Physics 419: Lecture 9: Searches for the Aether and the Relativity Principle
Feb. 23, 2021

1 Themes

- Searches for the Aether
- Relativity precursor
- Einstein's Two Postulates
- Length Contraction and Time Dilation
- Simultaneity

2 Searches for the Aether

The problem raised by Maxwell's equations is that the velocity of electromagnetic waves does not seem to change. It is fixed. This violates Galillean invariance. Initially it was thought that there was something wrong with Maxwell's equations. This turned out not to be true. The next suggestion is that Maxwell's equations are valid in some preferred reference frame–some absolute reference frame. This absolute reference frame was called the aether. Here are the three tests of this hypothesis.

Aberration Effect

Consider standing at a bus stop in the rain. If the rain is coming straight down, one simply holds the umbrella directly over head to stay dry. What if one were running to catch a bus? To stay dry, one would tilt the umbrella slightly ahead in the direction of motion. This is the aberration effect. The same thing is true for a telescope if one is to catch the light of some distant object as the Earth moves through its orbit.

If the telescope (mounted on the Earth) moves through the aether, you have to tilt the scope a little so that the rear end is in the right place when the light gets to it. As the Earth goes around the sun, the apparent direction of a star changes by 0.3 minutes of arc. This is only a factor of 10 smaller than Tycho could see by eye, and is easily measured with a telescope.

Conclusion: The Earth changes its motion through the aether periodically, just as it's supposed to if it orbits a Sun which is not accelerating.

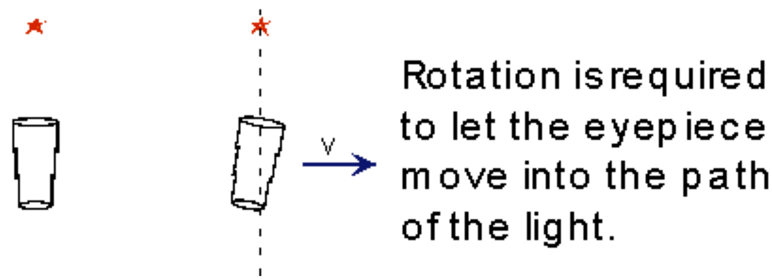

Figure 1: Abberation effect

(Proof of Copernicus' theory?) (Proof of aether idea?)

But since we don't independently know which is the "true" position of the stars, we don't know at what time our telescope is pointed straight at the stars and when it's tilted. We've measured that the Earth's velocity changes; that is, the Earth has an acceleration, but we have not yet accessed its velocity relative to the aether.

Fizeau's experiment: Aether Drag

Fizeau measured the velocity of light in water under three circumstances: 1) static water, 2) water moving in the direction of the light, and 3) water flowing against the light. He observed that the speed of light was faster when the water moved in the direction of the light than when it flowed counter to the light. Conclusion: the water drags the aether along for the ride. This helped confirm the aether hypothesis.

But we still haven't managed to measure the Earth's speed- here we just measured the change in velocity of the speed of light depending on the direction the water is flowing.

Something is frustrating us here: we have all sorts of experiments that fit a theory that says that Maxwell's equations only work in a special frame- but somehow we can't quite measure our motion with respect to that frame.

The time was ripe for a more serious experiment to measure the absolute motion of the Earth.

We need light just propagating in a vacuum, not any of these messy complications due to interactions with moving matter. And we need a round-trip, so that we can compare timing of two signals at the same place.

Michelson-Morley Experiment

Michelson and Morley oriented the apparatus so that the initial line of propagation of the light was nearly along the Earth's motion in its orbit at a certain time in the day. The orbital speed is 30 km/s. The aether speed should be at least this amount. If light propagated on the aether, then the velocity of light in the direction of motion of the apparatus should be different from that in the direction perpendicular to it. This is a very sensitive method, because the wavelength of light is 5×10^{-7} meters. The experiment was supposed to be sensitive enough to detect the rotation of the Earth (460 m/s) as well as the orbital motion. No effect was noticed. That is, the speed of light was the same in the direction of motion of the apparatus as well as perpendicular to the apparatus. This would imply that the aether speed is zero. Or??.

