. This is known as the cosmological principle. In crude words, it implies that if you are taken blindfolded to any

part of the universe, then from your observations you could not tell where you are or where you are going.

Why should the universe exhibit such a remarkable regularity in its structure? The laws of physics are not at present able to answer this question. The fault may lie with the local character of the laws. I shall return to this point in the next lecture.

I now turn to another interesting feature. This is the so-called conservation laws. In everyday life we are all familiar with such statements as "you cannot expect to get something out of nothing" or, "whatever goes in must come out", and so on. These describe conservation laws. The laws of physics tell us that in the universe certain quantities are always conserved.

To give an example, matter and energy together are always conserved when a physical system undergoes a change. If the system has a certain amount of matter and a certain amount of energy before the change, then after the change we expect the amounts of matter and energy to add up to the old ones. If we have lost some matter during the change it must reappear as energy and vice versa. The conversion from matter to energy is described by the celebrated Einstein equation $E = mc^2$. Another conservation law is that of conservation of momentum. When two bodies collide their momentum before collision is the same as their momentum after collision.

The conservation laws play an important part in the physical description of the universe. If in the description of a certain process we find that these laws are violated, we suspect that something is wrong with the description. A historic example is that of the beta decay. In this process a neutron decays into an electron and a proton. When this process was first observed the energy and momentum of the new particles did not add up to the energy and momentum of the original particle. To restore the balance, Pauli postulated the existence of an additional particle which carries the remaining energy and momentum. This particle is now identified as the anti-neutrino. It moves with the speed of light, but has no mass or charge. This is the reason for the difficulty of detecting it experimentally. In fact the neutrino and the anti-neutrino interact so weakly with matter that they can pierce through several light years of it without being absorbed! But for the conservation laws they might have escaped detection for a long time!

There are various conservation laws besides those of energy and momentum. They are consequences of the basic laws of physics. Why should such laws exist? It is now known, thanks to mathematics, that there is a strong connection between symmetries and conservation laws, if we follow what is known as the principle of least action. I shall presently describe this principle, but let me illustrate the connection. Take for example the symmetry of translation. This says that the laws of physics are unchanged if we displace the physical system as a whole in any given direction. This symmetry is connected with the law of conservation of momentum. If instead of displacement in space, we displace in time, *i.e.,* observe the system a little later, again the laws do not change. This symmetry leads to the conservation of energy. In fact, as mentioned before, if the least action principle is followed we get a conservation law corresponding to every symmetry we build into the physical laws.

What is the principle of least action? Action is a mathematical functional of the various physical quantities under consideration. Now suppose we have a system whose behaviour we want to study over a given space time region. Also suppose we do not know the laws of physics obeyed by the various quantities comprising the system. We then look at the action functional and say that the system will obey those laws which make the action over the whole region of space and time in question, a minimum. This is another way of saying that nature is lazy — of all the various possibilities involved it chooses that which involves the least action.* How is the action functional defined? There is no unique way of doing this although there are several guiding principles. For example, the symmetries which we want to build into the physical laws, severely limit the possible forms of the functional. The important point, however, is that once the action is defined the laws of physics follow uniquely by the principle of least action. And, as mentioned above, these laws imply conservation laws corresponding to the symmetries that went into the action functional.

To summarize — what I have said so far may have given you some idea of the beauty and pattern observed in this universe of ours, and how this is reflected in the laws of physics describing

* Actually we only require the action to be "stationary". "Least action" is in fact a misnomer of historic origin.

it. By beauty, I do not refer to what we see through our eyes such as natural scenery. The literary people can give you a much better description of it than I can. I refer to the beauty as seen through the eyes of a mathematician. Why should there be such a mathematical pattern in the universe? We do not know. The great astronomer Sir James Jeans expressed the view that "from the intrinsic evidence of his creation, the Great Architect of the Universe now begins to appear as a pure mathematician!"

