The Michelson-Morley Experiment and The Foundations of Einstein's First Postulate

In class, we have (will) explicitly show one context under which Galilean relativity does not work within the context of Electromagnetism, due to forces in one inertial frame being measured to be different than forces in another reference frame. This short note outlines some similar related issues of both historical and practical importance that help lay the foundation for one of Einstein's postulates of Special Relativity.

The Michelson-Morley Experiment

In 1887, Albert Michelson and Edward Morley conducted an important experiment that attempted to find the relative speed of Earth to the so-called "aether". To understand the foundations, we have to briefly go back to basic wave theory from PHYS 111.

As we know, light often propagates like a wave. In general, the speed of a wave traveling in a medium relies on the properties of the medium. You may or may not remember this, but the speed of a wave traveling along a string can be written:

$$v_{\text{wave}} = \sqrt{\frac{T}{\lambda}}$$

where T is the tension that the string is under and λ is the linear mass density (mass per unit length) of the string. This sort of relationship is common. For example, the speed of sound in a material (the speed that a compression wave travels) is found via the equation:

$$v_{\text{compression}} = \sqrt{\frac{\kappa}{\rho}}$$

where κ is the bulk modulus (related to the stiffness) of the medium and ρ is the mass density (mass per unit volume) of the material. The key to realize here is that, in general, the speed of a wave in a medium is related to the square root of the ratio of the stiffness of that medium to the density of that medium.

Now, let's extend the idea of a wave traveling through space. What is the stiffness of space? What is the density of (mostly) empty space? What other properties (if any) does that medium have? The medium that light propagates in (which we now know is pretty much just a vacuum) was once called the "ether", "aether", "luminiferous aether", or "quintessence".

If light is really propagating within the aether, then the speed of light should be (i) related to the properties of this aether, and (ii) should be *relative to the aether*. This second point is somewhat subtle. If we measure the speed of a wave on a string, we can use the formula presented earlier to come up with a value. However, that value is only going to be valid in one reference frame – where the string is at rest. [Technically, if the string is oscillating, parts of the string are moving. To make our alignment clearer, imagine a horizontal string that is "plucked" and vibrates up and down. When I say the string is fixed, I mean that we are putting ourselves in a reference frame that is not moving left nor right with respect to the string]. If we were to send a wave pulse to the right, and walked to the right at the same speed that the wave moves, we would view the speed of the wave in *our* frame as $v_{\text{wave}} - v_{\text{wave}} = 0$, due to the same sorts of Galilean relativity relationships we have developed in class.

Similarly, the Earth moves through space. We are in an approximately circular orbit around the sun. If the aether is at rest in some inertial frame, then there are parts of the Earth's orbit that are moving with respect to the aether at a different speed than some other parts of the Earth's orbit. (You can play with this idea by checking out http://tinyurl.com/MicMor). Thus, if the Earth's speed with respect to the aether at any time is v and the speed of light with respect to the aether is c, then the speed of light as measured on Earth should be somewhere between $|c - v|$ and $|c + v|$ (depending on the alignment of the Earth-aether relative motion). By measuring the speed of light on Earth at different times, the hope was to determine the velocity of the aether with respect to, say, the sun.

An experiment to measure the speed of light carefully at different times of the year was carried out by Michelson and Morley in 1887. For more information, see either your textbook or https://en.wikipedia.org/wiki/Michelson-Morley_experiment. The key thing to note – and the thing you should definitely take away from this discussion – is that *the speed of light was observed to be exactly the same no matter what time of year the speed was measured or what direction we measured the speed of light in!* This was *not* expected. It means that the entire discussion above – which, though perhaps new to you, was perfectly sensible to Physicists of the day – doesn't hold for some reason. The conclusion we draw (eventually, after testing many more things) is that *there is no such thing as the aether!*. The whole idea of light waves propagating through a medium like waves on a string isn't exactly right. There is something a bit different about light waves than there are about mechanical waves like those you studied in PHYS 111.

The Takeaway

Careful manipulation of Maxwell's equations (using some Math from Calc III and Differential equations) shows that a disturbance/wave made up of light moving through a vacuum should always move at speed $c = \frac{1}{\sqrt{\epsilon_\circ \mu_\circ}}$. The mathematical development is ambiguous as to which frame this should be measured with respect to, so the thought in the late 19th century was that this speed was relative to the rest frame of the medium that the light propagates through, similar to the propagation of mechanical waves through a medium. However, careful measurements showed that the speed of light in a vacuum ALWAYS seemed to take on this same value, no matter which way Earth is currently moving.

More careful study of the equations of electromagnetism reveals that light does not seem to obey traditional Galilean relativity; if light is created at some point in space and you move at some constant speed v away from the source location, you might expect the speed of the light moving in the same direction as you are to appear to move at speed $c - v$, but – in fact – you still view it as moving at speed c. This can be shown both analytically (through manipulation of Maxwell's equations) and experimentally (by actually conducting careful experiments). No matter what reference frame you are in – and no matter what frame the light was produced in – all observers always measure light in a vacuum moving at a speed of $c = \frac{1}{\sqrt{\epsilon_\circ \mu_\circ}}$. This is admittedly weird – and very important.