WHY WE BELIEVE IN THE EINSTEIN THEORY

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I am very happy to be invited to Carbondale and to have this opportunity of paying tribute to Einstein. His influence on the whole of modern physics is simply enormous and probably not always appreciated and I will try to give you a better understanding of it.

Relativity was first introduced to the world in 1918, just at the end of the first world war. Of course, the special theory of relativity was then quite old. It was discovered in 1905 but it was quite unknown except to a few specialists in universities, and no one had heard of Einstein apart from that. Then, at the end of the first world war, relativity just burst on the world with a tremendous impact.

The reason for this is that it was just at the psychological moment when a terrible war had at last come to an end. Everyone was quite sick of it, whichever side they were on, and people wanted something new, something to enable them to forget about the war and to start off on a new line of thinking. Relativity provided just that.

At that time, I was a student of engineering at Bristol University in England, just one of the undergraduates there. We were caught up in this storm of relativity. Everyone was discussing it. People had no really definite information to go on. Students and professors just were discussing it from the point of view of hearsay. Newspapers were continually writing articles about it and all the magazines were full of articles about it. The people who wrote the articles understood very little also, but they felt more or less competent to try to explain things.

B. Gruber et al. (eds.), *Symmetries in Science*

As engineering students we had been working all the time with Newton. Newton was our god and everything in engineering depended on Newton. Then we were told that in some mysterious way Newton was wrong. We had to adjust ourselves to new ideas.

Why should we believe in this new theory? There were two reasons that were given. One reason was that it was supported by experiemental evidence and another reason, given by the philosophers, was that philosophy demanded it. From general philosophical arguments they thought that it was necessary to have relativity and to get away from absolutism. I want to discuss these ideas more thoroughly. Neither of them is the true reason for believing in Einstein and appreciating the greatness of his ideas.

Special Relativity

If you just think of velocities, then in the first place it is quite obvious that the velocity of a body can have a meaning only with respect to the velocity of something else. It is only the difference of two velocities which is a well defined concept. But the question arises - is there some absolute zero to which all other bodies can be referred to give us an absolute velocity for a body. That is a question that cannot be decided by philosophy. It can only be decided by experiment, by observation. One must see if one can find this absolute zero of velocity.

Now experiments had been done by Michaelson and Morley to see if there is such an absolute zero in velocity. All physical theory at that time was based on the idea that there is an absolute ether that had to be used as a reference system. So one could talk about light moving with a definite velocity through the ether. Now the question arises - can one determine the velocity of the ether? More precisely, can one find out the velocity with which the earth is moving through the ether? That is just what Michaelson and Morley tried to do.

They did some careful experiments involving sending beams of light to and fro and making accurate interference observations. The result was that they were unable to find any velocity which could be counted as absolute zero. They were unable to determine what the velocity of the earth was through the ether. They did the experiment at different times of the year when the velocity of the earth would be different because of the motion around the sun, but their results were always negative. How could one understand that?

It was a great mystery to the people at that time. It was studied in particular by Lorentz and Fitzgerald and they supposed that one had to set up new ideas about how rigid bodies behave. The rigid bodies had to undergo a strange kind of contraction which was adjusted in such a way as just to neutralize the effects that would otherwise be produced by the motion of the earth through the ether.

At that time, the best physical theory we had was the electromagnetic theory, based on Maxwell's equations. Lorentz worked on these equations a great deal and made a rather remarkable discovery. He showed that from these equations, combined with suitable assumptions about how material bodies behaved when they were in motion, one could set up different frames of reference in space and time such that the equations appear the same with respect to all these frames of reference.

From this discovery of Lorentz you get an immediate explanation of the null result of the Michaelson and Morley experiment. It is just that, as the earth moves with different velocities, you have to pass from one Lorentz frame of reference to another, and then there won't be anything observable to show up with the different velocity of the earth at the different times. Lorentz found out that there are these different frames of reference, and he worked out the equations that transform from one frame of reference to another, the Lorentz transformation. As a result, one could see immediately that with any experiments just involving electromagnetic processes, you could not get the velocity of the ether to show up in any way. The results that you get will always be the same. The proof just involves passing from one Lorentz frame of reference to another.