I now return to the question of the direction of time. The puzzling thing from a physicist's point of view is that we observe an arrow of time in spite of the fact that the basic laws of physics are time-symmetric. Let me illustrate the problem by giving examples. Suppose we observe a certain process happening in the universe and make a movie film of it. If we run the film backwards in a projector, we would see — not the original process, but another. The process we would see is in fact obtained from the original one by reversing the arrow of time. We then ask the question, can this other process happen in our universe? Now there are some processes for which the answer is "yes", and others for which the answer is "no". As an example of the former type of processes consider the earth going round the sun. If we film the sun throughout the day we see it rising in the east and setting in the west. By running the film backwards we see it rising in the west and setting in the east. This, we would argue, is possible if the earth were spinning in the opposite sense, about its axis. Moreover, no law of dynamics is violated if we have the earth going round the sun in the same orbit but in the opposite sense. Such processes are called reversible — for obvious reasons. As a process of the other type consider a waterfall. We film a waterfall and then run the film backwards. We see the strange spectacle of water rising! We do not see such phenomena on the earth. Or take another example of a hot body in contact with a cold body. Heat passes from the former to the latter. We do not observe the time reversed process in which the heat flows from a cold to a hot body! Such processes are called irreversible.

Now time asymmetry or the distinction between past and future is observed through such irreversible processes. So the question arises — why do we have irreversible processes? Laws of physics alone do not help us. They tell us that every process obeying the laws must be reversible. In the case of the waterfall,

if we provide sufficient velocities to the water at the bottom, they will rise in a manner shown by the film run backwards. So we must look elsewhere for the cause.

The reason usually given is of a statistical nature. The argument roughly runs as follows. In a macroscopic system we do not know the behaviour of all constituent particles. So we use statistics to study the behaviour. We assign equal *a priori* probabilities to all microscopic states constituting the system. Then we discover that there is a high probability that the system will go one way rather than the other. Thus in the case of hot and cold bodies, we would say that it is extremely unlikely that heat passes from cold to hot bodies rather than from hot to cold ones. This argument commonly employed in thermodynamics appears convincing and it is easy to be brainwashed by it. There are two snags, however. First, if we knew the detailed motion of all constituents of the system, then we would discover that those motions are all reversible — because of the time symmetry of physical laws. Is time asymmetry introduced into the picture by our not knowing all details? This leads to the second snag. When we decide that we shall use statistical arguments, we put forward the law of *a priori* probabilities. And the emergence of the asymmetry is traced to this assumption. In other words, we have not really explained the asymmetry — we have simply found another way of describing it.

A similar situation exists in electrodynamics. We know a wireless transmitter radiates radio waves. As it radiates energy, it loses its own energy — as required by the conservation law for energy. To keep the transmitter going we have to supply energy. This appears reasonable. Now reverse the direction of time. The transmitter now receives energy from space and therefore increases its reservoir of energy. We never see this happening! But the interesting thing about this is that the laws of physics — in this case the laws of electrodynamics — do not forbid this event. In a wireless transmitter we have oscillating charges and currents. Now such charges and currents can lose or receive energy perfectly consistently with the laws of electricity. But they always appear to lose energy. This is another way time asymmetry is introduced in our everyday life.

As in the earlier example, we can probe a little deeper. We discover that when we solve the problem of moving charges

mathematically, there are two types of solutions. One describes wave propagation into the future and the other into the past. We call them the retarded and advanced solutions. We are faced with a choice between the two types of solutions. We choose the retarded solution, because it agrees with our experience. We know that what happens here now will influence a distant system, later than now. This is the principle of causality which is expressed in popular language by saying "cause comes before effect". Once we make this choice we come to the conclusion that the electric charges lose energy as they move. However, once again the choice is made not with reference to the basic physical law but to something else, *viz.*, the principle of causality. And the time asymmetry comes in through this principle. Again, we are far from the explanation of the cause of this asymmetry.

Many people believe that the cause of the direction of time may lie outside physics. Philosophers have also given considerable thought to the problem. Questions such as: 'What is memory?', 'Is subjective time different from physical time?' etc., arise when we consider the problem in all its aspects. However, to me it seems that we should be able to throw some light on the aspects which concern physics. A clue to this is provided by the universe.

