Space Medicine

Lecture by Dr. James Ryan
February 10, 1959
1 hour, 12 minutes, 19 seconds

Speaker: Dr. James Ryan

Transcribed by: Sherry Yin

Time	Transcription
00:00	Marian Longstreth: It’s always a pleasure to welcome the students at these Meet the Scientist lectures. They are co-sponsored by the Theatre and Arts Foundation of San Diego County, General Atomic, Convair, Convair Astronautics, and the Scripps Institution of Oceanography. Today we shall have the opportunity of hearing and meeting the director of the General Dynamics Division of General Atomic, who is also the director of the John Jay Hopkins Laboratory for pure and applied research. He is a native of Beaver Dam, Wisconsin, and was educated in Wisconsin. He obtained both his BA and his Ph.D. degree at the University of Wisconsin. During the war, he was the leader of the first group to undertake metallurgical studies of uranium, beryllium, and aluminum and he was also a leader of the group at Los Alamos Laboratory that did the primary work on the atomic bomb project. After the war, he was professor and head of the physics department of the Carnegie Institute of Technology. He has written many papers on the subjects of his research. He is a fellow of the American Physical Society, a member of the National Science Foundation Fellowship Awards panel, and a member of the American Association of Physics Teachers. I take great pleasure in presenting to you, Dr. Edward C. Creutz, who will talk on applications of the theory of relativity. Dr. Creutz.
01:56	[Audience clapping]
02:08	Dr. Edward C. Creutz: Thank you very much, Mrs. Longstreth. Fellow students, it's a great pleasure to be here today to talk to you on the theory of relativity. These words the theory of relativity are something that sometimes strike a little fear into our hearts because we think this must be a very complicated subject. I’d like to try to convince you today that relativity is not a very complicated subject in its basic principles. Some of the mathematics is rather complicated and that's why one ordinarily doesn't study the theory of relativity, [Albert] Einstein's relativity until he's had a good deal of mathematical background. But the actual physical ideas of the theory of relativity are not complicated. I'd like to try to show you what they are. Any new theory in science of course has to be supported by a great deal of research and a great deal of experimental work to find out if it really is a correct and a useful theory. This combination of theory and experiment then is the way that all of our science has, has developed. It’s sort of a series of stepping-stones, a man makes a theory, another man or maybe the same man does an experiment to check out the theory, finds that the theory isn't quite right, has to be modified a little bit so theory is changed and brought up to date. This suggests new experiments, those are done and so forth and that's the way our science does develop.
03:31	Dr. Edward C. Creutz: This reminds me a little bit of the story of the, the physics teacher who had been working pretty hard and he thought that, his friends thought it’d be best if he went to an asylum for some rest so he went to the asylum. His students liked him very much so they were kind enough to go and call on him one weekend.

And they went to see him and he said, well my students, how nice of you to come to visit me. I have made a very great discovery, I've continued my researches. And the students said, well that's very interesting, what is the discovery? He said, well, I will show you. So he reached up and he pulled a flea out of his head and he put it down on his arm. He said to the flea, jump. Sure enough, the flea jumped over like this. He said to the flea, jump back. And sure enough, the flea jumped back here again. And he picked up the flea and he pulled off the flea's hind legs, he put it back in his arm and he said, jump. And the flea stood perfectly still. So he said, you see my students. What I discovered is that when you remove the hind legs from a flea, it cannot hear.

04:33 [Audience Laughter]

04:35 Dr. Edward C. Creutz: So we sometimes, we sometimes have to be careful about the conclusions that we do draw from the things that we observe because it's just as easy, in fact, it's often easier to draw the wrong conclusions from an experiment as it is to draw the correct conclusions. Now, in the theory of relativity - this of course is the work of Einstein - and the concepts are really very, very simple to state that the original work of Einstein was in 1905 when the so-called special theory was announced. The special theory of relativity, the reasoning behind I think, went something like this, Einstein is trying to understand the natural phenomenon was like this. He said, supposedly, we have a railroad track and a train moving along this track with some velocity and suppose you're standing on the bank here and watching this train move along and somebody throws an apple core out of the window. Well, what do you observe? You observe this apple core follow some path like this, actually, it would be roughly a parabolic path. But if you're sitting in the car yourself and you throw something out the window, what do you observe?

05:54 Dr. Edward C. Creutz: Well, to you it seems that this object falls right straight down to the ground, some path like that. So if you were interested in the physics of this question, and want to know what is the actual trajectory of this apple core. In one case you say it's a parabola and the other case you say it's a straight line. Now those can't both be right because a parabola is generally quite different from a straight line. Well, you can say obviously it's different because you're looking at it from a different point of view and that's, that's true of course. The apparent trajectory depends upon the motion of the observer. Well, that's a satisfactory way of setting up a system of physics to have laws of nature so to speak that do depend upon the particular observer that is making the observation, but you can see how this awkward, how awkward this could get if for every separate person you had to have a different set of rules for the behavior of things in nature. So Einstein's attempt was to find laws of nature which would be the same for all observers, that is independent of the motion of the person doing the observing.

