

The Experimental Trail

If the facts don't fit the theory, change the facts.

Attributed to Albert Einstein

It is not immediately clear from the perspectives presented in the previous chapters why Lorentz and Einstein were led into their theories of length contraction and time dilation, especially since other interpretations seem much more plausible in hindsight. A chronological survey of the experiments and theories of Fresnel, Fizeau, Hoek, Airy, Michelson, Lorentz, Einstein and Sagnac, performed and derived over a hundred year period, beginning in 1818 will provide the necessary insight. These experiments were designed to test for the motion of the Earth through the presumed aether, or to test for the extent to which the aether was constrained and carried in a moving, material medium. The results of these experiments resulted in ever increasing complications or corrections to aether theory, from the Fresnel coefficient of aether drag to the Lorentz transformations; each designed to explain the nature of the aether as evidenced by the data obtained. Building on these results and much original thought, Einstein developed the special theory of relativity, keeping many of the historical results and corrections in form, but abandoning the aether concept. With this hindsight perspective, the errors in base assumptions and result interpretations will become apparent. It will also be clear as to how these errors compounded with each additional test. At the same time, equivalent results will be presented assuming aetherless, Galilean space, demonstrating that all experiments are compatible with these assumptions, without the need to invoke length contraction, time dilation or Fresnel's aether drag theory, our starting point.

Fresnel's Coefficient of Aether Drag

Augustin Fresnel was a French physicist who derived many formulas useful in understanding the properties of light. For example, he developed equations describing reflection and refraction of light by a surface and a theory of polarization by a crystal. He also demonstrated that the double refraction of light could only be described by considering light to be a transverse wave. One of his theoretical predictions shows the importance of backing up thought experiments or theory with actual physical measurements and observations. Having submitted a paper on optics for peer review, the reviewer, Simeon-Denis Poisson, rejected Fresnel's theory claiming that if one shined a light at a circular disk, there would be a bright spot at the center of its shadow. Poisson had simply assumed that such would not be the case. Without actually performing a physical experiment, Poisson performed an imaginary thought experiment. In his mind he imagined light shining on a circular disk, and the resultant shadow on a screen behind the disk. In his thought experiment, the shadow behind the disk would be a black circle. There was no reason in his thought experiment for a bright spot to appear at the center of the shadow, as if a hole had been drilled through the center of the disk to let the light through. However, when a trivial experiment confirmed that such an illuminated spot actually appeared, Fresnel's theory was given credence. Physical science was also reminded of the preference for actual physical data over pure mental conjecture.

Fresnel was a firm believer in the concept of aether, as it was "establishment" physics of the day. He proposed in 1818 that the density of aether in a material body was different than that in the free aether or free space. From an application of elastic waves to optics, Cauchy had demonstrated that the ratio of the elastic constant, p , of a substance to ρ , the measure of its density, or mass per unit volume, is equal to c^2 .

Building on this, Fresnel imagined a bar of some fixed cross sectional area moving through the aether with a constant velocity, as in figure 4-1. As with the objection of Poisson to Fresnel's paper, this was purely a thought experiment. In his thought experiment, the bar sweeps up aether, where it acquires a new density, ρ_1 yet is only partially carried along by the bar. Thus the velocity of the bar with respect to the constrained aether is less than the velocity of the bar with respect to the outside aether. This is not unlike special relativity's velocity addition formula, where the combined velocity of two objects, say that of a man walking on a moving sidewalk, is less than the sum of their individual velocities.

While the velocity and density of the constrained aether changes as it enters the bar, its mass must remain constant. Thus, if the bar moves for a fixed amount of time, we can state that the mass of the aether swept up by the moving bar equals the mass of the aether prior to its entering the bar. As such, the product of aether density, bar velocity with respect to the aether, time and cross sectional area of the bar is the same inside and outside the bar. The only parameters that change inside and outside the bar are the aether density and the velocity with respect to the

outside aether. Thus Fresnel derived a formula for the velocity of the bar with respect to the constrained aether by taking a ratio of the aether densities outside and inside the bar. The velocity of the bar with respect to the constrained aether was then given as the ratio of ρ to ρ_1 times the velocity of the bar with respect to the outside aether.

The definition of index of refraction, η , is the ratio of the velocity of light in free space (or free aether in this case) to its velocity in some other medium. Using this definition and Cauchy's relation, we can determine the velocity of the bar with respect to the constrained aether (which is also the velocity of the aether with respect to the bar). It is simply the velocity of the bar with respect to the free aether times one over η squared. The velocity of light in the moving bar is then the velocity of light through the aether in the bar minus the velocity of the constrained aether through the bar. Finally, the velocity of light as measured by an observer stationary in the lab frame of the moving bar is given by this velocity plus the velocity of the bar through the lab frame. While this multi-step analysis may sound complicated, it is really quite straightforward mathematically. The formula states that the velocity of light in a moving medium as measured from a stationary lab frame is simply the velocity of light in that medium when at rest plus the velocity of the medium times a factor equal to one minus one over η squared. This velocity is denoted by c'' in the figure.

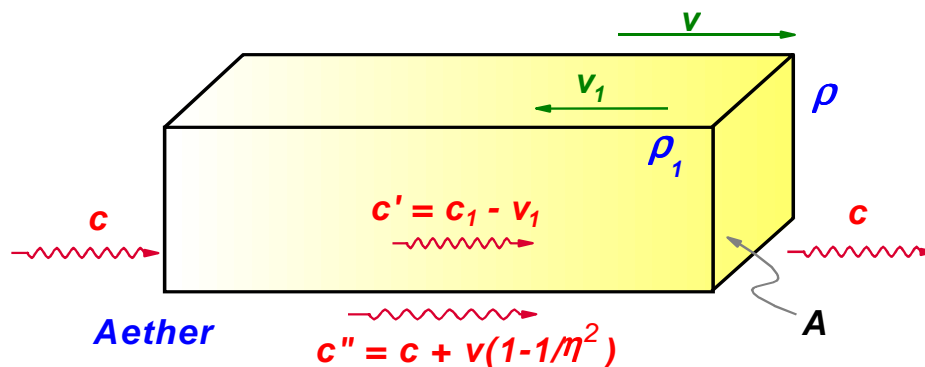


Figure 4-1 Fresnel's Thought Experiment to Determine the Coefficient of Aether Drag

This factor, one minus one over η squared, is the well-known convection coefficient, or "aether drag" coefficient as derived by Fresnel. We can visualize the nature of this factor with an example. Suppose we walk about at an average speed of four miles per hour as measured in a laboratory setting. We now step on a moving sidewalk that carries us forward at two miles per hour. In the lab frame, a Galilean transformation of velocity would calculate that we are walking with a velocity of six miles per hour as measured in the lab frame. What Fresnel proposed, with no experimental evidence to so indicate, was that we would slow down after stepping on the moving sidewalk, so that our lab frame velocity would be less than six miles per hour. It turns out, however, that Fresnel was correct in that the velocity of light through a moving medium appears to be less than the velocity of light through that same medium at rest, and by the same amount as proposed by his convection coefficient.