One significant point about the universe is that it is *not* time symmetric in the large. As already described before, it is expanding. All galaxies are moving away from each other. Thus if we photograph the same region of the universe at two different times, we could tell, by looking at any two galaxies, which photograph was taken earlier. In the earlier photograph the galaxies will be closer to each other. Now, does this asymmetry have anything to do with our local time asymmetry? Can we, for example, say that electric charges lose energy because the universe expands? I shall begin my next lecture with a discussion of this problem.

Lecture II

In my previous lecture I raised the question whether there is a connection between the local arrow of time and the arrow of time given by the expansion of the universe. Some work on this

problem in the last few years suggests that a connection might exist. Let me describe this work briefly.

Let me take the case of moving electric charges, that is the case of electrodynamics. We know that like charges repel, unlike charges attract. How can we describe this mathematically? There are two ways of doing so. In one we say that there is a direct interaction between electric charges situated in different places. Call this action-at-a-distance picture if you like. There is one important proviso, however. This influence between distant charges travels from one charge to another with the speed of light. Suppose charge B is situated one "light hour" away from charge A. If we move charge A at 5 P.M., say, charge B will feel the influence at 6 P.M. This is reasonable. But this is not all. Charge B will react back on charge A — and this reaction must be equal and opposite. The charge A will therefore feel the reaction at 5 P.M. Here we have the possibility that movement of B at 6 P.M. will affect that of A at 5 P.M. Clearly this is against the principle of causality which is seen to hold in everyday life. For a long time this was regarded as an insurmountable difficulty of the action-at-a-distance point of view.

In the other way of looking at it, we bring in a third agency — the electromagnetic field. We now say that charge A, by its movement, influences the field around it. The field is disturbed, and this disturbance spreads out in all directions in the form of waves — just as waves are created in a pond by dropping a pebble. The waves travel with the speed of light and hit the charge B. In this way an influence is conveyed from A to B. Notice that A and B do not react directly, so that the question of the reaction of B on A does not arise. This picture, called the field picture, gives a reasonable description of the situation and is generally preferred to the action-at-a-distance picture.

However, this picture is not able to throw any light on the arrow of time. In the above example, we always take the waves travelling in the future. Mathematically, we take the retarded solution I described yesterday. This is an arbitrary choice made to conform to the principle of causality. We therefore cannot expect to explain the principle of causality or the arrow of time in this manner.

To understand the arrow of time we must return to the action-at-a-distance picture. This picture is time-symmetric when

we consider any two particles A, B, as mentioned before. However, the time symmetry disappears when we take the *totality* of all particles in the universe. Thus when we move charge A, it gets reactions not only from B, but from all charges situated on the future light cone* of A, as well as on the past light cone of A. We have already mentioned that the universe as a whole is *time-asymmetric*. Thus a light ray from A going into the future, goes into an expanding universe, whereas a light ray going into the past goes into a contracting universe. The former ray is redshifted and the latter blueshifted. Thus the reaction of the future half of the universe to A is in general different from the reaction of the past half of the universe. What is the net reaction? We cannot determine it unless we know more about the universe. In some models of the universe the reaction is such that it cancels all past going signals from A and reinforces the future going ones. These universes allow only the retarded signals to exist. Moving charges in such universes only lose energy. In certain other types of universes the exact opposite is permitted. Thus advanced signals exist and moving charges gain energy. In some models we get a mixture of advanced and retarded solutions. To give examples of each class is not difficult. The steady state universe which always expands at the same rate and in which the matter density is kept constant by continuous creation belongs to the first class. The Einstein-de Sitter universe which expands from a big bang belongs to the second class. A homogeneous static Euclidean universe is of the third class.

What is the implication of all this? If we adopt the action-at-a-distance point of view we are able to connect the local arrow of time with the cosmological arrow of time, provided we live in the universe of the right type. The steady state universe is of the right type in this connection, but not the Einstein-de Sitter or the static Euclidean one.

