UNIT 1 THEORIES OF RELATIVITY

Contents

1.0 OBJECTIVES

Relativity has profoundly changed the whole physics. By the analysis of the fundamental concepts of space and time, of mass and of force, it has given a new orientation not only to science but also to our approach to philosophical problems in general. It is the theory which says that concepts like space, time, mass, simultaneity, motion etc., are not absolute but relative; absolute to frame of reference.

1.1 INTRODUCTION

The advent of the theory of relativity and of the quantum mechanics has revolutionized the whole domain of science. They questioned some of the age old concepts such as absolute motion, absolute space, absolute mass, wave nature of particles, unlimited perfectibility of experimental results etc. They brought in certain radically new concepts and gave new insights into several baffling phenomena in nature. Towards the end of the last century it became abundantly clear to scientists that the real trouble spots in scientific inquiry were in the fathomless depths of intergalactic space at the other end. Quantum mechanics arose in an effort to answer the problems hovering in the subatomic world and relativity in the 'ultra-giant' and 'ultra-fast' world.

To show the all pervasive importance and relevance of relativity in theoretical science of today, we give a few quotations from the leading writers. Thus H. Margenau writes, "In fact the theory is now so well corroborated by experience and by assimilation into the whole of modern physics that its denial is almost unthinkable. The physicist is impressed not solely by it's for long empirical verification, but above all by the intrinsic beauty of its conception which predisposes the discriminating mind for acceptance even if there were no experimental evidenced for the theory at all. Again Hutton, "Relativity has profoundly changed the whole of physics. By the analysis of the fundamental concepts of space and time, of mass and of force, it has given a new orientation not only to science but also to our approach to philosophic problems in general."

Before Einstein, physicist were confident which they understood distance, time, and mass. They believed any skilled person could measure distance with a ruler, tell time with a clock, weigh mass with a scale, and get the True values. With his theory of special relativity, Einstein proved that this was wrong that there were no true values and he shook the very foundations of science. Einstein developed two theories of relativity: special relativity and general relativity. Special relativity, published in 1905, covers only special, simple situations, those in which there are no forces. It was followed ten years later by general relativity, which includes Einstein's theory of gravity and is the more complex theory.

1.2 THE THEORY OF RELATIVITY

In everyday language we can say that relativity is a theory which holds that concepts like motion, length, time, mass etc. not absolute. They make sense only when referred to a frame of reference. Thus an astronaut of mass say 80kgs on the surface of the earth (first frame of reference) may have a mass of 100 kgs while inside a fast moving rocket (second frame of reference). A different definition is given by Eddington, "an attitude which leads to the conclusions that we observe only relations between physical entities."

Special and General Theory of Relativity

Einstein published his theory in two papers, one in 1905 and the other in 1916. The forms the special theory and this deals with only uniform motion of bodies. The second is called the general theory and this deal with all moving bodies including those with non-uniform velocities, (i.e. accelerated bodies).

Postulates of the Special Theory of Relativity

Einstein explained the "negative result" of M. M. experiment in the form of two postulates.

Postulate I: it is impossible to determine absolute motion by any experiment whatever. So in the universe no privileged frame of reference with respect to which absolute motion can be measured exists. Hence the phenomena of nature will be the same for two observers who move with any uniform velocity whatever relative to one another. Putting it in another way we can say that uniform motion does not affect physical laws. The general laws of physics are the same in all systems moving uniformly with respect to each other in a straight line. This is called the principle of relativity, from which the theory gets its name.

Postulate II: the velocity of light is a constant absolute quantity. It is independent of the motion of the source or of the observer.

Implications and Consequences of the Postulates

It is impossible to measure the uniform motion of a body by observing events taking place within the body. According to the first postulates all natural events are unaffected by uniform motion. So by observing them from within the body moving with uniform velocity we cannot measure its velocity. Consider a train moving with constant speed. Everything inside it happens as though it is motionless.

1.3 RELATIVITY OF MOTION, LENGTH, TIME, SIMULTANEITY

We must give up the classical platform of an immobile framework of space. It is meaningless to talk of absolute rest. All motion is relative; is makes sense only when referred to a frame of reference. As an illustration consider a station master at the platform and an engine driver in a moving train. The station master will say that the engine driver is moving with respect to him. The engine driver, on the other hand, will say that the station master is moving with respect to him and his engine.