Most books on relativity praise Fresnel for his insight and ability in obtaining this important formula, even though they contend he got there by using bad assumptions. Fresnel was trying to make sense of the concept of an all pervading aether, and the manner in which it could share space with material objects. The bad assumption is the assumption of an aether, a concept not endorsed by most modern theorists. Fresnel's theory is considered to be what Petr Beckmann refers to as a mere "equivalence," a theory that produces the correct answer mathematically, but is based on the wrong underlying assumptions.

Special relativity derives this same result as Fresnel, based on the relativistic addition of velocities as obtained by invoking length contraction and time dilation. The Fresnel equation has been "verified" experimentally, though, in all cases, the desired result was known in advance. These verifications also support the Galilean view, well within the limits of experimental error, leading to the firm possibility that both Fresnel's theory and Einstein's theory are mere equivalences. It is important to realize that experimental verification of a mathematical prediction of a theory is not the same as verification of the underlying principles and assumptions contained within that theory. In fact, both Fresnel's and Einstein's theory basically attribute the observed effect to an incomplete summation of velocities of two items. In Fresnel's theory, at least, there is a plausible physical basis for assuming that aether

traveling through a dense medium might move slower than aether traveling through free-space, much the same as a coin tossed in a fountain slows down once it leaves the air and enters the denser water. In Einstein's theory, the truncated sum of velocities occurs only due to motion with respect to the third party observer, and not due to any identifiable physical causes. In any event, we will continue to shed light on the path that nonetheless led ultimately to special relativity.

The Experiment of Fizeau

Armand Fizeau was a French physicist among whose many accomplishments include the measurement of the velocity of light using a toothed disk now known as the Fizeau wheel. In 1851, he carried out an experiment that tested for Fresnel's aether convection coefficient. This was the first such test of Fresnel's formula, derived without experimental evidence, over twenty years earlier. Fresnel, in fact, had died more than twenty years before this experiment took place, a point of interest only because many texts derive Fresnel's formula based on the results of experiment, rather than the other way around. In fact, most texts derive the formula on the basis of Einstein's special relativity, without even addressing the manner and concepts used by Fresnel in its initial derivation.

Experimental results, within the level of error available in the mid-1800's, were not sufficient to derive or verify Fresnel's formula. These results could only confirm that, within error limits, the formula provides answers consistent with experiment. In fact, Fizeau's experimental results were so coarse that the only conclusion he could draw was that the results obtained were less than should have been produced if light were completely convected by the moving medium. It was as if, in the moving sidewalk example, the only result he obtained was that his subject was traveling less than six miles per hour, but he couldn't determine how much less. From this crude result, Fizeau assumed the validity of Fresnel's formula on the partial convection of the aether.

Fizeau's experiment involved passing light two ways through moving water and observing the interference pattern obtained, as illustrated in figure 4-2. The interference pattern arises due to the wave nature of light. When light is split so as to follow two paths to a screen, differing path lengths will result in different patterns emerging on the screen. This effect was first observed by Thomas Young in 1820. The nature of the two-path interference pattern is the main topic of chapter eleven, and will not be dwelt on here.

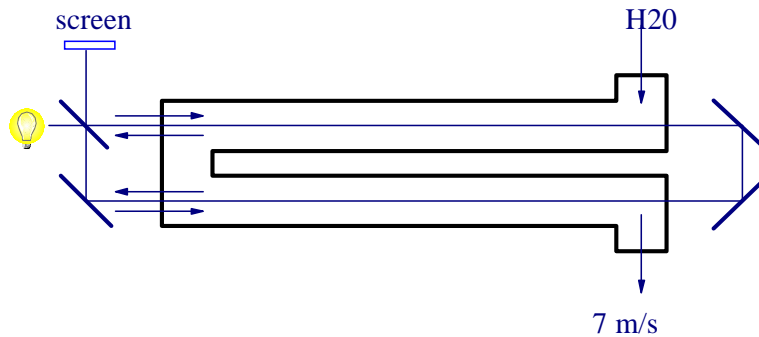


Figure 4-2. The experiment of Fizeau.

Fizeau's experiment was repeated by Albert Michelson and Edwin Morley in 1886 with much more rigor, and quantitative results were obtained. Working backwards from the observed fringe shift, Michelson was able to calculate an apparent convection coefficient equivalent to Fresnel's formula. Varying the velocity and direction of the flow allowed for a variety of test points, sixty-seven in all. By observing the change in interference pattern, the effective velocity of light through the moving medium, as measured in the lab frame, was calculated. Within experimental limits, the results obtained by measuring the fringe shift agreed with the results predicted by Fresnel's formula. Michelson felt that he had confirmed the theory of partial aether convection. One must bear in mind that Michelson's experiment took place nine years before Einstein introduced the special theory of relativity, and Fizeau's attempt took place fifty-four years before that theory. So no one was yet looking to confirm or refute the predictions of special relativity.

We now examine the Fizeau experiment in a purely Galilean environment, taking into account the Doppler shift (change in wavelength) experienced by each beam of light and described in the previous chapter. Michelson's paper

gives an excellent analysis whereby the retarded light velocity seen in the water may be considered as due to the number of collisions with atoms, the "velocity of light through the atoms," and the width of the atoms. Since there will likely be objections to that analysis based on current understandings of the microscopic world, we present a more general approach. In what follows, the retarded velocity is again considered as due to the "collisions" (absorptions and re-emissions) of the photons in the medium, as it must be, but we do not require any assumptions as to "atom width," or "velocity through the atom" as introduced by Michelson.