This was all done before Einstein came on the scene. Then Einstein made a very bold assumption: he said that all these different Lorentz frames were equally good and you had to adopt a new picture of space and time which treated all these Lorentz frames symmetrically. Then you would never be able to find out the velocity of the ether, because it was something which just didn't exist. That was really the start of relativity.

At that time Lorentz did not accept it. Lorentz had really done the hard mathematical work. He had discovered the transformations, but he did not accept the view that all the different frames of references were equally good. Lorentz thought that one of these frames of references was the really correct physical frame and all the others were just mathematical fictions. That was the point of view that Lorentz held. It was in direct contradiction to Einstein's. The disagreement remained for quite a number of years. Poincaré had also worked on the problem and held a similar point of view to Lorentz.

It turned out that it was quite impossible to find out which was the correct frame of reference. Under those conditions one should, of course, give up the idea that there is just one frame of reference which is correct. One then goes over to the idea that all the frames of reference are equally good, which is just Einstein's view.

In order to appreciate what Einstein's assumption involves you must see that it really goes a long way beyond the conclusions which Lorentz had obtained. Lorentz had established that so long as one keeps to electromagnetic forces it would be impossible to find an absolute zero of velocity. Einstein went beyond that and said it would never be possible to find an absolute zero in velocity, that there would not be other physical processes that would show up an absolute zero of velocity. It was something inherant in space and time that this absolute zero does not exist at all. You have to adopt a new picture of space and time.

This new picture was very much brought into prominence by Minkowski, the great geometer of that time. He set up the basic geometry. You have to describe physical events in a four dimensional world with this geometry, in which you don't have Lorentz frames of reference such that one is more basic than the others. It is called Minkowski space. You might say that Einstein's fundamental assumption was that the whole of physics has to be put into Minkowski space.

The Microwave Radiation

In one sense, Lorentz was correct and Einstein was wrong, because all Einstein should have said was that with the physics of that time it was impossible for an absolute zero in velocity to show up. But to say that it would never be possible for an absolute zero in velocity to show up was going a bit too far. An absolute zero in velocity has shown up with the more advanced technology which we have at the present day. This refers to the natural microwave radiation.

If one has suitable telescopes capable of observing microwaves of just a few centimeters wavelength, and one points these telescopes to the sky in various directions, one observes some weak radiation coming in. This radiation, called the natural microwave radiation, does not come from the sun, it does not come from the galaxy, it comes from all directions in space. It must be something of cosmological importance. People explain it by saying that it is the remains of the radiation which existed at a time close to the time when the universe was created. There was a lot of hot radiation then, which has cooled down and left some cold radiation which can be observed now by suitable telescopes.

This radiation is coming in equally from all directions for a suitable observer. If you take another observer who is moving relatively to that first observer, he will see it coming more strongly in the direction to which he is proceeding and less strongly from behind him. So it will only be symmetrical with respect to one observer. There is thus one preferred observer for which the microwave radiation is symmetrical. You may say this preferred observer is at rest in some absolute sense, maybe he is at rest with respect to an ether. That is just contradicting the Einstein view.

It is possible to observe the velocity of the earth through the ether as defined by the microwave radiation. One finds that the earth and the whole solar system are moving very rapidly, with a speed that can be observed. The only reason why Michaelson and Morley got a null result, why they failed to observe the motion of the earth in an absolute sense, was because their technology was inadequate. Present day technology can do much more than could be done in those days, nearly one hundred years ago. With the more modern technology, there is an absolute zero of velocity.

You might say that, with the microwave radiation showing Einstein was wrong, that would destroy relativity. But it has not destroyed the importance of Einstein's work. The importance lies in another respect. You shouldn't say that Einstein's theory rests solely on its agreement with observation. There is agreement with observation only provided that you don't use a sufficiently advanced technology. In the absolute sense the agreement no longer holds. The real importance of Einstein's work was that he introduced Lorentz transformations as something fundamental in physics. The whole of physics has to be expressed in Minkowski space, a space which is subject to Lorentz transformations. That I would say is the most important of the new ideas introduced by Einstein, and it is of tremendous importance and is not disturbed by the more advanced technology which cuts away the basis that Einstein had in proposing his theory.

