Inertial Reference Frames

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As you may know, to Aristotle the Earth was the center of the universe. Heavy objects naturally fell towards the Earth and light objects naturally rose away from it. In the General Theory of Relativity this view of motion is resurrected.

Galileo, Newton and others developed a different view. Crucial to this viewpoint is that there is an absolute space.

> "Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies .. because the parts of space cannot be seen, or distinguished from one another by our senses, there in their stead we use sensible [i.e. perceptible by the sense] measures of them ... but in philosophical disquisitions, we ought to abstract from our senses, and consider things themselves, distinct from what are only sensible measures of them." -- Newton, **Principia I**, Motte trans.

Newton's First Law stated that:

> "Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it." -- *Ibid*

This is often called the *Principle of Inertia*.

Is this "Law" always true? Of course not. Imagine you a sitting in a car at a red stoplight. A pair of dice is hanging from the rear-view mirror; it is optional for the dice to be fuzzy. As you sit there, the dice are at rest relative to you. The only forces acting on the dice are the force of gravity pulling them down and the string pulling them up. These two forces are equal in magnitude, so the total force on the dice is exactly zero. We imagine that the car is facing to the right.

The light turns green and the driver steps on the gas. The dice swing towards the back of the car. So Newton's First Law is not true: at one moment the dice are stationary and at the next moment they begin to swing towards the back of the car although no net forces are acting on them.

Now imagine that you are standing on the sidewalk watching the car. As it sits at the red light the dice are stationary relative to you. When the light turns green and the car begins to accelerate to the right, the dice remain stationary relative to you until the force exerted on them by the string forces them to follow the motion of the car. So Newton's First Law is true when you stand on the sidewalk, but is not true when you are sitting in the car.

Thus we see that to use Newton's analysis of motion, we must restrict ourselves to only certain viewpoints, certain *frames of reference*. Frames of reference where Newton's analysis works are called *inertial frames*. They are frames where the Principle of Inertia is true.

For Newton, there was a "master" inertial frame: a frame stationary relative to absolute space. And any reference frame that is moving at a uniform velocity in a straight line relative to this master inertial frame will also be an inertial frame in the Newtonian analysis. Any reference frame which is accelerating with respect to absolute space, such as the car's frame when the light turns green and the driver steps on the gas, will not be inertial.

Now imagine that you are riding in the car at, say, 100 km/hr down a straight highway. The dice are hanging motionless from the rear view mirror. The principle of inertia is true for you. A second observer is standing beside the highway, watching the car go by. For her the dice are moving in uniform motion in a straight line. So the second observer is also in an inertial frame.

In this case, a good question is: who is moving? And the answer is that you are moving relative to the observer beside the highway, but the observer beside the highway is moving relative to you. So you are both moving relative to each other.

Both your inertial frame and her inertial frame are equally "valid." This realisation is often called *Galilean relativity*. A classic illustration is a cannonball dropped from the mast of a moving ship. From the point of view of an observer on shore, the ball falls with a uniform acceleration downwards while moving with constant speed in the horizontal direction. For a sailor on the ship, however, the cannonball appears to fall straight down. For both observers the cannonball lands at the base of the mast. A small Flash animation of this circumstance is available here.

If you are riding in the car at 100 km/hr and the driver puts on the brakes, the dice will swing towards the front of the car. Thus during the deceleration you are not in an inertial frame. The observer beside the road will see the dice continue to move at constant speed in a straight line until the string forces them to slow down with the car.

Similarly, if the car keeps moving at 100 km/hr but goes around a right hand turn, the dice will swing to the left. So during the turn you are again not in an inertial frame. Again for an observer beside the road the Principle of Inertia remains true for the dice.

When it was proved by Young in the early nineteenth century that light was a wave, the question arose as to exactly what was waving? For other waves there is a *medium* that is waving. For sound waves the medium is the air; for water waves the medium is the water. It was postulated that there was a medium for light waves, which was called the *luminiferous ether*. This substance was believed to be massless and homogeneous everywhere in the universe. It seems natural to associate this luminiferous ether with the absolute space that Newton had proposed much earlier.

The Newtonian analysis then, and all the Physics that followed from it, works in a frame fixed in absolute space, or equivalently fixed relative to the ether, and also in any frame moving in uniform motion in a straight line relative to this absolute space. The upshot is: **We can only do Physics in these inertial reference frames**.

In 1905 Einstein's *Special Theory of Relativity* dropped a bomb on the Newtonian view. He made the concept of the ether, and the related idea of absolute space, "superfluous."

We know that there *are* frames in which the Principle of Inertia is true, and that we can only do Physics in such a frame. But without an absolute "master" inertial frame we are reduced to a circular argument:

- We can only do Physics in inertial reference frames.
- Inertial reference frames are frames in which the Principle of Inertia is true.

But the Principle of Inertia is itself one of the law of Physics. So essentially we are saying that the laws of Physics are true in frames where the laws of Physics are true. It is perhaps amazing that Physics, based on this tautology, works at all. But it does work very well.

You may wish to muse about the fact that post-1905 we can say that not only is uniform motion relative, but so is acceleration. If two observers are accelerating with respect to each other we can not say which one is "really" accelerating because there is no absolute frame to which we can compare the two observers' motions. However, we do know that if one of these observers is in an inertial frame of reference, then the other is not.

Considerations of relative acceleration is one topic of Einstein's *General Theory of Relativity* of 1916.

Why did the chicken cross the road?

Aristotle:
    It is the nature of chickens to cross the road.
Newton:
    Because no force caused the chicken's state of uniform road crossing to change.
Einstein:
    Is the chicken crossing the road or is the road moving under the chicken?

Author

This document was written by David M. Harrison, Dept. of Physics, Univ. of Toronto, harrison@physics.utoronto.ca in January 2002.

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