Chapter 2
Cracks in the Mortar

It would seem that Newton's fixed measuring grid and ubiquitous clock should provide ideal tools for measuring the Universe. Toward the end of the nineteenth century, however, evidence accumulated which contradicted this notion of absolute space and time. As we saw in the preceding chapter, Newtonian physics trips over itself: Newton's Principle of Relativity assumes the laws of physics remain the <u>same</u> for any observer in uniform translational motion, while his notions of absolute space and time infer that the speed of light, a crucial physical parameter, <u>varies</u> according to the observer's motion. In this chapter we will consider those contradictions and discuss the Michelson-Morley experiment in some detail. This experiment, which disproved the hypothesis of the "ether," serves as an introduction to the central ideas of special relativity.

<u>The wave-like properties of light</u>

To understand the Michelson-Morley experiment, we must digress briefly and review the wave-like properties of light. Physicists in the nineteenth century knew that light behaved like a traveling wave because it exhibited properties common to other waves.

Light refracts. When light passes from one medium to another, as from air to water or air to glass, the path of light bends. You have probably noticed how a straw or spoon seems to bend at the surface in a glass of water or the distortions when light passes from air into other common materials like glass and plastic. These result from refraction. Microscopes and telescopes use this property to bend light into focus.

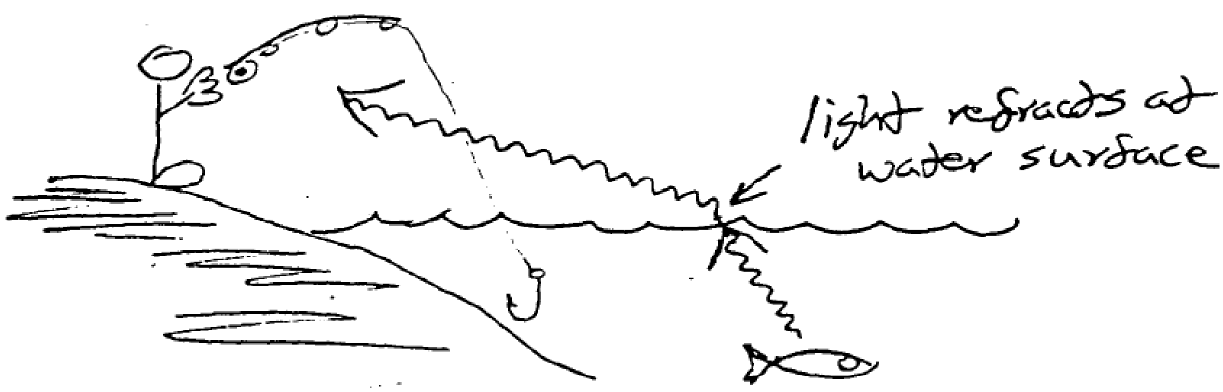

Figure 2.1. Refraction of light at the water's surface. To the fisherman, it would appear the fish was farther away from shore, along the beam of light coming to his eyes from the water surface.

This is a general property of waves and can also be seen, for instance, when water waves move from deep water into shallow water.

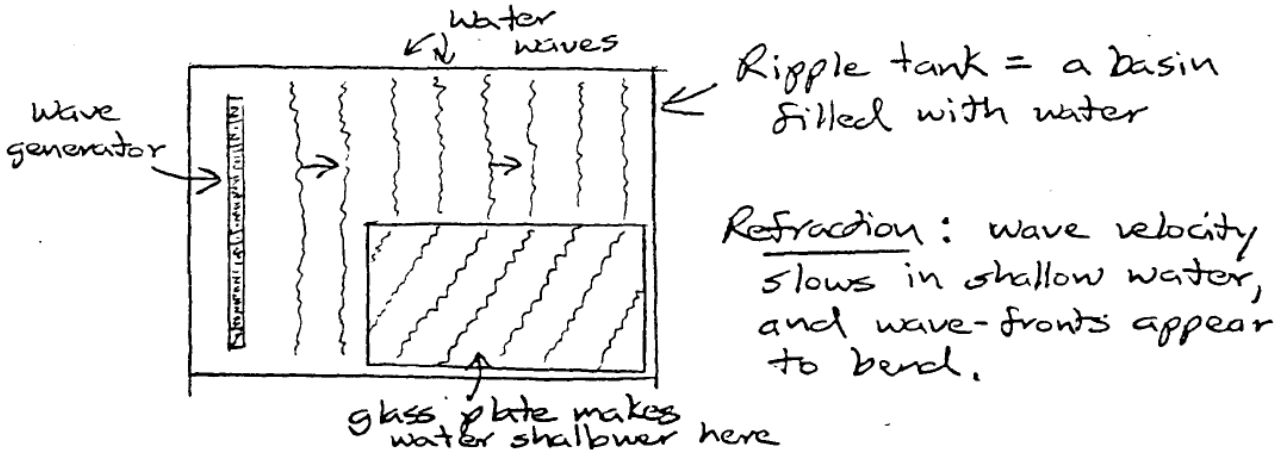

Figure 2.2. Water waves in a basin bend when the pass from deeper into shallower water.