07:04 Dr. Edward C. Creutz: Now, let's, let's take the case of the velocity of light. This is an interesting thing to talk about as we will see it has some very interesting properties.

The velocity of light is a limiting velocity in, in natural phenomena. Nothing can go faster than velocity, we will see some good reasons for that a little later. We know for example the velocity of light in free space is independent of the color of the light. If this weren't so, if this were not true, then whenever there's an eclipse. So here's the object being the eclipse, let’s take, consider the eclipse of a star by another star or even the eclipse of the sun by the moon, observer down here on the Earth. If let's say a red light went faster than blue light in free space then just as the moon eclipses the sun, what we would have observed is first of all, it would cut off the light that's going the fastest then it would cut off the light that’s going slower. So we would see color fringes around the edge of the sun, edge of the moon just, just before totality. But we don’t, all colors of light are eclipsed out at the same time. So the velocity of light is independent of the color in free space. Of course, it’s quite dependent on the color in, in materials such as glass. That's why a prism can separate the colors. But at least that is one thing about the velocity of light, it doesn't depend upon the frequency or the wavelength or the color in free space. Well now, another perhaps slightly more interesting phenomenon of light is that its velocity does not depend upon the velocity of the source, what does that mean?

08:41 Dr. Edward C. Creutz: Suppose again, we had a double star, two stars which are rotating about their common center of mass. Many such star systems are known, of course, have been observed for many years by astronomers. And so at any given time, suppose the Earth is down here, the astronomers observing the system with a telescope at a certain time then, this star is moving towards the Earth, this star is moving away from the Earth. Now, if it were true that the velocity of light were different depending on whether the star is coming towards us or going away from us, then you see that this light would get to us sooner than this light. The star is pushing it towards us so to speak and we would, we would observe this star then in two places at once because this light would come to us quickly when this star gets over here, that light would come to us more slowly and we would appear to see this star in two different positions at the same time. Well, this is certainly not true. The conclusion we must draw then is that the velocity of light coming towards us in these two cases is the same, whether the source is moving towards us or away from us. Now, this seems a little bit strange for the following reason: suppose we took, go back to our railroad car again and let’s suppose the railroad car is moving with a velocity, let’s say W to the right.

10:09 Dr. Edward C. Creutz: And now if you throw something from that car, suppose you throw it in the forward direction and suppose that relative to the car, you throw it with velocity V, then, of course, the net, the total velocity of that thing you throw is just the sum. The total velocity will be W plus V. Or, if you choose to throw something out backwards from the car and the car is going forwards, then the net velocity of the thing you throw of course, say V2 is just the car velocity minus the velocity, that’s well-known. If these were just equal, if you throw something backwards at the same velocity the car is moving forwards, then that velocity would be zero. It would drop straight to the ground. So this seems to be an inconsistency. Here's a case where something we're quite familiar with, we simply move along and throw something relative to ourselves and we can just add up velocities in a simple way. And yet here is a somewhat similar case where an object is throwing off, not apple cores but lightwaves, and yet in this case I don't observe C plus or minus V but I have observed the velocity C in both cases. Well, this is a little bit confusing when, when one first runs into this fact because our intuition says that velocity should just be added in this way. And here's an experiment which can be done quite carefully and we find that velocities don't seem to add up that way, at least when one of them is the velocity of light. There's nothing, no velocity greater than velocity of light. This is not C plus V but just C.

11:38 Dr. Edward C. Creutz: Well, how can this be? Let's look at another sort of peculiar phenomenon that can be observed in nature. Let's suppose again that we are in this railroad car moving along and let's suppose that at a certain instant, there is a lightning flash and suppose that lightning flash appears at two points, maybe there are two trees here that get struck. And to us moving along, we say well those lightning flashes were simultaneous, it happened just at the same time. On the other hand, if we're standing down here in the bank and by some appropriate system of mirrors let's say, we could observe the relative times of the two events. In this case, they would not appear simultaneous to us simply because this car is moving towards this source, so the total distance light has to travel is less than in this case. So what is simultaneous for the person moving in the train is not simultaneous for the person standing still, relative to the two events. Well, this is an experiment one can make and sure enough you have to decide. You say well, after all, I could get it to come out simultaneous if I corrected for the fact this car is moving along. And that's true, you could. But there's something slightly more elegant about a system of physics where you don't have to make all these corrections but you can say the same phenomenon, you can describe the phenomenon the same way independent of the fact whether you are moving or whether you are at rest. And that is the attempt of Einstein's special theory of relativity to find laws of nature which are independent of the motion of the observer.

