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Chapter 10

A PUZZLING INCONSISTENCY

By the latter part of the 19th century, physics was able to explain in detail a wide range of natural phenomena, using only a remarkably small number of principles. Some believed that physics had reached its peak, that Newtonian mechanics and Maxwell's theory of electromagnetism represented the completion of theoretical physics. It seemed that nature held no more secrets of importance!

Actually, between 1900 and the late 1920's, the very foundations of physics would change so radically that many historians describe this period as a scientific revolution comparable to the one that took place during the 16th and 17th centuries. Two fundamentally new theories emerged during this period: relativity and quantum theory, the two pillars on which contemporary physics rests.

Newton's and Maxwell's equations described two magnificent theories, each brilliantly successful in its own field. It was recognized, however, that there was a basic inconsistency between the two. It was natural to suspect first Maxwell's equations, which were only decades old, rather than Newton's equations, which had ruled unchallenged for some 200 years.

The solution came from Albert Einstein's drastic reevaluation of the concepts of space and time at the very roots of Newtonian mechanics. It is these concepts we need to review now, before we can see the nature of the inconsistency between Newton's and Maxwell's laws.

Frames of Reference

To a passenger sitting in a plane flying at 600 miles per hour, a stewardess appears to move around quite normally, just as if the plane had never taken off. To somebody on the ground, however, she appears to be rushing at high speed.

What is observed in nature is always relative to the particular "frame of reference", from which the observing is done (such as from the ground or from a plane). We might think of a reference frame as a "platform" carrying an observer equipped with some reference from which to measure distances, a clock to measure time, and whatever else might be needed to study the laws of physics.

Space and Time in Newton's Mechanics

Newtonian space is conceived as a vacuum, or empty space, within which particles move and interact, like fish swimming inside a water tank. Space is considered to be infinite and uniform. It is a passive, unchangeable stage that neither affects, nor is affected by, the presence and motion of matter.

In principle, regardless of where they are located and whether they are moving or not, any two observers can always agree on their measurements of distance. Moving or not, a yardstick represents the same length anywhere in the universe.

Similarly, time is thought to be absolute and universal. We can talk of a particular "moment in time" that is the same everywhere in the universe. Events that occur anywhere at the same "moment in time" are simultaneous and, in principle, can be so recognized by everybody. At least ideally, any two reference frames can have clocks that go at exactly the same rate. If some physical process takes, say, one hour, as determined in one reference frame, it will take precisely one hour with respect to any other frame, moving or not.

Many of the Newtonian notions just reviewed are very much part of our intuitive way of thinking about reality. That time flows equally everywhere for all observers, regardless of their state of motion, is so deeply ingrained in our minds that we cannot even imagine an alternative.

Inertial Frames of Reference

Newton's first law of motion, the law of inertia, states that, in the absence of any resistance, an object moving at some speed in some direction will continue to move at the same speed and in the same direction, without the intervention of any force. We say that the object continues to move on its own "by inertia". Only if some force starts acting on the object, will the object respond by changing its speed and/or direction.

The law of inertia raises the question: What frame of reference do we have in mind, when we talk of a state of rest, or of uniform motion? If somewhere in the universe one could find an object absolutely at rest, a "fixed center of the universe", Newton's laws would be valid with respect to a "platform" attached to that object. From it, an observer could measure absolute positions and absolute speeds anywhere.

We know, however, that our Earth is rotating about its axis and revolving around the Sun. The Sun, in turn, is revolving about the center of the Milky Way; at the same time, our galaxy is moving as a whole. With all this motion in the universe, it seems hopeless to determine whether anything at all is at rest. In practice, we can deal only with relative positions and relative motions. Absolute positions and absolute motions are unobservable.

Newton's laws are valid also on any platform that, without rotating, moves uniformly (with constant speed and direction) with respect to our hypothetical "fixed center of the universe". Any such platform, or frame of reference, is said to be "inertial". Any inertial frame can claim to be itself the "fixed center of the universe", because Newton's laws are valid with respect to it.