Possible explanations:

Complete aether drag: local matter is always at rest with respect to local aether (incompatible with aberration). Speed of light is determined by the source. Ruled out by using the Sun as the interferometer's light source. The apparatus shrinks in one direction as it moves through the aether. Similarly time slows down in the direction of propagation.

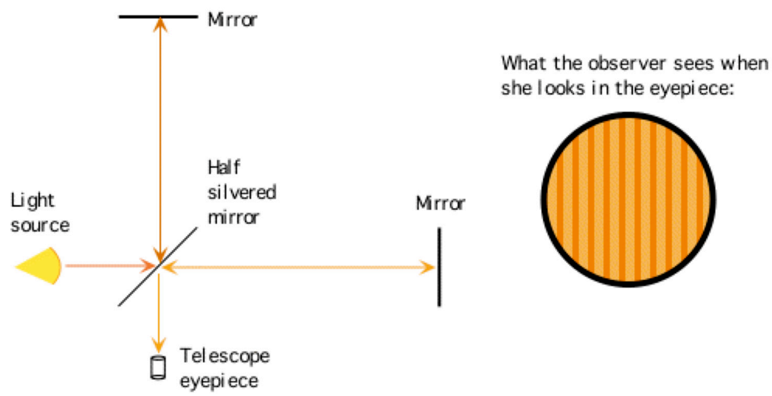

Figure 2: Michelson-Morley experiment set-up. The light makes a round trip excursion.

3 Percursors to Special Relativity

A possible interpretation of the Michelson-Morley experiment is that the apparatus shrunk in the direction of the motion. What if the length change was really tiny:

$$L \to L\sqrt{1-(v/c)^2} \tag{1}$$

and clocks on the apparatus experienced a time dilation

$$t \to \frac{t}{\sqrt{1-(v/c)^2}}. \tag{2}$$

Then any constancy of the speed of light would only be apparent not acutal. But what is the source of these transformations?

It turns out that Lorentz and Fitzgerald also noticed that under a set of transformations, not too distinct from the ones above, Maxwell's equations remained invariant. Could this possibly be the new invariance principle? All of this seems fine but there was no over-arching physical principle that would compel such a change in thinking.

In 1904, Poincaré suggested that it might be impossible to measure one's speed through the aether. He proposed that "A complete conspiracy is itself a law of nature." He asked, "What must be true if one's speed through the aether is to be unobservable?" He was able to show that the mass of an object (the "m" in momentum = mv) would increase as an object's speed increased. Also, the speed of light would be the maximum possible speed.

These conclusions may sound familiar to those of you familiar with Special Relativity.

However, there was still an underlying assumption (left over from the first impression made by Maxwell's equations, and perhaps from our Aristotelian instincts) that one reference frame was "right", however hidden it might be.

So will the special aether frame ultimately reveal itself or not?

"The principle of physical relativity is an experimental fact ... and as such it is susceptible to constant revision." "The principle of relativity thus does not appear to have the rigorous validity which one was tempted to attribute to it." Poincaré,quoted by Holton, p. 205.

The situation was unsatisfying from a philosophical point of view to Lorentz and Poincaré and others:

"...surely this course of inventing special hypotheses for each new experimental result is somewhat artificial. It would be more satisfactory if it were possible to show by means of certain fundamental assumptions ..." H.A. Lorentz, quoted by Holton, Thematic Origins of Scientific Thought, p.229.

Maybe the principle of relativity should be taken as a postulate, not just a contingent fact. (At least tentatively.)

Will that give us anything beyond the description of the phenomena in terms of Lorentz contraction, time dilation, etc.?

4 Einstein's Approach

Einstein declared that "The phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. The same laws ... will be valid for all frames of reference."

Postulate 1

If, relative to K, K' is a uniformly moving coordinate system devoid of rotation, then natural phenomena run their course with respect to K' according to the same general laws as with respect to K. This statement is called the principle of relativity (in the restricted sense).

Postulate 2

"experience in this domain leads conclusively to a theory of electromagnetic phenomena, of which the law of constancy of the velocity of light in vacuo is a necessary consequence."

The insistence that these two "apparently incompatible" principles are consistent is the new idea.