Relativity of Length

Length is not something absolute in the sense that it has the same value everywhere. The stationary observer will notice the contraction. But the observer in the moving frame will not be able to measure any contraction because his scale also will have contracted by the same amount. Thus it follows that it is meaningless to speak of length without specifying the frame of reference, without specifying whether the length is taken with respect to a moving observer or a 'stationary' observer. (Contraction is perfectly reciprocal. Each observer notices a contraction in the system of the other. It is not a contraction of bodies, but of the measurement of bodies or of length, where 'length is not an intrinsic property of the body a conception we associate with the body')

Relativity of Time

We must give up the classical notion of 'steady, unvarying, inexorable universal time flow, streaming from the infinite past to the infinite future'. In a moving frame time slows down, two observers moving with different uniform velocities will have different values to the duration of an event. Newton assumed time was absolute and universal. He assumed time ran its own intrinsic rate, unaffected by anything else, flowing at the same rate everywhere and always. But Einstein showed that all this was wrong. Time is relative; there is no one, TRUE time. Time runs at different rates in different inertial frames; different clocks will inevitably measure different times. Let us try to see why it is true. Time is our way of measuring how rapidly things change. If nothing ever changed, time would be a meaningless concept. Every clock counts the number of 'times' something changes. In truth, it is time itself that appears to us to be slower in a moving frame; this is called 'time dilation.' Hence according to relativity there is no absolute before and after. Absolute topological time is ruled out. This means that there is no absolute past, present, future applicable to the cosmos as a whole. Also there is no absolute duration. This rule is out absolute metric time.

Space-Time and Four-Dimensional Continuum

Hermann Minkowski, realized Einstein's theory changed our understanding of the geometry of our universe. The three dimensions space can no longer be considered distinct from time; space and time must be viewed as a combined four-dimensional entity that Minkowski named space-time., In four-dimensional space-time, points are called events and four quantities are required to specify an event such as latitude, longitude, altitude, and time. Time measurements and normal three-dimensional distance measurements are relative (different from different observers), but the distance between two events in four-dimensional space-time is invariant (the same for all observers). Space is the relation of things and time is the relation or order of events. They are a relating system expressing certain general features of physical objects. Thus they describe the world in an orderly way. It is true that they are constructs of the mind, but they are not pure, empty concepts. They are concepts fit to describe the physical world. In Hans Reichenbaclis words, “these conceptual systems describe relations holding between physical objects. In addition these relations formulate physical laws of great generality, determining some fundamental features of the physical world. Space and time have as much reality as; say the relation “father” or the Newtonian forces of attraction.” Thus the relations we talk of our objective relation.

In ordinary language the word ‘space’ itself is used as the name of a continuant. We can say, for example, that a part of space has become, or has contained to be, occupied. Space-time, however, is a ‘space’ in a tense less sense of this word, and because time is already in the representation it is wrong to talk of space-time as itself changing. Thus, in some expositions of relativity it is said that a certain ‘world line’ is a track along which a material body moves or a light signal is propagated. Here the body or light signal is propagated. The body or light signal, however, cannot correctly be said to move through space-time. What should be said is that the body or the light signal lines (tenselessly) along the world time. To talk of anything moving through space-time is to bring time into the story twice over and in an illegitimate manner. When we are talking about motion in terms of the space-time picture, we must do so in terms of the relative orientations of world lines. Thus, to say that two particles move with a uniform nonzero relative velocity it is expressed by saying that they lie (tenselessly) along straight world lines that are at an angle to one another. Similarly, the recent conception of the position as an electron moving backward in time is misleading because nothing can move, forward or backward, in time. What is meant is that the world lines of a position and electron, which are produced together or which annihilate one another, can be regarded as a single bent world time, and this may indeed be a fruitful way of looking at the matter.

Check Your Progress I

Note: Use the space provided for your answers.

1) What is Einstein’s theory of relativity?

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2) Give small explanation on relativity of motion and length.

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3) Write on relativity of time.

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Relativity of Simultaneity

Up to now our considerations have been referred to a particular body of reference, which we have styled as a "railway embankment." We suppose a very long train travelling along the rails with the constant velocity **v** and in the direction indicated. People travelling in this train will with a vantage view the train as a rigid reference-body (co-ordinate system); they regard all events in reference to the train. Then every event which takes place along the line also takes place at a particular point of the train. Also the definition of simultaneity can be given relative to the train in exactly the same way as with respect to the embankment. As a natural consequence, however, the following question arises: are two events (*e.g.* the two strokes of lightning A and B) which are simultaneous with reference *to the railway* embankment also simultaneous relatively to the train? We shall show directly that the answer must be in the negative.