13:15 Dr. Edward C. Creutz: Well, here we have to sort of take, take a choice because if we're going to end up with these laws, we are going to find that we have to give up some of our intuitive ideas about what the physical world is like and we must make this choice. Are we willing to say that perhaps our intuition is fallible and the things that seem that that's the way they ought to be maybe aren't that way? Or are we going to say well I'm going to trust my intuition but then I'll have to have a much more complex system of description, a system of physics? Well, this is of course one place where one can take his choice but one generally finds it is much simpler to describe the physical world if he's willing to give up some of his intuition about how natural phenomena ought to be. Let's consider another situation I think will make this a little clearer. I'd like to use some of the notation that Einstein used now in describing such systems.

14:11 Dr. Edward C. Creutz: Let's talk about a frame of reference by which we simply mean a coordinate system, some origin, O for origin, at the center of things here, and then some way of measuring distance along a line in this frame of reference. Let's call this the X-axis. So I can measure out here one meters, two meters, three meters, anything I want. And one other thing we'll have to talk about in, in this kind of frame of reference besides the distance of objects, we want to talk about the time when events occur. So we'll say that we measure time and I'll call that T, time T in distance, X for any particular event I want to talk about. And a combination of a T and an X, we will call an event. For something to happen, it has to happen someplace and at some time. So some T and some X give me an event. But now let's talk about another frame of reference which at first looks just like the other one. The difference is though this frame of reference is going to be moving along to the right with a velocity V relative to this frame.

15:16 Dr. Edward C. Creutz: You can see what we're getting at here are two observers with different motions and we want to find laws of nature that are the same for both these observers. Now just to keep these systems separate, let's call the distance measured here X prime because we'll find it isn't going to turn out quite the same as X, and let's call our time that we measure here T prime. So remember that in the prime system, or the prime frame of reference, the only difference is that this whole system is moving to the right with velocity V relative to the system without any primes. Now, let's see how we can relate the prime quantities to the unprime quantities. Well, that'll be pretty easy. Let's consider some point out here someplace and let's see what the distance is. Well, let's say the distance to that is just X but if I want to measure it relative to this frame of reference, I'll call the same, the distance to the same point, I'll call it X prime. And the relationship between those two will be just X prime is X minus VT. In other words, the distance X prime will be getting smaller as time gets greater because the system is moving towards this point. In fact, we can see that after a certain, after a certain time, the X prime distance will become zero, that simply means the origin of this frame of reference will coincide with this point because this frame of reference will have moved to the right that distance. So this is the relationship between any distance measured in the prime system and the unprime system. At least that seems intuitively correct.

16:54 Dr. Edward C. Creutz: Now, how about the times? How should we relate T and T prime? Well, clearly we are going to measure time with some kind of a clock and a clock shouldn't care if it's moving along or standing still, so the way that seems intuitively correct is to say T prime equals T. That is, if the clocks are good clocks, then whatever time one reads the other one should read the same. And let's call this set of equations, this is sort of the intuitive said. That seems like the way our intuition would tell us we should relate Xs and X primes and Ts and T primes. Now let's consider a physical law and see how this, this works out. And let's take for our physical law again because it's a very convenient thing, let's take the motion of light. Now light moves with a velocity C, let's, let's use a symbol C for the velocity of light. Then, if we look at this system over here, the distance that light goes in a certain time, let's call it X prime because we're calling distances X prime in this system. X prime will simply be C times T prime.

18:05 Dr. Edward C. Creutz: The distance is the velocity times the time. C is the velocity of light. T prime is the time in that system. So that's, if we want we can call this a law of nature you see, how far does light go? It goes its velocity times the time in the prime system. Now let's try to, let's translate that, or let's write the law of this system. Well clearly the law of nature intuitively would be the distance of light goes, X is just the velocity times the time T. Distance is velocity times time, here I won't use the primes because I am referring to my own frame of reference, this one, where distances are X times T. So there's a law of nature. There's a law of nature in this other language and we need some way to translate one set of words to the other set of words and here is my intuitive dictionary for translating unprime numbers into prime numbers. Well, let's try that and see how we come out.

19:06 Dr. Edward C. Creutz: Let's try to translate this statement by going to our dictionary. Wherever it says X prime, the dictionary says put an X minus VT. So I'll do that, X minus VT equals, C is the same but where it says T prime, I will put in T. So when I try to translate from this statement into the language of this other country by this dictionary which is intuitively correct, we do not arrive at the statement of the other system. So something is wrong and here again, we can take our choice. We can say either we can't use the same law of nature in the two systems as we so nicely did, distance is velocity times time, be sort of too bad if we couldn't say that. But if we don't, if we don't stick to this being true, then we have to find some new law of nature or, on the other hand, perhaps we can find a law of nature that is correct if we use something other than the intuitive way of translating from one frame of reference to the other. Well, this is, this is Einstein's suggestion. In fact, this is the special theory of relativity, that we'd be willing to give up this relationship between space and time that is shown here.