Consider a tube of some fixed length filled with standing water. The velocity of light through the water is less than c due to the index of refraction of the water. In fact, the index of refraction of water is 1.33, and the velocity of light through standing water is c divided by 1.33 or about three-fourths of c . We will call this velocity b . Next we allow the water to run through the tube with a small velocity. The velocity of light through the water is still b , but if the light is moving in the same direction as the flow of water, its total velocity through the tube is $b + v$. Likewise, if the light is moving against the flow of water its velocity is $b - v$. We can compare the time required to traverse the tube in each direction, and determine the shift in fringe pattern due to this time delay alone. The time for each path is equal to the length of the path divided by the combined velocity of the water and the light through the water. Returning to the moving sidewalk example, the time to traverse the sidewalk is equal to the length of the sidewalk divided by the sum of the sidewalk's speed plus the speed of the person walking on the sidewalk. In terms of the fringe pattern seen on the screen, the pattern will shift by an amount equal to the difference in time required of each path times c divided by the wavelength of the light. But this is only the first part of the solution.

Next we must consider the Doppler effects. Recall from the previous chapter that as light strikes a moving observer, the frequency, or wavelength, is shifted. Since the water is moving with respect to the source, the two paths of light will experience Doppler shifts upon entering the water--one a red shift, the other a blue shift. While traversing the length of the tube, each light path is at a different wavelength. Two waves of unequal wavelength entering a tube in phase will arrive at the end of the tube out of phase. For example, if the tube length is an exact multiple of wavelengths for one beam, then the other beam will be able to fit in slightly more or slightly less wavelengths, depending on whether each wavelength for that beam is shorter or longer than the first beam, respectively. By in phase or out of phase, we are simply counting the number of wavelengths each beam fits in the tube. If that number is, say, two for one beam, and two for the second beam, the waves will be in phase. If that number is two for one beam, and two and one-half for the other beam, the waves will be out of phase by one-half wavelength. The shift in fringe pattern due to this effect is given by the difference in phase at the end of the tube.

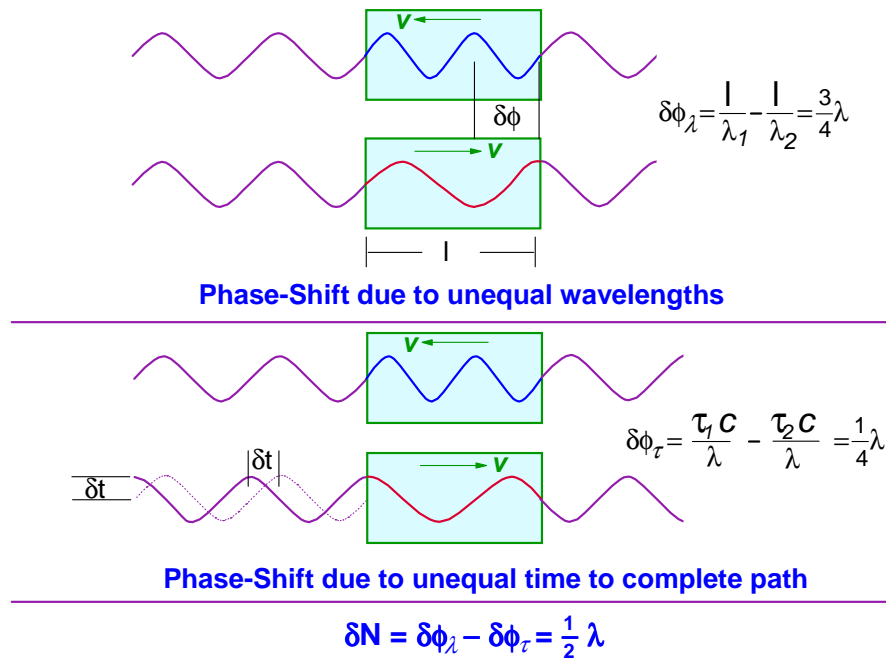


Figure 4-3 The Phase Shifts due to Unequal Wavelengths and Unequal Times Combine to Produce the Observed Results of Fizeau's Experiment

The phase at the end of the tube for each beam is given by the length of the tube divided by the wavelength of the beam. By subtracting the phase of one beam from that of the other, we arrive at an expression for the shift in the fringe pattern seen at the screen attributable to the unequal wavelengths. These two effects, unequal wavelength and unequal time are in the opposite sense and tend to cancel each other, as is shown in figure 4-3. Thus, the total fringe shift at the screen is equal to the difference of the two effects. When these two effects are calculated and applied to the Fizeau experiment, the result obtained is mathematically equivalent to the Fresnel aether-drag coefficient. However, this result is obtained without consideration of an aether, and without resorting to special relativity.

Special relativity derives this result by applying the relativistic velocity addition rule. This rule states that the velocity of light through the moving water is less than the sum of the velocity of light in the water plus the velocity of the water. However, in so doing, relativity fails to take into account the Doppler shift experienced by light from a stationary source interacting with moving water. This is the same mistake made in stating that observers in relative motion cannot agree on the simultaneity of distant events. As demonstrated in the previous chapter, once each observer measures the frequency of the light reaching their test equipment, they can determine who is in motion with respect to the source of the events, and by how much. After accounting for their individual motions with respect to the sources, all observers will ultimately agree on the simultaneity of the initial events, despite the assertions of untested claims of special relativity to the contrary. When the effect of the wavelength shift are included in the analysis of the Fizeau experiment, special relativity predicts results inconsistent with experiment. Thus, not only is this particular experiment better explained without the assumption of an aether, but it actually served to invalidate special relativity nine years before that theory's publication.

Hoek's Interferometer

In 1868, Dutch astronomer M. Hoek performed an experiment similar in nature to that of Fizeau, but one that is much simpler in concept and easier to explain in the absence of an aether. Hoek's experiment lies about midway in simplicity between that of Fizeau and the later Michelson-Morley experiment.