I should try to give you some idea of the immense importance of our having to express all our physical theory in Minkowski space which is subject to the Lorentz transformations. There are many examples I could give. One of them, concerns de Broglie, a French physicist. Just by studying the relationship between particles and waves and using the Lorentz transformations he found that one could set up a relationship between particles and waves which was invariant under Lorentz transformations. That led him to postulate the existence of waves associated with particles. That was a fundamental idea in atomic physics. It was taken up by Schrodinger and developed by him. It has proved to be right at the basis of the whole of modern atomic theory.

Further developments of the theory of Lorentz transformations show that when you try to set up an equation for the motion of electrons agreeing with Lorentz transformations and the fundamental laws of quantum mechanics, you are led to a theory which provides an explanation for the spin of the electron. If you go a little farther, you are led to the existence of antimatter. These are all consequences of the Lorentz transformations. They all follow smoothly from Einstein's assumption that Lorentz transformations dominate physics. This dominance of the Lorentz transformation is something which is excessively important and has affected the whole of physics since it was introduced at the beginning of the century.

I might put things a little differently and say that the Lorentz transformations are beautiful transformations from the mathematical point of view, and Einstein introduced the idea that something which is beautiful mathematically is very likely to be valuable in describing fundamental physics. This is really a more fundamental idea than any previous idea. I think we owe it to Einstein more than to anyone else, that one needs to have beauty in mathematical equations which describe fundamental physical theories.

That is certainly the situation with regard to the special theory of relativity. I would say the reason why we believe in special relativity is because it puts importance on these Lorentz transformations which are beautiful mathematically. There is certainly no general philosophical basis for it, and we cannot say that it is supported by experiment if we allow experiments involving the most advanced technology. We can say that it dominates atomic theory and that the examples in which a special zero velocity shows up refer to cosmological questions which should be left out of consideration in the development of atomic theory.

General Relativity

That is the situation with regard to the special theory of relativity. How does it go with the general theory? The general theory was introduced in 1916 by Einstein and it came from his attempts to make gravitation fit in with the ideas of the special theory with Lorentz transformations. It was a very difficult problem to satisfy. It took Einstein many years and he got the solution only in 1916 in the middle of the war.

At that time people in England knew nothing about Einstein's work except for one man, Eddington, the great astronomer. Eddington kept in touch with de Sitter in neutral Holland. De Sitter kept in touch with Einstein, so that indirectly Eddington was in touch with Einstein. Eddington was extremely interested in this theory of Einstein, the general relativity, and wanted to know whether it would be in agreement with observation. This could be tested because the theory of Einstein predicted certain effects.

There were three effects which were immediately predicted. One of them concerned the motion of the planet, Mercury. It had been known for a long time that the motion of the planet Mercury was not adequately described by Newton's Laws. The perihelion of the orbit of Mercury was seen to be advancing in a way that could not be explained by Newton. It advanced by 42 seconds per century, a very small amount, but still something which is quite large enough for astronomers to detect and measure. It was soon found that Einstein's theory did provide for this advance of the perihelion of Mercury, and just by the right amount, 42 seconds per century. That was the first success of the Einstein theory.

Another way of testing the Einstein theory was that according to the theory light passing close by the sun should be deflected. There would also be a deflection according to the old Newtonion theory, but the Einstein deflection would have been twice the Newtonion one. That was something that one could check by observation at the time of a total eclipse. It was impossible to observe it at any other time, because the light of the sun was too strong and would have obscured the light of any stars whose light passed close by the sun. So one had to wait for a suitable total eclipse.

Eddington noticed that there would be a total eclipse occurring in May 1919 which would be very suitable for checking on this effect. He made preparations for sending expeditions out to observe this eclipse. Of course, he knew very well that it would be quite impossible to send out such expeditions as long as the war was still going on, but he was hoping that the war would be finished in time, and it so happened that it was finished in time. Eddington sent out two expeditions, one of which he led himself. He made observations of the deflections of the stars just behind the sun at the time of total eclipse, and the results supported the Einstein theory.

There was tremendous excitement when these results were announced in November 1919. I doubt if there has ever been any other occasion when a scientific discovery has produced such a tremendous effect on the public. Here was Einstein's theory, which everyone had been talking about for so long, several months, being actually confirmed by observations.