Note that the Earth is not an inertial frame of reference, because it rotates about its axis and revolves around the Sun. Thus, strictly speaking, Newton's laws are not valid on such a reference frame. Solutions to most engineering problems, however, can be obtained with satisfactory accuracy, if we view an Earth-bound reference frame as if it were inertial.

The Special Principle of Relativity

In the Principia, Newton stated what is now called the "special principle of relativity" or the "Galilean relativity principle":

> *"The motions of objects contained in a given space [such as a room] are the same relative to one another, whether that space is at rest, or moving uniformly in a straight line without any circular motion."*

It is called the "special" principle because it is valid only if the "room" is at rest, or moving uniformly in a straight line, without rotating.

Let us imagine, for instance, two trains on separate tracks fixed to an inertial "platform": their tracks go on for miles and miles, perfectly straight. On each train, a physicist sets up a laboratory in a car without windows, to carry out various experiments. Each train may be at rest or moving at constant speed. When the train moves, the ride is perfectly smooth.

The special principle of relativity tells us that, inside the two windowless laboratories, all experiments performed will appear exactly the same to our two physicists. For instance, upon dropping a ball, each will observe that it falls straight down. If he throws the ball straight up, shortly after, the ball will start falling straight down toward his feet.

Whether moving or not, everything looks perfectly normal to each physicist. Since he cannot look out, *he has no way of telling whether he is moving or not*, because the same laws of mechanics hold in both trains, whether at rest or in uniform motion.

A stowaway inside a ship with a very quiet engine, on a very smooth ocean, would not be able to tell whether the ship is moving or not. Looking up, he might see clouds going by, but could still wonder whether the ship or the clouds were moving.

It is only uniform velocity that cannot be detected without looking out. Even inside an enclosed space, without looking out, we can detect an acceleration, i.e., whether we are changing speed and/or direction, because we feel pulled or pushed in some direction. If the change is sudden enough, we might even be thrown against a wall.

Views from Two Platforms

Let us compare now observations made by two people on separate inertial platforms. In Newtonian mechanics, measurements of time, distance, speed and acceleration made on two inertial frames are related in a way that appears to us intuitively obvious.

Suppose you are standing by a long straight train track on some inertial platform. There are no trees, buildings or other landmarks that can be used as reference points. You see me standing on a very long flat car (my inertial platform) moving East along the track at 20 miles per hour with respect to you. From my viewpoint, however, I am standing still; you and the track are moving West at 20 m/h.

At some point along the track, you have planted a pole from which you measure distances along the track. I am measuring distances from a pole at the rear of my train.

We both have equally reliable clocks and are always in agreement as to the *time* t elapsed since our reference poles passed by one another. We are both observing some jogger on my flatcar jogging toward the front.

Our measurements of *distances* to the jogger will differ by a changing amount, namely, the changing distance between our two reference poles (which is equal to the constant speed of the train multiplied by the time t).

Our measurements of the jogger's *speed* differ by a constant amount, the speed of the train, 20 m/h. What is 5 miles per hour to me is 25 (20+5) m/h to you. (If the jogger were moving in the opposite direction, it would be 20-5=15 m/h.) This "obvious" way of *combining speeds by addition (or subtraction)* is a key point to keep in mind.

When it comes to *acceleration*, however, we are always in agreement. Whether the jogger, in one second, accelerates from 5 to 6 m/h, or from 25 to 26 m/h, it is the same acceleration, 1 m/h in one second.

Whether on your inertial platform or mine, Newton would have written his mathematical laws in exactly the same form. His laws were invariant to (not affected by) uniform motion. Maxwell's laws of electromagnetism, instead, were not invariant from one inertial platform to another in the way Newton's laws of mechanics were. This is the inconsistency that puzzled physicists in the latter part of the 19th century.