As shown in figure 4-4, the Hoek interferometer passed a beam of light two ways around a loop where one leg passed through a glass tube. By rotating the apparatus through various angles, and observing the manner in which the interference patterns shift, Hoek hoped to determine the degree to which the aether is constrained by the glass due to the motion of the earth in its orbit.

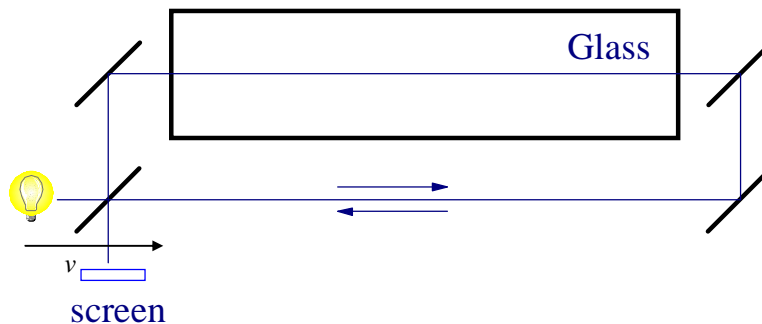


Figure 4-4. The Experiment of Hoek

When Hoek carried out the experiment, the fringe pattern did not change at all for any orientation. This implied that each of the light beams take equal time to complete the circuit, regardless of the orientation of the equipment. Hoek wrote down the equations for the expected path time differences assuming the Earth was moving through the aether. He then determined that the equations were correct if the aether was partially constrained and carried along by the glass. Solving his equations, he arrived once again at Fresnel's aether drag coefficient.

Hoek's analysis proceeds well if an aether and motion with respect to the aether are assumed. However, if we eliminate the aether, as we have done so far, we see that Hoek's experiment demonstrates nothing. The apparatus is small, thus, during the time of the experiment the motion of the equipment due to the earth may be considered as linear and inertial. Further, all components of the apparatus maintain the same speed and direction. Thus, in the

frame of the apparatus, we can assume the experiment to be at rest, and no fringe shift is expected. If we rotate the equipment, it is still at rest in its own inertial frame, and, thus, we would expect no change in the interference pattern. For example, turn the book to one side. You have reoriented the apparatus, but clearly, there is no change in the diagram. Thus if the equipment is self-contained, and there is no aether blowing through it, we would not expect any shift in the fringe pattern simply by rotating the equipment to a new position. Thus, in Hoek's equations, we would simply eliminate any terms relating to the velocity of the equipment through the aether. With no velocity terms, we need no aether drag terms, and the equations state that the fringe pattern is consistent for all equipment orientations.

Bradley, Arago and Airy

We can't leave the discussion on experiments related to Fresnel's aether drag hypothesis without first discussing aberration. When you are standing still in a light summer rain, the raindrops fall directly on your head and shoulders. If you now begin to walk forward, the raindrops will appear to be coming toward you at an angle, striking your face and body. As you increase your speed, the angle of attack of the raindrops becomes sharper. This is a basic example of aberration. The angle of aberration is proportional to your velocity perpendicular to the falling raindrops. Aberration is a very important topic in future discussions in this text, and will be addressed in detail later. In this section, we are mainly interested in its role with respect to our discussions on Fresnel.

In 1728, Oxford astronomer James Bradley discovered this effect in the distant stars as viewed from earth. He found that, in order to aim a telescope at a particular star (in this case a star in the Dragon constellation), he had to point his telescope in the direction of the earth's motion around the sun. Thus, in one season, he noted that the star appeared in a slightly different position with respect to the meridian in the summer than in the winter.

When Fresnel proposed his aether drag coefficient, Dominique Arago, a French mathematician and astronomer, suggested in a letter that one could test for the aether by filling a telescope with water and noting the different angle of aberration that would appear due to the velocity of light through the medium. Fresnel wrote to Arago in 1818 claiming that no such effect would be observed. He stated that, "Although this experiment has never been performed, I do not doubt that it will confirm my conclusion." Fresnel determined that, while the velocity of light would slow in the water, the coefficient of drag on the aether constrained in the water would increase the velocity. In other words, even though the speed of light in the medium is less than that in free aether, the constrained aether will have a net positive velocity through the telescope due to the telescopes motion through the aether. The telescope will be sweeping up aether as in the derivation of Fresnel's coefficient earlier. The velocity of the aether combined with the velocity of light through the aether then cancels the effect of the light's slower velocity with respect to the medium. The math involves not much more than a combined application of Fresnel's aether drag coefficient and the Pythagorean theorem, and supports his argument. The two effects would exactly cancel, and no shift in the angle of aberration would be observed.

The experiment was finally performed in 1871, by Sir George Airy, English Astronomer Royal, forty-four years after Fresnel's death. The results supported Fresnel's conclusion that no change in aberration angle would be seen, but, as with the experiments we have seen so far, the results do not support the assumption of an aether. Without going into the details as to why the aberration effect appears in the first place in aether-free, Galilean space (this will be discussed later), we will simply state that the aberration effect occurs due to the earth's motion around the sun, and occurs in its entirety before the light ever strikes the telescope. The telescope is simply pointed in the direction that the light waves are approaching the earth, taking account of the shift caused by the earth's motion. It does not matter, therefore, what medium fills the telescope. Once the telescope is pointed in the proper direction, light is falling parallel to the center axis of the telescope's tube. This light will travel properly down the length of the telescope whether it is filled with air, water or solid glass. Thus, once again, if we refrain from considering the existence of an aether, constrained or otherwise, Airy's results are completely anticipated.

The Michelson-Morley Experiment

Albert Michelson was a German-American physicist who contributed many ideas to the design of interferometric telescopes, and who was a great experimentalist. One of his earliest experiments was the determination of the velocity of light in a laboratory to a very high precision. It was Michelson who was quoted in the opening of the first chapter as stating in 1894 that, “It seems probable that most of the grand underlying principles [of physics] have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles.” At the time, Michelson was unaware of the implications and debate to be caused even to the current day by a simple experiment he performed with Edward Morley, the experiment now commonly referred to only as the Michelson-Morley experiment. Michelson actually performed many experiments with Morley, one of which has already been addressed, the repeat of Fizeau’s experiment. But in history’s way of determining priority and importance, it is the experiment described in this section for which they are remembered and debated.