Light diffracts. When light passes by a sharp edge its path bends, a process called diffraction. You can demonstrate this yourself with a needle and a linear or point light source. (A bulb with a straight filament serves a line source, or a distant fluorescent bulb.) Hold the needle in line with the source and blocking it. Instead of the needle's shadow, you will see a bright line where light from the source has diffracted around the needle and focused at your eye.

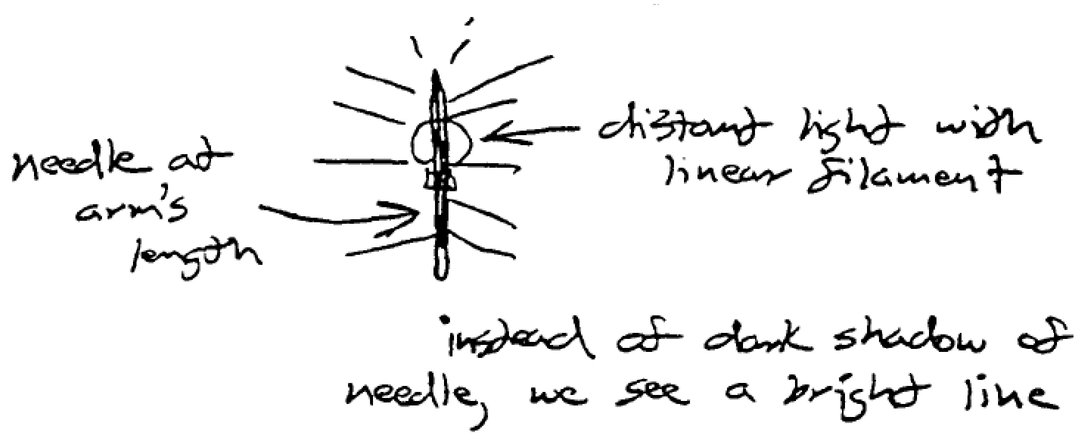

Figure 2.3. Diffraction of light around a needle.

Diffraction is a general property of waves. Water waves bend as they sweep past a barrier such as a sea wall. Sound waves bend going through doorways: this is why, if the classroom door is open, you hear people talking out in the hallway even if you can't see them.

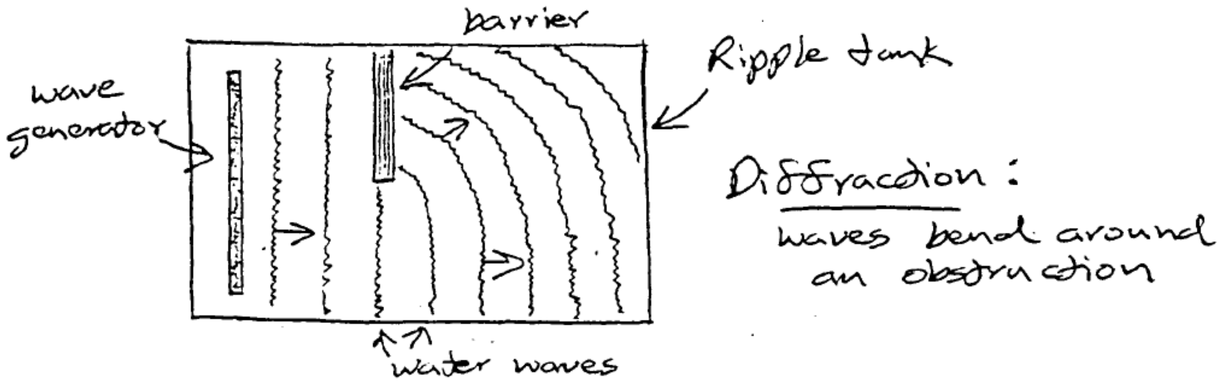

Figure 2.4. Diffraction in a ripple tank. Water waves that were initially parallel will bend around the edge of a barrier.