20:24 Dr. Edward C. Creutz: Let's try another dictionary or another vocabulary here for translating and see how that works out. And of course, I'm, I'm fudging a little bit here because I'm going to write down the vocabulary that is correct, that gives the same law of nature in each system. The correct statement in this, correct in this sense, is that X prime is equal to X minus VT just as, as we had here but now divided by the square root of one minus V squared over C squared and we'll talk about that in a minute. And T prime is equal to T minus VX over C squared, over the square root of one minus B squared over C squared. Now you can say, what a peculiar combination, what a peculiar way to translate from unprime numbers to prime numbers. You're really messing everything up because when you want to measure an X prime, you not only have to measure X, you also have to know the time. So this is a peculiar combination of space and time measurements. So up to now, it looks like this is a hopelessly complicated sort of way of translating from the unprime system to the prime system but let's not give up yet. Let's see what this does for us if we try to translate from one law of nature to the other.

21:49 Dr. Edward C. Creutz: Well, the rules of the game are that wherever I see an X prime, I should write this quantity here. So here's X prime. I'll write X minus VT over the square root of one minus B squared over C squared equals C. And wherever I see T prime, I should write this peculiar expression. T minus VX over C squared square root of one minus B squared over C squared. Now let's see if we can simplify this equation a little bit. We can multiply through by this denominator. Let's collect the terms here with X, here I have X on this side times the quantity one. On this side, I have X times V over C and when I move it over to this side, it becomes plus. So it's one plus V over C and let's put on the right side, the terms with the time in them. Here I have CT times one plus V over C. And I can now cancel out the one plus V over C. And so, I have succeeded in going from this equation to the same equation in the other country's language but I've only succeeded in doing it by using a very complicated relationship between the prime and unprime system. Well, that's the lesson that Einstein pointed out to us that if we want to end up with the same equation X equals CT in the unprime system as we started out in the prime system, we may have to use something other than a simple intuitive relationship between the two frames of reference. Well, let's for the time being, assume then that this is the right way to translate from a moving system to a stationary system that is from the prime system to the unprime system, and let's see what the consequences of this are.

23:53 Dr. Edward C. Creutz: Let's consider a very simple experiment, just measuring the length of an object. And to do this let's simply say that we will put down in the, let's put it in the moving system. Prime always means moving to the right at the velocity V. Let's put a meter stick down in that system with the, with the origin, with the, the beginning of the meter stick at the origin and if it's just one meter and we use one meter for our unit of length, then of course the end of the meter stick will come out just to 3.1 on my distance scale here. Now let's see what we would measure this meter stick to be in our unprime system, as our X system. Well, the, to measure a distance we have to, one way of doing this, of course, is to take a reading at the, each end of the meter stick, then just take the difference of those two readings. So let's take a reading at the beginning of the meter stick and let's assume we do this for simplicity at that instant of time when the two origins coincide.

25:07 Dr. Edward C. Creutz: See this is moving to the right so sometime not very long ago, these two were sitting right on top of each other. If we do that then, we simply have to use these equations at some time, and let's call at time T equals zero when the two origins do coincide. We can arbitrarily say we'll start our watches at that instant, you see. Then the, I have to use this equation to get the the value of X when X prime is zero as X prime here is the X prime at the beginning. So that X at the beginning of the meter stick let's say is equal to the X prime times this quantity here. T is zero so I won't worry about this time. So X is X prime times the square root. Let's just write it this way. But the X prime at the beginning of the meter stick of course is just zero because it's beginning at the origin. Now let's also measure at the same instant by some device, the X value at the other end of the meter stick. Well, to do that I'll go back to this equation. The X value of the other end of the meter stick will be the X prime value but times the square root. The X prime value of course is just one because it is a meter stick. So this will be 1 times the same square root.

26:25 Dr. Edward C. Creutz: Now the length of the meter stick, as measured in the unprime system, will be just the difference of these two measurements, X end minus X beginning. So the length is 1 times the square root of 1 minus B squared over C squared. Well, that's sort of strange, isn't it? We said it was a meter stick, to begin with in the unprime system the length was 1. But as measured in the, I'm sorry, in the prime systems its length is 1. But as measured in the unprime system, its length is somewhat less than 1. In fact, less by just this factor, the square root of 1 minus B squared over C squared. Well, this is the so-called Fitzgerald-Lorentz Contraction which says what? It says if you're observing an object which is in motion relative to you, it appears to have a shorter length than if it is at rest. That certainly isn't very intuitive, as we certainly don't think of things getting shorter as they move along, and yet this is a consequence again, let me remind you, it's simply a consequence of trying to set up a system of translation which gives us laws of nature which are the same in all coordinate systems. And it certainly isn't very intuitively correct.