Utilizing an interferometer similar in principle to that depicted in figure 4-5 (but with many more reflections than indicated), Michelson and Morley hoped to measure the velocity of the earth through the aether by measuring the degree to which the observed fringe pattern shifted as the apparatus was rotated through ninety degrees. Michelson and Morley performed their experiment twice, once in 1881 and more successfully in 1887. The reason for the two trials is worthy of some discussion. The reason a fringe shift was expected upon rotation of the equipment was that, at certain orientations, one leg of the interferometer would be traveling parallel to the direction of the earth’s motion through the aether. By rotating the equipment through an angle of forty-five degrees, both legs would be moving through the aether to the same degree. It was assumed that because of the earth’s motion through the aether, when one leg was parallel to this motion, the light would be delayed in one direction, and sped up for the return trip, but that these motions would be unequal. In the figure, this corresponds to the observation that the length o to d' is longer than the return trip d' to o . Combining these unequal path lengths with unequal light speeds would result in a fringe shift. This marks the basis for their 1881 experiment. Michelson and Morley obtained a null result from this experiment—there was no fringe shift for any orientation of the equipment, nor for any time of day or season. They concluded from this experiment that motion with respect to the aether is undetectable, for which a variety of explanations sprang forth.

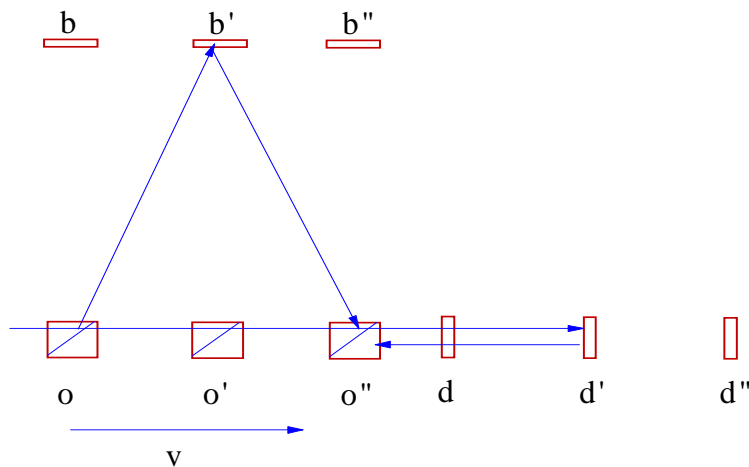


Figure 4-5. The Michelson-Morley experiment

After this experiment was performed, and the results published, Lorentz pointed out that Michelson and Morley had incorrectly calculated the effects they should expect to see. In the above description, the entire effect occurs in the leg lying parallel to the direction of motion through the aether, and a rather large effect, proportional to the earth’s velocity divided by c was expected. However, Lorentz showed that the other leg also shares some motion through the aether, as illustrated in the figure. In this leg, the light follows the zigzag path o to b' to o'' . Thus the effect of this path’s motion with respect to the aether must be included. The reason that this observation is of importance is that the effect described by Lorentz for this leg of the trip follows the same argument proposed by Fresnel to Arago for the reason no change in aberration angle should be seen in a telescope filled with water. This

analysis had been presented over sixty years earlier, and should have been known to Michelson, as he was, after all, searching for evidence of the very aether Fresnel had been describing

Michelson and Morley improved their apparatus and repeated the experiment in 1887. The results expected this time were of the second order in v/c , meaning they expected to see a fringe shift proportional in some manner to the square of the earth's velocity to c squared. Specifically, a shift of just under four tenths of a fringe was expected. When the experiment was performed, no fringe shift was observed. This should have been expected, since Hoek had already demonstrated that there was no aether. In the absence of an aether, this experiment is even simpler than that of Hoek. Not only is there no relative motion between the various components of the apparatus, but there is also no material with a refractive index different from air placed in the path of the beam. If Hoek predicts no fringe shift, then clearly Michelson-Morley predicts no fringe shift. However, since the derivations of Fresnel, Fizeau, Hoek and Airy had all been interpreted in terms of an aether, this null result was entirely unexpected. But even at this point, the aether concept was not abandoned. Instead, Fitzgerald in 1892, and later Lorentz, came up with an explanation—all material bodies contract in length in the direction of their motion with respect to the aether by a factor dependent on the velocity through the aether. This factor is equal to the square root of one minus the ratio of the velocity of the object to the speed of light squared. As we shall see, Einstein obtains this same factor in special relativity, where it adopts the symbol $1/\gamma$.

Rather than admitting the obvious, that there is no aether, Lorentz and Fitzgerald found a correction to the aether theory that allowed it to survive—simply change the length of every object placed in motion, and continue to change that length as the velocity continues to change. Another part of this balancing equation indicates that time also changes with velocity, but Lorentz did not need this piece to explain Michelson-Morley, and considered the effect a mathematical oddity only.

Lorentz was trying to save the aether concept. Even though we, the observers, the lab and the entire interferometer set-up are all in the same inertial reference frame, the length contraction still occurs. The reason it occurs, according to Lorentz, is that the apparatus is moving with respect to the aether. It is this motion which causes the length contraction. This length contraction would also apply to all the experiments analyzed so far. However, in these prior experiments, all relevant paths of the light traveled in the same direction, so the effect of the length contraction could be ignored. The new Fitzgerald-Lorentz correction to aether theory was thus compatible with all previous experiments.

At this point, we see that Hoek created an equivalence—developing a value for aether convection that supported the observed results, but was better represented by eliminating the term altogether. As experiments improved, and Michelson and Morley obtained second order results, the theory had to change to maintain equivalence and length contraction was added. The aether theory was saved temporarily, but not for long.

In 1905, Einstein realized that, in order to maintain the mathematical validity of this equivalence theory, the time contractions could not be ignored. Working through the mathematical details, he was able to show that by considering the time and length contractions as real, and abandoning the aether concept, all experimental results could be explained. As importantly, keeping both the length and time contractions as well as the aether, the results could not be explained. Einstein chose to keep the length and time distortions and eliminate the aether. As a result, Einstein was also able to explain some purely imaginary thought experiments. But, as we have seen with Poisson's objection to Fresnel's hypothesis, such results not borne out by experiment do not require any explanation at all.