Light interferes. Light beams, like other waves, add to or subtract from each other. This property can be demonstrated using a diffraction grating: when a laser shines through a diffraction grating, the grating splits the beam into many beams that interfere with each other, so we see an alternating series of bright spots (where light waves have added to each other) and dark spaces (where the waves cancel each other).

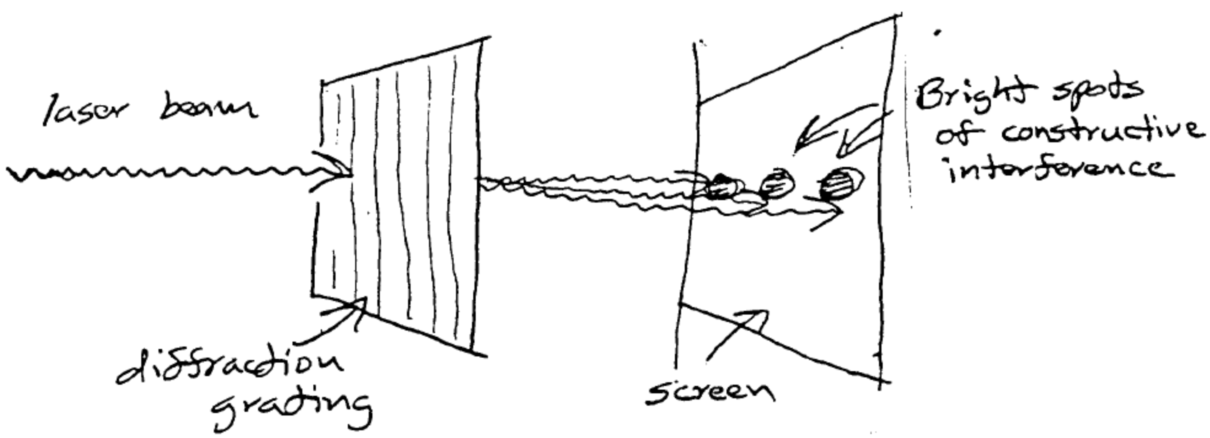

Figure 2.5. Diagrammatic representation of interference pattern that results when a laser passes through a diffraction grating. The grating re-radiates many light waves generated by the laser, and those waves interfere.

Interference results because the amplitude (roughly, the height – see formal definition below) of two waves passing a point in space is just the sum of the heights they would have passing separately.

You can easily demonstrate another incidence of interference: hold your thumbs, nearly touching, about five or six centimeters from your eye, and look toward a distant bright light. Alternating bright and dark stripes of light appear in the narrow gap between your thumbs. The bright stripes represent regions where light waves are adding to each other. The dark stripes are regions where light waves cancel.

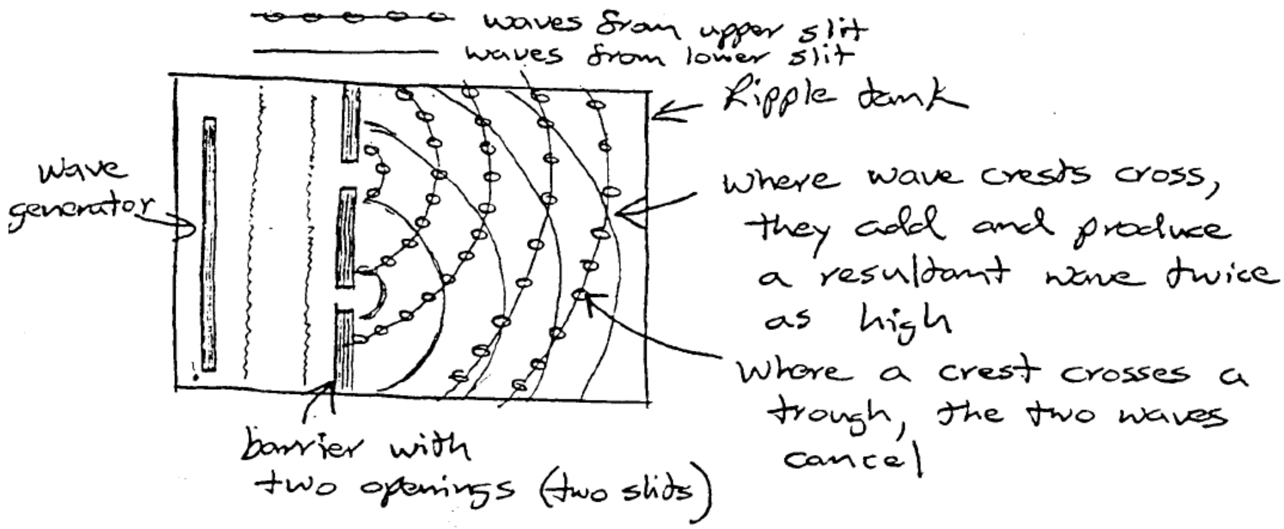

Figure 2.6. Interference in a ripple tank. Waves from upper slit interfere with waves from lower slit.