When we say that the lightning strokes A and B are simultaneous with respect to be embankment, we mean: the rays of light emitted at the places A and B, where the lightning occurs, meet each other at the mid-point M of the length A→B of the embankment. But the events A and B also correspond to positions A and B on the train. Let M^1 be the mid-point of the distance A→ B on the travelling train. Just when the flashes (as judged from the embankment) of lightning occur, this point M^1 naturally coincides with the point M but it moves towards the right in the diagram with the velocity v of the train. If an observer sitting in the position M^1 in the train did not possess this velocity, then he would remain permanently at M, and the light rays emitted by the flashes of lightning A and B would reach him simultaneously, *i.e.* they would meet just where he is situated. Now in reality (considered with reference to the railway embankment) he is hastening towards the beam of light coming from B, whilst he is riding on ahead of the beam of light coming from A. Hence the observer will see the beam of light emitted from B earlier than he will see that emitted from A. Observers who take the railway train as their reference-body must therefore come to the conclusion that the lightning flash B took place earlier than the lightning flash A. We thus arrive at the important result: "Events which are simultaneous with reference to the embankment are not simultaneous with respect to the train, and vice versa (relativity of simultaneity). Every reference-body (co-ordinate system) has its own particular time; unless we are told the reference-body to which the statement of time refers, there is no meaning in a statement of the time of an event."

Now before the advent of the theory of relativity it had always tacitly been assumed in physics that the statement of time had an absolute significance, *i.e.* that it is independent of the state of motion of the body of reference. But we have just seen that this assumption is incompatible with the most natural definition of simultaneity; if we discard this assumption, then the conflict between the laws of the propagation of light *in vacuo* and the principle of relativity disappears.

In it we concluded that the man in the carriage, who traverses the distance w per second relative to the carriage, traverses the same distance also with respect to the embankment in each second of time. But, according to the foregoing considerations, the time required by a particular occurrence with respect to the carriage must not be considered equal to the duration of the same occurrence as judged from the embankment (as reference-body). Hence it cannot be contended that the man in walking travels the distance w relative to the railway line in a time which is equal to one second as judged from the embankment. Moreover, these considerations of are based on yet a second assumption, which, in the light of a strict consideration, appears to be arbitrary, although it was always tacitly made even before the introduction of the theory of relativity.

The Limiting Velocity of Light

No body can travel faster than light. So the law of addition of velocity is such that the combined velocity does not exceed the velocity of light. If a body moves with the velocity of light, it would have contracted to nothing! This can never be reached. At the velocity of light, a clock will stop moving and so then duration will be infinite.

1. 4 MASS AND ENERGY

The fact that nobody can travel faster than light suggests that the inertia (resistance to motion) of a body increases with increasing velocity, approaching infinity as the velocity of light is reached. Now mass is nothing but inertia, a tendency opposing motion. So as velocity increases mass also increases. Mass is not absolute, but relative to the frame of reference. Mass of a body in a moving frame reference is increases and relativist correction is needed thing to move very fast. Energy of motion of a body depends on its inertial mass and the velocity. So energy can increase either with inertial mass or in velocity. But velocity cannot increase indefinitely. Its maximum value is the velocity of light. So as energy increases the inertial mass also should increase. Thus we have the famous mass-energy equation of Einstein: E=mc2 (E = Energy produced due to conversion, M= Mass that is converted, C= Velocity of light).

1.5 GENERAL THEORY OF RELATIVITY

The general theory of relativity was Einstein’s crowning achievement. It revolutionized the theory of gravitation and initiated the new field of cosmology, the study of universe. Einstein pumped out the special theory of relativity in a quick five week, in contract the general theory took Einstein almost ten years from first version to final eloquent equations. “The General Theory of Relativity” was initially presented in a paper by Albert Einstein in 1915. Its primary thrust was to add the effects of gravity to “The Special Theory of Relativity,” making special relativity a special case of general relativity. In the same way, ten years earlier, Einstein proposed the Theory of Special Relativity with the primary thrust of eliminating the concept of a fixed reference frame in favour of relative inertial frames in conjunction with the newly learned fact that the speed of light was a constant when measured in any inertial reference frame. This theory, in a similar way, makes the Newtonian Euclidian geometry of space a special case of special relativity. So rather than these new theories refuting the old theories, they actually verified that the previous theories were special cases of a more complicated theory that explains more of reality.