To me this point of view appeals for two reasons. First it shows that a connection exists between two quite different events — the expansion of the universe and the radiation by an electric charge. Secondly, it enables us to draw important con-

* If we draw a space-time diagram, the future light cone of A is the section reached by all future directed light signals from A. The past light cone is similarly defined.

clusions about the large scale structure of the universe from purely local observations. We can say, for example, that because a wireless transmitter radiates the universe cannot be static or of the big bang type. No telescopes are necessary to arrive at this sweeping statement!

This point of view has implications for physics, which are of great significance. Ever since Newton, physicists have believed in the extrapolation of physical laws, arrived at from terrestrial knowledge, to bigger and more distant regions. This has proved to be a fruitful way of research. Thus suppose you have a scientific theory which works in the limited region of your laboratory. You then stick your neck out and say that it will work in more general cases also. It is for the experimenter to put this hypothesis to test. Some of his experiments will result in support of the theory, which means the theory works in more general cases. However a time may come when some experimental result does not agree with the predictions of the theory. The theory will then have to be rejected or modified. Although this may be a loss from the point of view of the theoretician, it is a gain from the general scientific point of view, because a new experimental result has been found. For example, the experiments in beta decay revealed that the universe is not symmetric with respect to space reflection. Although we had to abandon the space reflection symmetry, we were rewarded with this important piece of information.

This method of approach can be extended to bigger and bigger regions until we apply it to the entire universe. Thus we use the local laws of physics to study the universe.

The point of view I have been discussing makes this one-way process into a two-way one. We no longer just extrapolate our local knowledge, but we also use our knowledge of the universe to study local phenomena. In other words, what is happening "here and now" may have something to do with what is happening "then and there".

The idea that the distant parts of the universe influence the behaviour of a local system is not a new one. In fact it was seriously put forward as a physical concept by Mach, a philosopher of the last century. Mach made this suggestion with reference to a specific effect, the inertia. Newton's second law of motion tells us that to accelerate a body we must apply force.

If no force is applied the body will continue to be in the state of rest or of uniform motion. This inability of the body to change its motion by itself is called inertia, and its quantitative measure is the mass. The greater the mass, the bigger the force required to change the motion. Now we cannot talk of motion without a frame of reference. The motion referred to one frame of reference would be different when referred to another frame in relative motion with respect to the first. Whereas motion is relative, the concepts of force and inertia appear to be absolute. Clearly Newton's law cannot be expected to hold in all frames of reference!

Newton had realized this difficulty and he circumvented it by postulating an absolute frame of reference in nature. If we use a frame of reference which is itself accelerated relative to the absolute frame, Newton's law has to be modified. The modification consists of adding an extra force to the given force. This extra force arises simply because we use a "wrong" frame of reference. To give an example, suppose we tie a stone to a string and whirl it round in a horizontal circle. The stone is moving in a circular motion which therefore has acceleration. The acceleration is directed towards the centre of the string. Newton's law tells us to look for a force which causes this acceleration. This force is provided by the tension in the string. So all is well with this description. Now suppose we decide to change our frame of reference to one in which the stone is at rest. That is, we now go and sit on the moving stone and observe it. We find that the stone is being pulled by the string to the other end. We ask: Why does the stone remain where it is? To make this consistent with the Newtonian description, we invent a fictitious force in the opposite direction to balance the tension of the string. We call this the centrifugal force. It arises simply because we decided to choose a frame of reference different from Newton's absolute frame.

How do we determine the absolute frame? Does the earth provide such a frame? We can determine this by an experiment. We set up a Foucault pendulum. This is like an ordinary pendulum, only it is free to oscillate in any vertical plane. If the earth is non-rotating relative to Newton's absolute frame, we would find the pendulum oscillating in one plane, if it is started off in that way. What we find is that the plane of the

pendulum slowly turns round. Moreover the rate of turn round depends on the latitude — being zero on the equator and maximum on the poles. This is consistent with the view that the earth is rotating with respect to the absolute frame at the rate of one revolution per day.

The remarkable point about this result is that it can be arrived at without reference to the sun and the stars. We could perform the experiment in a closed room. It then follows that Newton's absolute frame is the same as the one in which the stars are at rest.