It is important to realize that the length contraction proposed by Einstein is not the one proposed by Lorentz. In the Michelson-Morley experiment, length contraction occurs in Lorentz theory due to motion of the apparatus with respect to the aether, and the length contraction is physical and real. In Einstein's theory, no such length contraction exists, as there is no relative motion between apparatus and observer. The length contraction only occurs in the reference frame of and as measured by an independently moving third party observer. In Michelson-Morley, there is no motion among any of the various components of the test, including the observing screen, the laboratory, and the observers of the screen stationed in the laboratory. Thus, Michelson-Morley is not a test of special relativity. In fact, Einstein claimed to have been completely unaware of this experiment or its results when he developed the special theory. However, since he was aware of the Lorentz-Fitzgerald hypothesis on length contraction, he must have been at least partially aware of the experiment, if only because this hypothesis would not have been put forth in the absence of the Michelson-Morley results.

In special relativity, Einstein effectively replaced the aether with any arbitrary observer, such that motion through the inertial frame of the observer obtained all the characteristics of what was formerly motion through the inertial frame of the aether. The apparatus contracts in length in the reference frame of the observer, but not in the

reference frame of the equipment itself. It was at this point that the mathematical time dilation became real and necessary. As with length, the time dilation of clocks on the apparatus occurs only in the reference frame of the observer, and cannot be seen or measured by anyone traveling with the apparatus itself.

At this point we have arrived at the final equivalence theory, one which has eliminated the aether that was never required in the first place, but which has kept all the ad-hoc corrections induced to save that theory from the contradictory results of real-world experiments. How much more appropriate it would have been to simply eliminate the aether at the time of Fizeau's experiment, and arrive at the correct Galilean results we have seen so far—results which fully support the observations of each of the experiments documented.

We are now in a position to analyze experiments that prove problematical for special relativity. The general explanation for this difficulty is that the experiments in question involve rotation, and that special relativity does not apply to systems in rotation. Such non-applicability of special relativity to these experiments would be acceptable, if it were not that the domain of validity of special relativity is routinely applied to situations which are more out of range than the cases we are going to address. These include the Hafele-Keating round-the-world clocks experiment, milli-second pulsar timing algorithms and Global Positioning Satellite (GPS) clock synchronization to name a few.

The Sagnac Experiment

The experiments of Sagnac in 1913 and Michelson-Gale in 1925, proved an embarrassment for special relativity, requiring the full force of general relativity to explain their results. That these solutions are complicated explains the experiments' absence from most standard texts on Einstein's theories. Aether theories may be used to explain these experiments, but these theories, then, often fall short of explaining the experiments of Fizeau or Airy. However, if one abandons Einstein's second postulate, the results can be explained quite simply without the need for general relativity, and without resorting to concepts of aether or absolute space. This is true of Fizeau, Hoek, Airy, Michelson-Morley-Gale, and Sagnac.

The idea of abandoning SRT's second postulate begins again with what Petr Beckmann [4] referred to as an equivalence—a mathematical description that, while it produces correct answers, is based on faulty assumptions. Beckman uses what he refers to as the "Grandiose Theory of Railroad Tracks," (GRT). In this hypothetical theory, he claims that lengths contract with distance. This is demonstrated by staring down a long set of railroad tracks, and noting that the separation between the tracks becomes narrower with distance. We know this effect as perspective, and understand that it is a consequence of our field of view taking in more space proportional to the square of the distance from us as we look farther away. But Beckman's GRT says otherwise. In his example, a ruler that is twelve inches long when held close to your face will measure a similar ruler held at arm's length to be only four inches. At greater distances, the ruler becomes even smaller. We could develop a complete mathematical model as to how lengths contract with distance, and the model would provide perfectly correct results every time it is applied. The problem is, while the mathematical model provides equivalent results to what we see, its underlying assumptions are faulty—lengths do not contract with distance—and as a physical model the theory fails.

Einstein had one observation—that measurements always record the same observed velocity of light, apparently regardless of the observer's velocity with respect to the source. He also had Maxwell's equations. His goal was to make these equations invariant under transformation between inertial reference frames (IFRs), while keeping them compatible with the observed speed of light. He had at his disposal three concepts, those of space, time, and the velocity of light.

Einstein made the assumption that light velocity, even in transit, was absolutely consistent from all IFRs. From this assumption, he derived that lengths contract and time dilates due to the relative velocities of these IFRs. He could just as easily have assumed that lengths and time remain absolutely consistent between IFRs, and that light emerges from its source in a continuum of velocities, from zero to some undetermined upper limit. The two approaches are mathematically equivalent as far as any experiment dealing with both a light signal and a measure of length or time is concerned. Thus, for example, Doppler equations and apparent increase in mass with velocity will appear in both approaches. Only when considering an experiment which covers only one issue, say determining the simultaneity of distant events, or the one-way speed of light for two distinct IFRs, will a difference arise between the two approaches. Unfortunately, there were no such experiments for Einstein to rely on in support of or in contradiction to his theory, so he was forced to rely on thought experiments. In these thought experiments, Einstein proposed a hypothetical test, applied his theory to this imaginary test, and, to no surprise, arrived at imaginary results consistent with his theory. We looked at one of these thought, or *gedanken* experiments in the chapter on

simultaneity when we considered Alice and Bob as observers of distant flashes as seen from a train and the railway embankment. To this day, no test actual physical experiment has been performed in support of this thought experiment, thus the imaginary results obtained by Einstein cannot be confirmed or refuted. The Sagnac and Michelson-Gale experiments are, however, real experiments with real results that must be explained by any viable theory.

In the Sagnac experiment, we have a source, mirrors and screen all on a rotating platform, as in figure 4-6. The source light is split so that one beam travels clockwise and the other counter-clockwise around the apparatus. When the beams are brought together, an interference pattern forms and the fringe displacement is measured. The displacement is found to be proportional to the rotational velocity of the platform and to the area enclosed by the light path. The general relativistic solution to this problem is too complex to discuss here, and the special relativistic description is non-existent. Instead, we derive the Galilean solution.