Many of us who have studied physics remember an equation that states that force equals mass times acceleration (f = ma) for a mass being accelerated by a constant force. We also remember how strange it was that an almost identical equation, force equals mass times the gravitational acceleration constant (f = mg) was used to determine the weight of a non-accelerating object in a gravitational field. This similarity (or relationship) between "a" and "g" forms the conceptual basis for general relativity. Consider yourself standing on a scale in an enclosed elevator at rest. Also consider yourself standing on a similar scale in an enclosed spaceship accelerating at one "g." Both the equation and our intuitive knowledge tell us that we cannot distinguish between the one situation and the other. We would be standing balanced on the scale with the scale reading our weight in both cases. Also consider the opposite situation where the elevator was in free fall and the spaceship was way out in space away from any star with the rockets off. In both cases, again, we cannot distinguish between being in the elevator or the spaceship. In both cases, the scale would read zero and we would be floating with no forces on our body.

Based on this conceptual foundation, additional general relativity concepts and effects have been developed. One concept is the effect of gravitational fields to cause the space-time continuum to be curved or warped by large masses. Another effect is that gravity, in addition to bending light, also can cause it to slow down. This slowing down of light results in a time dilation effect where time actually slows down. The slowing down effect of earth's gravity on time at its surface is very little. Compared with space, the earth's gravitational field slows down time by only one second per billion seconds. Experiments have verified the validity of general relativity. Some of these experiments include the precession of the perihelion of Mercury, the deflection of light, and the gravitational red shift of light.

Although the earth with its low gravitational field is at one end of the spectrum, black holes predicted by general relativity and observed in space have extremely high gravity and are at the other end of the spectrum. Black holes, in addition to bending light, slowing down light, and slowing down time, can stop light from escaping and make time stand still. For us, watching a space probe speeding toward the event horizon of a black hole, the space probe would appear to slow down and virtually stop. The fact that science can show that time can virtually stop helps our understanding of how a transcendent God, beyond time and space, can exist.

1.6 THE GRAVITATIONAL FIELD

"If we pick up a stone and then let it go, why does it fall to the ground?" The usual answer to this question is: "Because it is attracted by the earth." Modern physics formulates the answer rather differently for the following reason. As a result of the more careful study of electromagnetic phenomena, we have come to regard action at a distance as a process impossible without the intervention of some intermediary medium. If, for instance, a magnet attracts a piece of iron, we cannot be content to regard this as meaning that the magnet acts directly on the iron through the intermediate empty space, but we are constrained to imagine-after the manner of Faraday -that the magnet always calls into being something physically real in the space around it, that something being what we call a "magnetic field." In its turn this magnetic field operates on the piece of iron, so that the latter strives to move towards the magnet. We shall not discuss here the justification for this incidental conception, which is indeed a somewhat arbitrary one. We shall only mention that with its aid electromagnetic phenomena can be theoretically represented, much more satisfactorily than without it, and this applies particularly to the transmission of electromagnetic waves. The effects of gravitation also are regarded in an analogous manner.

The action of the earth on the stone takes place indirectly. The earth produces in its surrounding a gravitational field, which acts on the stone and produces its motion of fall. As we know from experience, the intensity of the action on a body demises according to a quite definite law, as we proceed farther away from the earth. From our point of view this means: The law governing the properties of the gravitational field in space must be a perfectly definite one, in order correctly to represent the diminution of gravitational action with the distance from operative bodies. It is something like this: The body (e.*g.* the earth) produces a field in its immediate neighborhood directly; the intensity and direction of the field at points farther removed from the body are thence determined by the law which governs the properties in space of the gravitational fields themselves.

In contrast to electric and magnetic fields, the gravitational field exhibits a most remarkable property, which is of fundamental importance for what follows. Bodies which are moving under the sole influence of a gravitational field receive an acceleration, which does not in the least depend either on the material or on the physical state of the body. For instance, a piece of lead and a piece of wood fall in exactly the same manner in a gravitational field (in vacuo), when they start off from rest or with the same initial velocity. This law, which holds most accurately, can be expressed in a different form in the light of the following consideration.

According to Newton's law of motion, we have

(Force) = (inertial mass) x (acceleration),

where the "inertial mass" is a characteristic constant of the accelerated body. If now gravitation is the cause of the acceleration, we then have (Force) = (gravitational mass) x (intensity of the gravitational field), where the "gravitational mass" is likewise a characteristic constant for the body. From these two relations follows:

(Acceleration= (gravitational**)** = (intensity of the gravitational field)

(Inertial)

If now, as we find from experience, the acceleration is to be independent of the nature and the condition of the body and always the same for a given gravitational field, then the ratio of the gravitational to the inertial mass must likewise be the same for all bodies. By a suitable choice of units we can thus make this ratio equal to unity. We then have the following law: The gravitational mass of a body is equal to its inertial law. It is true that this important law had hitherto been recorded in mechanics, but it had not been interpreted. A satisfactory interpretation can be obtained only if we recognize the following fact: The *same* quality of a body manifests itself according to circumstances as “inertia” or as “weight “(lit. “ heaviness ‘). In the following section we shall show to what extent this is actually the case, and how this question is connected with the general postulate of relativity.