This observation has been performed in more and more refined ways with present-day instruments. It seems certain that within observational errors, the absolute frame of Newton is the same as the one in which the distant parts of the universe are non-rotating and moving radially away in an isotropic way.

Although the observational status of this result in the last century was not so precise as it is today, it was striking enough. What have the distant parts of the universe to do with the absolute frame? Mach read more into the result than just coincidence. He argued that the absolute frame provides a basis for measuring inertia. The fact that this frame is somehow related to the distant parts of the universe shows that the property of inertia of an object is somehow connected with the universe as a whole. If there were no other piece of matter in the universe the object would have no inertia. Mach did not give a mathematical formulation of this idea which is now known as Mach's principle.

The attitude of physicists to Mach's principle varies from scepticism to firm belief. Einstein was initially a believer, and hoped to include this principle in his theory of gravitation — that is, in the general theory of relativity. He did not succeed, however, and later began to doubt the validity of the principle. Others since Einstein have attempted to give a mathematical formulation of Mach's principle with varying degrees of success.

Three years ago Fred Hoyle and I were led to a theory of gravitation which incorporated Mach's principle. Our approach to it was along the lines I have described before in connection with electromagnetism. As in electromagnetism, it turns out that the action-at-a-distance approach is more suitable as a description of Mach's principle than the field theoretic approach

followed by Einstein and others. In fact, had action-at-a-distance been the common way of describing physics such an approach would have been tried long ago. But, as I described before, that approach had led to conflict with causality and therefore was abandoned. Now that the conflict is removed there is no reason not to reinstate it in physics.

The question may be asked "Is it really necessary to try a new approach at this time? Are we not happy with the old established approach of the field theory and general relativity?" The question will be answered differently by different physicists. I give my views here.

There are two motivations for changing the basic structure of a well-established physical theory. The prime one is observational. If the theory does not agree with observations it must be discarded. For this the observations must be well-founded of course! The second one is mathematical. The development of the full implications of the theory may lead to mathematical difficulties which canot be avoided unless we change the theory.

Take the case of electrodynamics. On a classical level, it is a fairly complete theory. However, when we study quantum electrodynamics we encounter numerous mathematical difficulties. Certain integrals diverge. Artificial aids are necessary to get sensible results out of the theory. The fact that the results show remarkable agreement with experiments lends the hope that there is something in the theory that is right. In such an event it is worthwhile to try other formulations of electrodynamics, in particular, the action-at-a-distance formulation.

Turning to gravitation, there are very few experiments that can be performed to test various theories. This is because gravitation is a basically weak force. In this case we must look for the second criterion — the mathematical one. For example general relativity also has its own difficulties with infinities. These make one suspicious of the overall consistency of the theory. Here again, it is worth trying out the consequences of the action-at-a-distance approach. The preliminary investigations of this have yielded promising results.

Having described the present state of physical laws I will now end with a few speculations about the future. I know it is dangerous to speculate lest one is proved wrong. Many well-known scientists in the last century believed that physics had

come to an end — that it had solved all fundamental problems. The arrival of special relativity and quantum theory upset all complacency of the nineteenth century physics. All the same it is fun to let the imagination run a free course for a while and speculate about the future.

In speculating about the future we can take guidance from the past. Looking at the history of physics I am struck with the similarity between the development of physical theories and what is asserted in the famous verse from the Bhagavadgita* :

यदा यदा हि धर्मस्य ग्लानिर्भवति भारत ।
अभ्युत्थानमधर्मस्य तदात्मानं सृजाम्यहम् ॥

Likewise, in physics, the time is ripe for a new theory whenever the old ones get entangled in mathematical inconsistencies and there is a growing pile of unexplained facts in the universe. The arrival of Newton solved the outstanding problem of planetary motion and inspired Pope to say

"Nature and Nature's laws lay hid in night;
God said, "Let Newton be !" and there was light."