The results were not so very accurate because of the great difficulty of making the observations. But they were as good as one could have expected under the circumstances. Many other eclipse expeditions have been sent out more recently to check on this Einstein effect. And the results have supported Einstein in every case, with a greater or less accuracy; always with as much accuracy as one could expect depending on how good the observing conditions were.

Then there was a third effect which the Einstein theory predicted at that time, namely that there should be a red shift in the spectral lines of light that is emitted in a strong gravitational field. The natural case to look for this red shift was in the light from the sun. One should examine light from the surface of the sun and compare the spectral lines with similar lines produced on earth. This turned out to be not a very good way of checking on the Einstein theory, because the motion of the atmosphere of the sun is quite large and produces a Doppler effect, which disturbs the Einstein red shift and makes the interpretation of the results rather uncertain. Still, there was some rough support for the Einstein theory from this third effect.

Several years later Eddington noticed that this effect could be checked more accurately from certain stars, called white dwarfs, where the matter is extremely condensed and extremely compact. The light from the surface of a white dwarf exhibits the Einstein red shifting quite strongly, much more strongly than the light from the sun. When we know enough about the white dwarf so that we can estimate its size and mass roughly, we can make the calculations and we then get good support for the Einstein theory.

Much more recently it has been found that this effect can be checked just from terrestrial experiments, if one uses suitable radiation. It could be gamma rays. One takes the rays emitted from a source at the top of a tower and observes them lower down. Then these rays, while moving downward, get their spectral lines shifted from the difference in the gravitational potentials at the top and bottom of the tower. Just from these terrestrial experiments one can get a confirmation of this Einstein effect.

This effect can also be checked astronomically with the use of radio waves instead of light. If there is a radio star, a source of radio waves, behind the sun, then the light from this source, in passing close by the sun, should also get deflected. That is an observation that you can make at any time, because the sun does not emit very strong radio waves. You don't have to wait for a total eclipse of the sun to do that. This provides an independent way of checking on this effect.

There is a complication coming in with this way of checking the effect in that the sun's corona gives rise to a deflection of radio waves. But this deflection is different for different frequencies. So by comparing the deflection for two different frequencies, you can separate the effect of the corona from the Einstein effect. You get very good confirmation of the Einstein theory in this way.

Now I am going to speak about a fourth test for the Einstein theory; namely, that waves passing close by the sun get delayed. Not only are they deflected, but they are delayed. If you send radar waves to a planet lying behind the sun and then observe the reflected waves that come back and measure how long it takes to make the journey to and fro, then you can check to see whether there is such a delay. That is work that has been done in the last few years by Shapiro. Again, as you work with radio waves, the sun's corona has an effect, but you can separate out the effect of the corona from the Einstein effect by using two different wave lengths. The result is again a confirmation of the Einstein theory.

Another check has been provided in recent times by a binary pulsar. A pulsar is a star which emits radio waves in pulses with a very definite periodicity, extremely constant. Now, if this pulsar is a part of a binary system and moves around another star, the periodicity of the pulses will be changed by the motion, and that is something which can be observed. With the pulsar passing close by its companion, you get a very big effect, like the motion of the perihelion of the planet Mercury, but very much larger. This doesn't provide a very accurate test of the Einstein theory, because we do not know enough about the different parameters describing the binary system to be able to calculate just what the effect ought to be. But with reasonable estimates, it does come out approximately right and so it does provide a further rough check of the Einstein theory.

The Need for Mathematical Beauty

We have all these observations which have been made since Einstein first proposed his general theory of relativity. Every time the Einstein theory is confirmed; it has passed all the tests with flying colors. With all these observations you could say that there is very strong support for the Einstein theory of gravitation.

Still one should face the question: Suppose a discrepancy did turn up, how should one react toward it? How would Einstein himself have reacted toward it?

I don't think one should say that the whole foundation of the Einstein theory would be destroyed. Not even if the discrepancy is very well substantiated. One should interpret it rather by saying that there is some new effect that is not adequately explained. Our theory, at any time, should be looked at as in a temporary state and it is always liable to be improved upon. Any discrepancy which should show up should not be looked upon as fatal to the theory, but just as indicating that there is some further work to be done. It should stimulate people to look for further changes which could be made to account for the discrepancy.