27:37 Dr. Edward C. Creutz: Well, one can easily write down other consequences of this set of equations. In fact, a very interesting one is the result for a mass, if we try to measure the mass of an object in two systems. I won't go through the mathematics of that, but will simply write down the result. And one result is that if we, we can do this by setting up a little experiment. This was a very simple experiment where we just made a measurement. A somewhat more complicated experiment would be to take two balls, let them collide, bounce off each other, and then if we assume momentum is conserved and energy is conserved, we arrive at the interesting relationship that the energy of the object is equal to, of one of these balls say, is equal to its mass times the square of the velocity of light and divided by one minus B squared over C squared. This looks a lot like the formula you see in newspapers these days about the relationship between energy and mass.

28:33 Dr. Edward C. Creutz: E equals MC squared. It differs by this factor here and the reason is we're now considering an object which is not at rest but it's moving with a velocity V and this is the correct expression when the object is in motion. E equals MC squared holds only when the object is at rest. But, let's look at this a little further. Let's write this in a form where we can easily expand it by the binomial theorem. Let's write this MC squared times the quantity one minus B squared over C squared to the minus one-half power. Now the binomial theorem tells us how to write such things as infinite series. Let's do that. Get MC squared times 1 then we're supposed to take minus one half, this quantity to the first power, and of course minus, the minus gives us a plus. So we have plus one-half B squared over C squared and we're supposed to take minus ½ times three halves which is minus ¾. This quantity minus-minus-minus gives us a minus and so forth. We get higher terms here which we won't bother to write down because the next term you see, well let's write one more down. The next term is going to have in it a V fourth over C fourth because it's the square of this term, you see. Actually, it's a coefficient here, ⅜, and four other terms.

29:59 Dr. Edward C. Creutz: Now for a large range of experiments that we can do in the laboratory, the velocity of our balls and our protons and our electrons and so forth, is very small compared to the velocity of light. So if we raise this very small ratio to the fourth power, it'll become negligibly small in many cases. So let's, let's neglect that term for the time being. And say that the terms we want to talk about are just the first two and let's write those out. If I drop a term of course I can't write equals here anymore, so I'll use the symbol that means approximately equal by putting a dot over the equals sign. Then I have MC squared plus one half MC squared times B squared over C squared which is one half MV squared. Now this, I think some of you may recognize one-half MV squared what we call the kinetic energy of an object. It's the object, the energy an object has because of its motion. But notice that according to this statement that comes directly out of the special theory of relativity, the energy of an object is its kinetic energy, all right, and of course, I haven't assumed any potential energy here, if I did I have to add that on. But it is its kinetic energy but plus another term MC squared, which tells that even if the object were at rest if the velocity were zero, there still would be an energy MC squared and that's the equation here used to seeing. Well, why didn't we know this long before 1905? This is about, a large amount of energy. It's very large compared to this term because C is very large compared to V ordinarily.

31:36 Dr. Edward C. Creutz: Well, the reason we didn't is that when we do experiments the thing we can vary on balls rolling down hills and so forth, we can vary the velocity but we can't vary the velocity of light. And what we actually measure is changes in the energy and so ordinarily, this is the term we change. So this is the term that's important for us. We don't change this term but there are experiments where you can change this term of course. Usually, these changes are rather hard to make except under special conditions. The one case where you do change this term. of course, you can change it by change C, changing C which you do change it by changing M, the mass of the object such as in a nuclear reaction where the actual mass of the particles after the reaction is less than the mass of the particles before the reaction. So large amounts of energy are given up. Well, that's another consequence of the so-called special theory of relativity. Why is it special? It's special because we considered only those cases where one system was moving with a fixed velocity V relative to another system and that certainly is not the most general kind of motion one can think of. In general, you could have acceleration as well as velocity. So all the special theory was able to handle were those problems of dealing with laws of nature where one observer was moving relative to another observer but with a constant velocity, V. It wasn't until 1915, 10 years later that Einstein succeeded in putting into some suitable mathematical language, the so-called general theory of relativity. Which just as the name suggests, was generally true for showing a way of writing laws of nature independent of the motion of the observer no matter what that motion was, whether it was accelerated or constant velocity. Now the way of looking at this is somewhat different than we did in the special theory because it covers a great deal more conditions of course.

33:35 Dr. Edward C. Creutz: The observations that led Einstein to the very deep insight into nature which, by which he was able to express the general theory were the following, first of all, he noticed the interesting fact that all objects in a given part of the universe experience the same gravitational field. Now, perhaps that doesn't sound too surprising that if I have two objects here, they are in the same gravitational field but really is a little strange if you think of it because it doesn't matter if that object is made out of uranium or led or heavy water or ordinary water or oxygen, it still finds the same gravitational field. And Einstein pointed out that this same condition would exist if you had instead of a gravitational field if you had some sort of a closed box here let’s say, and this box we’re being accelerated upward with some acceleration A, just like an elevator starting out. And of course, when you're in an elevator starting up, you feel that extra gravitational field. But the argument is that if you're in this elevator starting up and you release something, say you drop a ball, that ball will fall to the floor apparently with accelerated motion. Now if you're not in the elevator, if you are looking through the window, say the ball really essentially stands still and the floor comes up and hits it, but it doesn’t matter if this ball is made out of wood or lead or whatever it is, it will follow just exactly the same motion. And remember, we’re thinking of this experiment now far away from the Earth where there is no gravitational field.