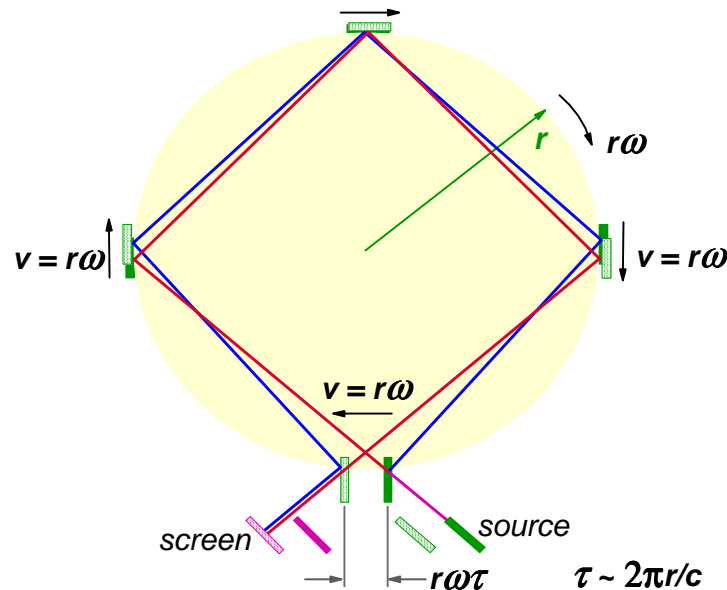


Figure 4-6. The Sagnac Interferometer

As with the experiment of Hoek, the motion of the beam-splitting and combining mirror may be considered linear during the term of the experiment. It is of value to note that the acceptable region of linearity can be extended indefinitely. We are concerned only with the location and velocity of the mirror as a source compared with the location and velocity of the mirror as an observer at a later instant. The path taken by the mirror to get from its origin to its final destination is not important. We can always model the trip as having been along the most linear route, at a speed equal to the distance between these points divided by the time required to make the trip. We are then left with a small component of velocity at each mirror that is normal to our presumed linear route. However, this normal velocity component would be the same for light traveling each direction of the circuit, and would therefore have no effect on the final solution, whether considered under SRT or any other theory.

Now, as the apparatus rotates, the beam-splitting mirror moves a small distance during the time it takes light to complete a circuit. The time required for light to complete a circuit is roughly the length of its path divided by c . During this time the beam-splitting mirror moves a distance equal to the rotation velocity multiplied by the time. If the apparatus is rotating clockwise, then the clockwise beam must travel one full circuit plus this additional distance. The counterclockwise beam travels slightly less than one full circuit by the same amount. Thus the total difference in path length encountered by the two beams is twice the distance moved by the mirror in the time it takes light to complete a circuit. The shift in the fringe pattern seen at the screen is equal to this path length difference divided by the wavelength of the light used.

If the apparatus rotates faster, the fringe shift is greater, as the path length change is greater. This experiment serves as the basis for modern day ring-laser gyroscopes. One of these devices installed in a ship or a plane, for example, can tell exactly how much and how fast the craft is turning, basically by comparing the fringe pattern.

These devices use sophisticated electronics to measure the fringe shift, but they are basically just highly accurate Sagnac interferometers. The developers of these systems generally use the solutions provided in this section to build and calibrate these devices. They do not resort to general relativity or special relativity, but use this simple Galilean procedure.

R. W. Ditchburn discusses the Sagnac experiment in his book *Light*. He states, “It is sometimes stated that rotation experiments are ‘equally well’ explained on (a) non-relativistic theory, (b) special relativity theory, (c) general relativity theory. This is not correct.... Special relativity is not applicable to any system involving rotation, and therefore does not give any explanation. Langevin has shown that general relativity does give a satisfactory account of the phenomenon. This is the only theory to account for these results without creating inconsistencies elsewhere.”

Ditchburn’s statements regarding special relativity are, however, without merit. One of the most crucial “confirmations” of special relativity involves placing what are effectively clocks on the axle and edge of a rotating platform. One then observes that the clock on the edge of the rotor slows down due to its velocity with respect to the axle according to the special relativistic time-dilation equations. A similar experiment by Hafele and Keating involved flying clocks in two directions around the globe and comparing their accumulated time with a clock at rest on the earth, moving with the rotational velocity of the earth. A third experiment involves the synchronization of clocks in orbit and on earth comprising the Global Positioning Satellite (GPS) system. These clocks are all synchronized using the velocity time-dilation effects first proposed by special relativity, without which the system would be useless. A fourth example involves the timing algorithms used for monitoring millisecond pulsars, which are perhaps the most stable clocks in the universe. These algorithms place all measurements in a hypothetical sun-centered reference frame, and then use the slowing of earth clocks due to their velocity with respect to the sun to calculate the hypothetical solar barycenter time. All four of these examples, which will be addressed in greater detail in later sections, involve rotation. These rotations are of four types: small radius with relatively high velocity, large radius with relatively low velocity, large radius with higher velocity, and much larger radius with substantially higher velocity, respectively. The GPS system, after accounting for gravitational effects, can actually be thought of as a giant Sagnac experiment. It is inconceivable that special relativity could be applicable to all these systems and yet, at the same time, be non-applicable to Sagnac and Michelson-Gale. Nonetheless, claiming non-applicability in select cases provides an easy out for special relativity’s failure to provide consistent results.

The Michelson-Gale Experiment

In 1925, twenty years after the introduction of special relativity, Michelson and Gale were still looking for evidence of the aether, and of the earth’s motion through it. This experiment was performed even after Eddington’s famous solar-eclipse expedition allegedly confirming the general theory of relativity in 1919. Apparently not all physicists at the time were as convinced of the infallibility of the special and general theories as are the physicists of today. The Michelson-Gale experiment utilized a large rectangular array of pipes and mirrors, with the legs lying in the direction of the earth’s rotation having a length of 2010 feet, and the legs lying along longitudinal lines having a length of 1113 feet. A calibration loop had the same longitudinal length, but only a very short length in the direction of the earth’s rotation. It was hoped that the effect of the earth’s motion in the direction of the light traveling the 2010 foot legs could be compared to the effect in the calibration loop in which light traveled only a negligible distance in this direction. By observing the fringe displacement of the large loop from that of the calibration loop, the effect of the earth’s motion through the aether was to be discovered. This setup is depicted in figure 4-7.