In the beginning of the present century, the experiments in atomic physics defied any explanation along classical lines. It was not until the advent of the wave mechanics as developed by Schrödinger, Heisenberg and Dirac that the experimental results began to make sense. Turning to astronomy, the problem "What keeps the sun shining?" could not be solved until about thirty years ago. It was clear that gravitational energy could not provide the energy which the sun keeps pouring out every day. In the twenties, Eddington's calculations of the structure of the stars led him to temperatures of several million degrees in the sun. He suggested that nuclear reactions may provide the required fuel. When nuclear physicists objected to this explanation on the grounds that the temperatures were not high enough for the reactions to take place, Eddington's classic retort was :

"We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find

* "O Bharat ! Whenever there is a decline of righteousness and a rise of unrighteousness, then I send forth (create incarnate) myself" — Lord Krishna, Chapter IV, verse 7.

a hotter place". Ultimately it was shown that Eddington was right, only that his calculations came a decade earlier than the development of sub-atomic physics !

What is the present situation in physics ? Today also there are unsolved problems which challenge man's ingenuity. Let me describe some of them.

Turning to the very small — to the world of elementary particles, we find that with the new experimental tools available to us, there are a large number of different elementary particles. Gone are the simple days of the electron, the proton and the neutron. We have mesons, hyperons, strange particles and what not. Attempts are being made to see if these form a pattern — like the periodic table for elements. These attempts are only partly successful. Why do these particles have the different masses that they seem to have ? What is the basic unit of charge in the universe ? Is it the electronic charge, or the charge ascribed to a quark ?

Another puzzling problem is connected with the fine structure constant. It is composed of three basic entities — the charge of the electron, the velocity of light and Planck's constant which occurs in quantum theory. This constant has the value approximately 1/137. Why this and no other value ? The fact that this constant is not explained shows that our present structure of the quantum theory is incomplete. In future, a more complete theory may be developed which would give this value uniquely.

A somewhat related problem concerns the dimensionless ratios built out of different branches of physics. If we compare the electromagnetic force between an electron and a proton with their gravitational force we get an enormous number of the order

1,000,000,000,000,000,000,000,000,000,000,000,000,000.

Again if we compare the length scale associated with the large scale structure of the universe with the radius of an electron we get another number of the *same* order. Why do such large numbers exist in physical theories ? Is it just an accident ? Again, a more complete theory will give the answer.

Just as the sun and stars posed a problem to the astrophysicists of the last generation, the radio sources and quasars present a difficult problem today. What is the source of energy

in the radio galaxies? So far no conventional explanation has proved adequate. The somewhat spectacular viewpoint that radio sources originate when two galaxies collide has not been borne out by observations. The observations support a picture of explosion of some form or other in the centre of the source. But explosion of what? We do not know. The problem is even stranger in the case of quasars which are much brighter and much more compact than radio galaxies. What keeps them going? Also why do they fluctuate in their output of energy — sometimes in as short a period as one day? Are they nearby objects or are they very distant as their large red shifts indicate? As yet there is no rational explanation. Perhaps we are here encountering an entirely new aspect of the universe, for which we have nothing to go by.

Lastly, turning to the problem on the biggest scale, the large scale structure of the universe, we have the question: "Did the universe originate a finite time ago?" Did it explode into existence — as many astronomers believe, or did it never originate? Many people do not like the idea of a steady state universe, without a beginning and without an end, for the simple reason that they are accustomed to the idea that everything must have a beginning. It is still possible to have a universe without a beginning, in which every single object did have a beginning. Mathematically speaking there is nothing wrong with this idea, or with the concept of continuous creation of matter. Granted, however, any type of universe, we have to account for the different types of matter in it. Why do we find different elements in different proportions? How did matter accumulate in big lumps which we call galaxies? These questions are only partially solved today, but will be solved when our observational knowledge of the universe has improved.

This brings me to the final question: "Will physics ever succeed in giving a complete explanation of the universe?" If it did, that will be the end of physics. It will then be a very dull kind of life — all we have to interest ourselves in will be the solution of some superficial problems. I for myself would not like to live in such an era. But I do not think such a situation will ever arise. As our understanding of the present problems improves the universe will provide us with fresh ones, and so the chase will go on for ever.