35:12 Dr. Edward C. Creutz: So we can describe this motion, one of the frame of reference now - which is the elevator - being accelerated upward or we can describe it as a ball falling downward and the statement is if there's no way of saying by any experiment which one is happening, whether the ball is falling or the elevator is going up. Now you might say ah, but maybe we can do this by using light. We can send a light beam let’s say from this point to this point. And if the box is actually being jerked upward then the light beam is going to fall short of the mark, you see. And to an observer on the outside, he'd say well no the light went in a straight line but the box was jerked upward. So you jerked the target away from the light, but again there's no way you can tell because one of the consequences of the general theory of relativity is that light itself is affected by a gravitational field. So you'd have the same effect with a box standing still and a very large planet here producing a gravitational field that pulled the light down. It'd be the same effect as having no planet here, nothing at all except the box but having a box accelerated upward.

36:20 Dr. Edward C. Creutz: This is the so-called theorem of equivalence, which simply states that a gravitational field is completely equivalent to an acceleration. I won't go into any more details on that except to say that there are, the question of course arises, is this the correct explanation of a gravitational field? Einstein was able to do it by using the theorem of equivalence or is it not? After all, Einstein's or rather [Isaac] Newton's gravitational theory is quite satisfactory. It gives us a very good picture of the motion of planets, the motion of objects in gravitational fields. However, there are a few experiments where one can actually distinguish between the two theories, they are not quite identical. Of course, the basic idea behind them is entirely different, but actually, the consequences are somewhat different. And there are three famous examples where one can look for effects that would be brought in if Einstein's theories were correct. One is the motion of the planet Mercury around the Sun. Mercury is the planet nearest the Sun. It's close enough to be in a very strong gravitational field compared to the field which the Earth is.

37:24 Dr. Edward C. Creutz: Now, one knows that if Newton's laws were strictly correct, Newton's law of gravitation, that the planet Mercury would travel around the Sun in an ellipse with the Sun at one of the foci of the ellipse, and that's very nearly true. However, the orbit of Mercury has been observed for well over a hundred years with some precision and it's known that orbit does not quite close but actually processes. I'm exaggerating it very much of course but the orbit does not stay put but moves in this fashion, so-called precession. Now, this angle of precession, one speaks about the precession of the perihelion of Mercury. The precession of this point which is closest to the Sun on the orbit, this rate of turning of this, of the perihelion is well known. In fact, it's about forty-three seconds of arc per century, not a very large angle but something that can be measured with some precision.

38:18 Dr. Edward C. Creutz: Well, one reason that the orbit precesses is that this is not simply a two-body problem, there isn't just the Sun and Mercury in the universe. There are a number of other planets and these perturb the orbit. But these effects can be corrected for with very high accuracy and even after one corrects for those, he still finds a precession of this order which cannot be accounted for by Newton's law of gravitation and is accounted for with quite high accuracy by going to Einstein's general theory of relativity, which equates a gravitational field to an accelerated system. Another example, of course, is the bending of light around the Sun which astronomers always look for during total eclipses and it's always cloudy so it's a hard experiment to make. But this is further evidence that there is a deviation from Newton's law of gravitation in favor of Einstein's special or general theory of relativity. And the third interesting observation is the so-called redshift, the fact that the space and time get all tangled up in the theory of relativity and can't be kept separate as we would intuitively like to do means that the clock runs slower. The clock actually runs slower in a gravitational field than it does not in a gravitational field.

39:33 Dr. Edward C. Creutz: And this is a small effect but if we go to very heavy stars like the white dwarfs of the stars like the dwarf companion of Sirius, the Dog Star, or the density of materials perhaps a million times greater than it is on Earth. The gravitational field is so large that it does slow down a clock. Well, how in the world do you know if a clock is running slower on a star than it is on the Earth or not? Well, simply because there are atoms of the same kind on the stars as there are on the Earth. And the atom is emitting, you can think of it as a pendulum clock beating, but of course, it's really sending out a light wave. And you can measure the frequency of this light wave and sure enough, it is found to be a lower frequency on these very dense stars. So this is a third example, a kind of a verification, of Einstein's general theory of relativity. I'd like to give you one other interesting consequence for this theory and just put down a few numbers. Out of Einstein's theory of relativity comes a relationship, in fact, see could I borrow that sphere now down, please? I brought along a little different kind of blackboard because this one is kind of hard to draw curved spaces on. Einstein's theory makes use of the so-called curvature of space and we can just as well have a two-dimensional space that's curved as a three-dimensional space and it's a lot easier to make.