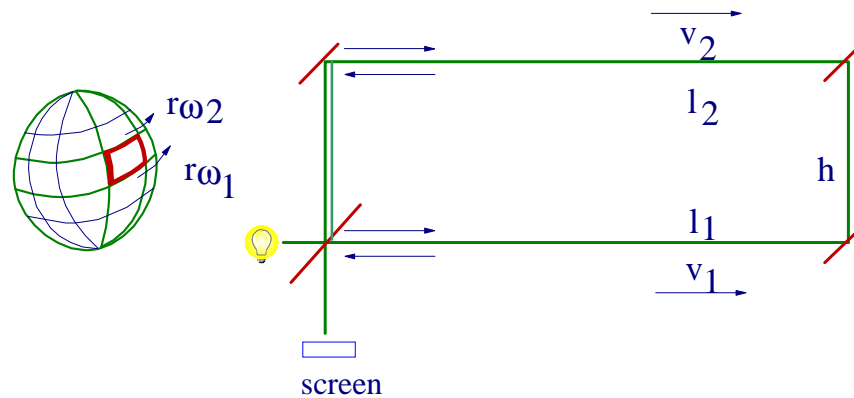


Figure 4-7. The Michelson-Gale experiment

Unlike the Michelson-Morley interferometer, this experiment did not produce null results--a displacement was observed, and that displacement was proportional to the rotational velocity of the earth, apparently lending support to aether theories. Here we will show that, without the initial assumption of an aether, the Michelson-Gale experiment proceeds quite naturally in a Galilean framework.

Since the equipment is very large, and is located on the earth, the long legs of the equipment are not equal and adjustments of the mirrors were used to compensate for this. The reason for the unequal leg length is as follows. At any two latitudes in the Northern Hemisphere, the higher latitude line will have a smaller circumference than the lower one. Taken to the extreme, at the equator the latitude line has a circumference equal to that of the earth, while at the North Pole the circumference is zero. If we wish to approximate the circumference at two latitudes by, say, a series of five hundred straight line segments, then each of the segments at the higher latitude will be smaller than each of the segments at the lower latitude. This is the same effect we would see if we projected a flat rectangle from space onto the globe at these latitudes—the northern leg would be shorter than the southern one, and the two side legs would angle in ever so slightly to accommodate this.

Also, as can be seen in the figure, the velocities of these latitudinal legs are not equal. The higher latitude leg travels more slowly than the lower leg. This is because each leg completes one entire revolution with the earth in one day, but the circumference traveled by the lower latitude leg is greater than that of the upper leg. Covering a greater distance in the same amount of time implies a higher velocity. The combination of unequal pipe lengths and unequal pipe velocities is what produces the observed fringe shift at the screen.

As light makes its way around the circuit, one beam clockwise and the other counter-clockwise, there is a difference in the time to complete these trips, due to the different velocities and lengths, even in the frame of the apparatus. The clockwise moving beam travels an increased distance in the upper leg, and a decreased distance in the lower leg. The counterclockwise beam travels an increased distance in the lower leg, and a decreased distance in the upper leg. But these effects are not equal and opposite. The counterclockwise beam in the lower leg travels a greater distance than the clockwise beam in the upper leg. This is because the velocity of the mirrors is greater in the lower leg, thus this leg travels a greater distance in the time it takes light to travel through the pipe, and the effective path covered by the light in that leg is also greater. Returning to the moving sidewalk, a man walking at four miles per hour on a sidewalk moving at 3 miles per hour will travel further in a given amount of time than the same man walking on a sidewalk that moves at only two miles per hour. The decreased distance in the lower leg for the clockwise beam is to a greater extent than the decrease for the counterclockwise beam in the upper leg for the same reason. These effects compound for the two paths.

We can easily calculate the total path length traveled by each beam. This is so because we know the rotational velocity of the earth at the latitude location of each pipe, as well as the length of the pipes. Noting that light travels the length of each pipe at a speed of c , we can determine the travel time in each pipe, and therefore determine how far each pipe moves during this time for each beam. When we divide the difference of these two path lengths by the wavelength of the light used, we can determine the amount of fringe shift to be seen at the screen. The results obtained by Michelson and Gale are completely consistent with this approach. This result is obtained without invoking an aether, time dilation, length contraction or general relativity.

We have seen how the initial assumption of the existence of an aether led to more and more corrections to the theory to explain continually improved experiments. In the end, Einstein did away with the aether, and was left only with the “corrections” to Galilean theory. In this chapter, we have seen that none of these corrections were actually necessary. Thus, through a strange series of bad assumptions and faulty interpretations, Einstein was led to the special theory of relativity, a theory that provides a mathematical equivalence to many of the areas to which it is applied, but which is based on faulty underlying principles. How much simpler it is to go back to first principles when experiment contradicts theories, rather than to keep building “castles in the air” to rescue a doomed theory.

It is very difficult to find adequate tests between special relativity and other competing theories. Most theories overlap special relativity on a vast majority of predictions made by each, yet these predictions are made on different underlying physical principles. Ultimately, one must find a test that checks not only the results of the application of the mathematical theory, but also the underlying physical assumptions. The major conceptual difference between special relativity and most competing theories is the idea of relative simultaneity—that distant events that are simultaneous for one observer will not be simultaneous for another observer in motion relative to the first. The relativistic velocity addition rule is a direct consequence of relativistic simultaneity, and, as we have seen in this chapter, the Fizeau experiment represents a direct test of the velocity addition formula. Regardless of what the correct theory is or may be, it is clear that special relativity fails to give predictions consistent with results in this experiment—an experiment initially performed fifty-six years before the introduction of special relativity.

In recent times, more experiments and systems have been devised which continue to challenge the acceptability of special relativity. These include pulsar timing algorithms, stellar aberration, unipolar induction and the Global Positioning Satellite (GPS) system, to name a few. We will explore more of these experiments and systems in Chapter twelve, but first we must spend a few more chapters discussing the conceptual problems with special relativity and the Galilean resolutions to those problems.