I feel that the situation here is very similar to what it is with the special theory of relativity, where with modern technology applied to the observation of the microwaves one finds that there is an absolute zero of velocity. That doesn't spoil the Einstein theory, it just shows an inadequacy. It might very well turn up that there is an inadequacy with regard to the general theory of relativity, but so far it has not yet showed up. We shouldn't be too disturbed if it does show up in the future. It is not something that one should consider as destroying the foundations of the theory.

The foundations of the theory are, I believe, stronger than what one could get simply from the support of experimental evidence. The real foundations come from the great beauty of the theory. They come from the circumstance that Einstein has introduced new ideas of space which are extremely exciting, very elegant, and these ideas will survive no matter what the future brings before us. These ideas are based on the possibility that one can describe a physical force like gravitation just in terms of the properties of space. They lead one to look upon a physical field in general as just a disturbance of space, like a curvature.

Curvature of space is a bit difficult to understand, for a non-mathematician. Mathematicians have now gotten very used to it. Einstein introduced the simplest kind of curvature in space, a curvature which was first studied mathematically by Riemann a hundred years previously. Riemann worked out the basis of the mathematics which was used by Einstein for his general theory of relativity just like Lorentz had worked out the basis of the mathematics for special relativity.

It is the essential beauty of the theory which I feel is the real reason in believing in it. This must dominate the whole future development of physics. It is something which cannot be destroyed, even if there are experimental discrepancies turning up in the future. These experimental discrepancies must be looked upon merely as inadequacies in our present theory.

The Model of the Universe

There is one respect in which the present Einstein theory is clearly inadequate. It is a theory which gives equations describing the gravitational field, but does not give sufficiently complete equations for one to be able to get answers to definite problems. In order to be able to get definite answers, we have to have the field equations supplemented by boundary conditions. We have to know something about the conditions at very great distances. People up to the present have been working on the assumption that to study the gravitational field of particular masses, one can assume that at great distances space is just the flat space of Minkowski. That is certainly not a correct assumption, even though it has worked in describing phenomena in the solar system.

In order to understand the conditions at great distances, one has to have a model of the universe. One has to have some appreciation of what the universe is like when the local irregularities produced by the stars and galaxies being scattered about in it are smoothed out.

Einstein himself realized the need for these boundary conditions and thus the need for a model of the universe. Einstein proposed a certain static model, Einstein's cylindrical model, it is called. It was soon realized that this model would not do, because it was observed that the matter at great distances from us, the galaxies, are all receding from us. They are all moving away from us and from each other. This contradicts Einstein's model, so Einstein gave it up.

Another model was soon afterwards introduced by de Sitter. De Sitter proposed a model which gave correctly the matter at great distances moving away from us. It was a good model in that respect. But it failed in another respect; namely, the de Sitter model requires the average density of matter to be zero. That plainly won't do. So, the de Sitter model had to be abandoned.

People then set to work to discuss other models and a great many were p posed. General theories were set up by F edmann and Lemaitre. Among all these other models, there is one hich I would like to call to your attention. It was proposed jointly by Einstein and de Sitter. They joined forces and produced a new model, the Einstein - de Sitter model, in 1932. This model gave distant matter to be receding from us in the way that it ought to and also gave a non-zero average density for matter, an average density roughly of the correct value. This Einstein - de Sitter model is the simplest model which is acceptable, which does not have some obvious flaw.

I would like to bring this Einstein - de Sitter model into general consideration. I believe it is a very good model and that it should govern the cosmological development of the future. It is certainly the simplest acceptable model. It gives the universe starting off at a definite time, the Big Bang, as it is often called. It was a terrific explosion. According to the model, the universe will go on expanding forever. World without end, as they say in religion.

Many of the other models which have been proposed would require that the universe expands up to a definite limit and then contracts again. This is an unnecessary complication and I believe there is no justification for it. I would like people just to stick to the Einstein - de Sitter model, where you have an expansion which goes on forever, although it is continually slowing up. It will get slower as time goes on, but never actually stops.

The law of expansion fits in very well with the properties of the microwave radiation. I could talk a great deal about this development, but I don't want to go into technical details. I have been working for a good many years on developing these ideas, using a theory on the Einstein - de Sitter model, which I feel very satisfied with, although it is not yet definitely proved. I am hoping that soon the proof will be obtained. I would like to stop at this point and I shall be very happy to answer any questions.