40:59 Dr. Edward C. Creutz: So we have here a three-dimensional space. One of the consequences of such a space is that the sum of the angles of a triangle is not 180 degrees but it's somewhat different. In fact, that's a way you can test whether a space is curved or flat. We can easily see that if we simply draw a triangle. Let's start at the North Pole and draw a line down to the equator. Let's draw, start again at the North Pole, and draw another line down to the equator. And let's connect those two at the equator. There we have a triangle. Of course, it's not a plane triangle, it's a spherical triangle. But if we look at the sum of the angles, I purposely drew these lines ninety degrees apart, and here's a line. This is a what do you call, a meridian intersecting a parallel of latitude so this angle is ninety degrees, same way here. So the sum of the angles of this spherical triangle is 270 degrees and not 180 degrees. Well, that's not surprising because it's not on a plane surface but there is a simple relationship that we can write that tells us what to expect for the sum of the angles of a triangle in terms of the curvature of the space.

42:06 Dr. Edward C. Creutz: First, we have to define a quantity which is called a spherical axis. The spherical axis is defined as the sum of the angles. Let me call this sum of theta, sum of the angles minus what it ought to be. It ought to be 180 degrees. Or let's do it in radians. It ought to be pi radians minus pi. This we'll call a spherical axis epsilon. The spherical axis, as spherical geometers will prove to you, is just equal to the area of the triangle divided by the square of the radius of curvature of the space. Let's just check that one just for fun and see how it works out. We said the sum of the angles of a triangle here is three times ninety, that's 270 degrees but let's call it three pi over two, put it in radians. Three pi over two minus pi. So the spherical axis here is just pi over two. And according to my formula, the spherical axis pi over two ought to be the area of the triangle divided by the square of the radius.

43:09 Dr. Edward C. Creutz: Well, R squared of course is the radius of the sphere. Let's see what the area is. The total area of a sphere is 4 pi R squared but I have, I have drawn just 1/8, one octanth, one octant of the total sphere. So the area is 1/8 of 4pi R squared or the R squareds cancel and I have 4 pi over 8, 4 pi over 2. So the formula checks out at least for this particular case that I can measure the curvature of a space, in this case, a two-dimensional space, by drawing a triangle, finding the spherical axis and dividing the area, dividing the area by the radius squared. The radius of the space gives me the spherical axis. So this curvature of a space is closely related to the gravitational field. I won't have time to go into that now but that is one of the things that Einstein shows, that the gravitational field does depend very closely on the curvature of the particular space. Well, this brings up the immediate question, of course, is all of this true? That space is curved, and that space and time are tangled up so that we can't go from one coordinate system to another without rather complicated equations with the result being that we can use the same laws of nature in all for all observers. But we have to of course decide what we mean by, by true and here we actually have a choice. We can say are the postulates true? Our postulate in this case was that we wanted the laws of nature to be the same.

44:47 Dr. Edward C. Creutz: If that's a good true postulate then the other follows immediately so by definition is true. On the other hand, if we'd rather have things be intuitively correct, if we define that as what is true what our intuition tells us, then of course none of this is true, the theory of relativity is wrong. Is it true that space is curved or it’s sort of hard to imagine a three-dimensional space being curved in a fourth dimension? Well, there again, it is curved if we wish to adopt that postulate that we want relatively simple laws of nature. And the things we’ve talked about here are, the things that Einstein pointed out certainly gave us some more unified set of, of laws and a much, much simpler way of talking about the phenomenon that we do observe in the physical world. I think perhaps the very important statement in this idea was made by the great Swiss physicist [Wolfgang] Pauli, who just died about a month ago. Pauli’s statement was that it's probably more important to have the ideas in physical theory simple than to have the equation simple. Well, this is certainly something that Einstein has done for us with the theories of relativity. He’s given us very simple ideas even though the equations are not quite so simple. Thank you very much.

46:03 [Audience Clapping]

46:14 Marian Longstreth: Thank you so very much, Dr. Creutz. Now I’m sure all the students here appreciate having a man who really bears a very great responsibility give so much time in coming here today and I'm wondering if you could give a little more time and answer a few questions.

46:31 Dr. Edward C. Creutz: I would be glad to talk with you some more.

46:33 Marian Longstreth: Are there any questions from the floor and we have a traveling microphone that can -

46:41 Speaker 1: The equations on the board apply to a spherical space. Do they also apply to negative space, saddle-shaped?

46:50 Dr. Edward C. Creutz: Yes. By negative space, I imagine you mean a space where the curvature is negative. Is that what you mean? Yes. One can imagine a saddle-shaped space of this sort, and the reason we'd call it a negative space is that notice that I didn't use just the radius of curvature in any of the equations. I use the square of the radius of curvature. More generally, if I had an ellipsoidal space rather than spherical space at any given point, there would be two radii of interest because this band about the eclipse is more curved than this band here so the quantity that really comes in as the product of the radii, of the reciprocal radii, of those two circles as this is R1 say and this would be R2. So the quantity that comes into these equations is one over R1 times one over R2. And in a sphere, of course, R1 is equal to R2, there's only one radius so that's why I call it R squared. Now if we have a surface like this, notice that the center of curvature of the saddle here is up and the center of the curvature this way is down, so we have to call one of those negative. So the product R1 R2 is a negative quantity and these equations then hold exactly, except one has to put it in the minus sign for the, this product of the principal curvature as they are called. Yes sir.