A New Interpretation of Gravity

Accelerated motion can be as equivalent to a gravitational field only because inertial mass is equivalent to gravitational mass. This was known already in classical physics, but no explanation was given to it. Einstein suggested that ‘the same quality of a body manifests itself according to circumstances as ‘inertia’ or as ‘weight’. Thus because of inertia bodies in ‘empty space’ is travel with uniform velocity in straight lines. Because of gravity bodies in non-empty space (gravitational field) are travel with accelerated motion in parabolic paths. Hence inertia and gravity are two aspects of a single law, ‘Every body tends to move along a geodesic’.

The New Picture of Gravity

According to Newton, gravitation is a force of attraction between two bodies. Thus the sun attracts the earth and because of this gravitational force the earth revolves round the sun. Gravitation causes the earth and other planets to describe curved paths in a straight space. According to Einstein, massive bodies distort the space-time continuum in their neighborhood. The curvature formed because of this distortion deflects the planets and they move in curved paths. Thus the paths of the planets etc., are the shortest courses in a curved space-time continuum. Gravitation is hence reduced to a geometrical property of the space-time continuum. It is not force acting at a distance, but simply is the ‘path of inertia’ which the bodies follow. A massive body like the sun keeps the space in its neighborhood continually curved. It is as though the sun takes ‘grooves’ around it. The bodies move in these ‘grooves’. Another metaphor used is that the gravitating bodies produce ‘hills’ or other deformities in the continuum and bodies are rolled along the ‘hillside’. We quote from Barnett: “ A gravitational force as much a physical reality as an electromagnetic field, and its structure is defined by the field equations of A. Einstein”.

Gravitational Deflection of Light

Now light can be looked upon as a stream of minute particles called photons. Therefore they also should behave like any other material particles. So in a strong gravitational field a ray of light should undergo deflection. This is called gravitational deflection of light.

Check Your Progress III

Note: Use the space provided for your answers.

1) Give small description of General Theory of Relativity.

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2) What is the Gravitational Field?

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3) Give description on the new picture of gravity.

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1.7 LET US SUM UP

Relativity dealt a death blow to the so called absolutes: absolute time, absolute space, absolute frame of reference, absolute objectivity etc. In doing so it has revolutionized the traditional notions of space, time etc. According to relativity space and time are relative. Space is the relation of things and time is the relation between the events. As Jeans says when we question nature through our experiments, we find that nature knows nothing of a space or time common to all people. When we interpret these experiments in the new light of the theory of relativity we find that space means nothing apart from our perception of objects and time means noting apart from the our experience of events. Space and time fade into subjective conceptions, just as subjective as right or left hand and 'only the four dimensional continuum is objective.'

The denial of absolute space, absolute observer and absolute frame of reference has one important impact on scientific method. This shows that since no preferential frame or absolute observer exists, we can get scientific knowledge not by referring to any special space or frame of reference, but simply by performing the experiments accurately, no matter in whatever frame of reference we are. Thus extreme dexterity and accuracy will underlie any knowledge of the laws of nature. Relativity has sparked off speculations and theories on the origin of the cosmos and its nature.

1.8 KEY WORDS

$E=mc^2$: (E = Energy produced due to conversion, M= Mass that is converted, C= Velocity of light).

In four-dimensional space-time : points are called events and four quantities are required to specify an event such as latitude, longitude, altitude, and time.

Force : inertial mass x acceleration (Acceleration= (gravitational) = (intensity of the gravitational field) (Inertial)

1.9 FURTHER READINGS AND REFERENCES

Bergmann, G. Peter. *The Riddle of Gravitation.* New York: Charles Scribners's son, 1987.

Bojowald, Martin. "Big Bang or Big Bounce." *Scientific American India*. Vol.3 (October 2008), 30-33.

Bojowald, Martin. "What Happened Before Big Bang?" *Nature Physics*. Vol.3 (August 2007), 523-525.

Hawking, Stephen. *The Essential Einstein his Greatest Work.* Penguin Books, 2007.

Kennefick, Daniel. *Travelling At the Speed of Thought and Einstein and the Quest for Gravitational Waves.* Oxford: Princeton University Press, 2007.

Thomas, Jeevan Job. "Will Man Find That God Particle." *Mathrubhumi.* Vol.85 (September 2007). 55-57.

Trenkler, Gerhard. "Creation". *Encyclopedia of Biblical Theology.* 1st ed. Vol. 1. 151-153.