Let's see if we can make sense of these two statements. Einstein took the results of the Michelson- Morley experiment to be a fact of the world. It is a law that the speed of light is independent of the uniform motion of an observer. But if this is true, how can different observers see the same laws of nature are holding in their respective reference frames. Let's make this clearer. We know from Galileo that if two objects are in motion relative to one another, then the velocity that they see is related to the difference or the sum of their velocities depending on whether the two objects are moving towards one another or away from one another. Let's assume we are travelling with a velocity v towards a light source. On the Galilean account, we would expect to measure that the light beam is moving at a velocity of c-v. But Einstein tells us that this is not the case. We instead see that the light speed is c not c-v. That is, our velocity does not matter. So we expected a smaller number than what Einstein tells us is the case. How do we reconcile this? Speed is length/time. A simple way to reconcile this is to say that the time increment that we are experiencing is actually shorter as a result of our motion. That is, time is slowing down for us as we move. Let's make this more concrete. Let's assume that we are moving with velocity v. Once we get to point A, a light bulb is turned on. We then measure the time for the light to move to another point B immediately ahead of us. Let us say that on the ground the distance between A and B is L. Then the speed of light is simply c=L/t, where t is the time for the light to travel from A to B in the stationary reference frame. Now what about our moving frame. In our moving frame, we see the light reach B at some time t' which is shorter than t. However, the speed of light that we measure must be the same. Hence, the length that we measure to be the distance between A and B must be different from L. Let us call this length L'. In the moving frame, we have that $c = L'/t' = L/t$. If we solve this equation for L', we find that $L' = L(t'/t)$. Because $(t'/t) < 1$, we measure that L' is less than L. That is, in the moving frame, lengths are contracted. Hence, the constancy of the speed of light tells us two profound things: lengths contract and time is dilated upon uniform translation. These results follow from the simple law of the constancy of the speed of light.

5 Simultaneity

As a result of Einstein even the concept "at the same time" is relativized. Here's how. Suppose a train is moving past Fred, who is standing on the embankment. Barney is riding in the middle of the train. Two lightning strokes hit the ends of the train at times such that Barney sees the two flashes at the same time. At that instant, he is passing by Fred (i.e., they are at the same place when they see the flashes).

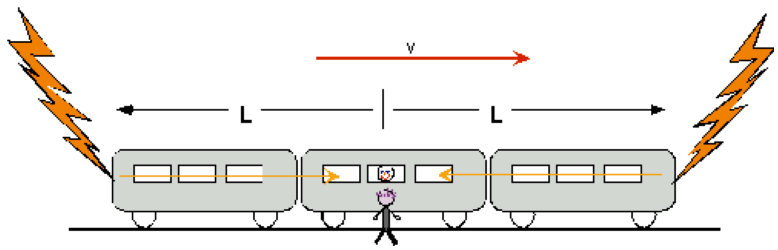

Figure 3: Simultaneity of two light signals in two frames moving at uniform speeds relative to one another.

The question is, "Were the two lightning strokes simultaneous?" According the Galileo, the frame does not matter because someone on the station says the events were also simultaneous because the speed of light at the front of the train is $c + v$ whereas the speed of light at the rear of the train is $c - v$. The difference in the distance the light travels at the front and rear of the trains makes is such that the times work out so that the events are simultaneous. But according to Einstein, Galileo is all wrong as we cannot change the speed of light. Hence, Barney and Fred must tell different stories.

Barney says:

The lightning hit the two ends of the train, which are the same distance from me. Since I saw the two flashes at the same time, the two strokes must have occurred at the same time, namely L/c before I saw the flashes.

Fred says:

When the lightning struck (some time in the past) the front of the train was closer to me than it is now, and the rear was farther. Thus the two flashes traveled different distances. Since I am seeing them at the same time, they must not have been simultaneous. The one at the rear happened first.

There is no way to tell who is right, so:

Simultaneity of distant events depends on the motion of the observer

As with time dilation, this effect results from the invariance of the speed of light. In this case, it depends on the fact that Fred sees both flashes moving at c, even though they are moving w.r.t. each other.

This raises a subtle point. It is impossible to prove that the light moves the same speed in both directions. That is an assumption, based on the apparent isotropy of space, and the simplicity of Maxwell's equations. It is not important in this situation, because if we assume that the speed of light is different just exactly to cancel the effect, it will double the effect when the train moves to the left.

Note: We could consider a different pair of strokes, which Fred says are simultaneous. (They wouldn't be at the ends of the moving train.) Barney will say that they aren't simultaneous.