48:11 Marian Longstreth: Thank you.

48:12 Speaker 2: Certain cosmological theories, present cosmological theories, require that certain parts of the universe expand more rapidly than the speed of light. How is that possible?

48:27 Dr. Edward C. Creutz: Well, I don't know of any theories that, that need to assume that, are we maybe thinking of something that I don't know about? The usual theory of the expanding universe simply says that the, that the velocity of expansion is a constant times the distance from any given point. So this looks a little suspicious because you might think this distance is large enough, this velocity could become large without a limit. But any such theory also assumes that space is curved back on itself, so there is some maximum value to this radius. In fact, this maximum value is such that the velocity you get at that distance is just the velocity of light because there is no good physical meaning to a velocity greater than velocity of light. As you can see from this expression right here that we wrote down. The energy is MC squared divided by one minus B squared over C squared, so if V were greater than

C, this would be a negative number and would have a square root of a negative number. This would give me an imaginary quantity and there is no meaning in physics you see to imaginary energy. It's only real energy has significance. So I don't know of any serious cosmological theory that talks about velocities greater than the velocity of light but -

49:44 Speaker 2: I read a book by Fred Hoyle, in which he states that it's a common misconception. In that, the general theory of relativity, that doesn't apply. I don't have the book with me, unfortunately.

49:59 Dr. Edward C. Creutz: Well, we should, I should look that up. The concept, one of Hoyle's concepts of course is the creation of matter also. So you might say, really we don't need to stick to this equation because this, this equation would be true if there's a conservation of matter and energy and one of his postulates is that actually matter is being generated at a very small rate, a rate we can't really notice but that atoms are being born in free space at some finite rate. So one can certainly set up theories with velocities greater than the velocity of light. One can set up theories where the, where energy and matter are not conserved. The question always comes, do these theories give you anything new? Do they help you describe the physical world? Again as, as I said, you can take a set of postulates and that you can build a theory. Somebody else can take another set of postulates and build another theory and it's a perfectly fair question, which theory is, is the better one?

Dr. Edward C. Creutz: It's probably not fair to say which is the right one because each one can give you some description of nature. But it is, it's fair to say which is the better one. And most, most physicists do adopt the view that energy is conserved and that the velocity of light is a limiting velocity. But certainly one can make other theories. And who are we to say they are wrong because to test between these various areas is extremely difficult. I did point out some tests to choose between Newton's theory of gravitation and Einstein's theory of gravitation but these are very complicated things and for almost all of physics on the Earth at least, we don't need to distinguish between them. We will have to worry about distinguishing between them when we, when we get out in space and it will be easier to distinguish between them then too. We can do better experiments when we're outside the atmosphere of course. I know I haven't answered you very well but I think the point is that there, you can make almost any set of postulates you want and arrive at a theory. The choice then must come by seeing which is the more convenient set of postulates and theories to suit the observations.

52:06 Marian Longstreth: Over there, in the corner.

52:08 Speaker 3: Any of these equations apply to hyperbolic space?

52:12 Dr. Edward C. Creutz: Yes. Yes, they certainly do. This type of space is sometimes called hyperbolic space. It has a negative curvature.

52:25 Marian Longstreth: Over here. [Unclear] Last few questions.

52:33 Speaker 4: In your last equation, your figure is 3pi over 2. How are they, where do they come from?

52:42 Dr. Edward C. Creutz: I'm sorry, I didn't hear the question.

52:48 Speaker 4: In your last equation where you have 3pi over 2 times pi. What, how did you arrive at your figures?

52:56 Dr. Edward C. Creutz: Where do I get the pi from? Yeah, one way of measuring angles besides using degrees is to use what are called radians, and if we consider a circle and then draw some angle over the apex at the center. We of course can measure this as a certain number of degrees. Another way that's often used is to take the length of R, which let's call S, and divide by the radius, which let's call R, and define this angle which I'll call theta. Say that theta is equal numerically to S over R. This is just, this isn't in degrees anymore, this is said to be in radians. So let's see how many radians there are in a whole circle, all the way around. Well, it'd be 360 degrees of course but in my notation here of radians, the total R is
2PiR, the circumference divided by R. So there are two Pi radians around a point, just like 360 degrees around a point. Well, if I choose to use that unit, then what we ordinarily think of as a right angle, 90 degrees corresponds, to just 1/4 of 2pi or pi over 2 radians and that's the units I was using.

54:20 Marian Longstreth: Any more questions? Thank you very much, Dr. Creutz.

54:22 Dr. Edward C. Creutz: You're welcome.

54:23 [Audience Clapping]