We can demonstrate interference of water waves in a ripple tank. If we direct a series of parallel waves through a double slit apparatus (a barrier with two holes in it), the incoming parallel waves generate circular waves (by diffraction) from each of the two slits. The two waves from the slits interfere with each other: where the crest of one wave crosses the crest of a wave from the other slit, the amplitudes add and create a wave twice as high. Where the crest of one wave crosses the trough of another, the waves cancel, and there is no net displacement of the water surface.

Interference is a general wave phenomenon: where there is interference, there must be waves.

Since they knew light behaved like a wave, nineteenth-century physicists assigned wave properties to light:

The amplitude (A) of a wave is the height of the wave from its resting level to its crest. For example, the amplitude of a water wave is measured from the flat surface of undisturbed water to the crest of the passing wave. For light (an all electromagnetic radiation) the amplitude is a measure of the maximum displacement of the electric field.

Figure 2.7. Wave amplitude.

The wavelength (represented by λ, the Greek letter lambda) is the distance from the crest of one wave to the crest of the next. For light, wavelength (which is related to frequency by the velocity function, below) determines the color of light: blue light has relatively short wavelength (and high frequency), while red light has long wavelength (and low frequency).

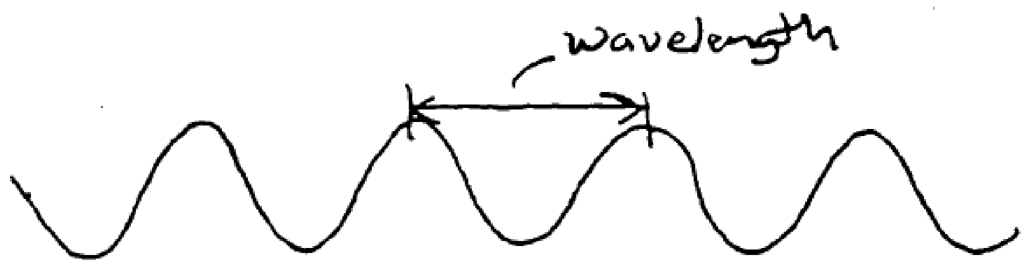

Figure 2.8. Wavelength.

Frequency (*f*) is the number of wave crests that pass a fixed location in a given time, usually measured as waves per second. Or, same thing, frequency is the number of oscillations per second at a fixed point in space. For sound waves this is what we sense as the pitch of the sound.

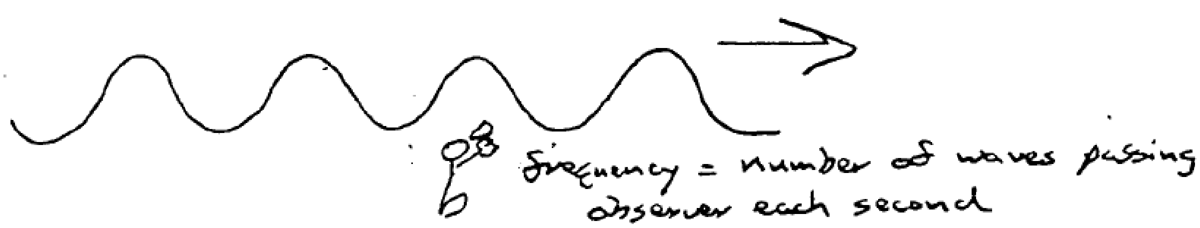

Figure 2.9. Frequency.

The period (T) is the time interval between successive crests. It's easy to see that the period is just the reciprocal of the frequency. If ten wave crests pass by an observer in one second, then the time between crests must be one tenth of a second: $f = {}^{1}/_{T}$

Velocity is the speed of a wave, and it is a function of wavelength and frequency.

$$v = \lambda f$$

The speed of light (about 300,000 km/sec) is represented by the letter c .

We can understand why velocity depends on wavelength and frequency with an example. Imagine two soldiers in basic training. One is tall and lanky, the other very short. The drill sergeant forces them to march at the same velocity as the rest of the company. To do so, the tall soldier, with his long stride (analogous to long wavelength) can amble along at a relatively slow pace (low frequency, i.e. fewer steps per second). The short soldier, with his short legs (short wavelength), must step quickly (high frequency) in order to keep up.

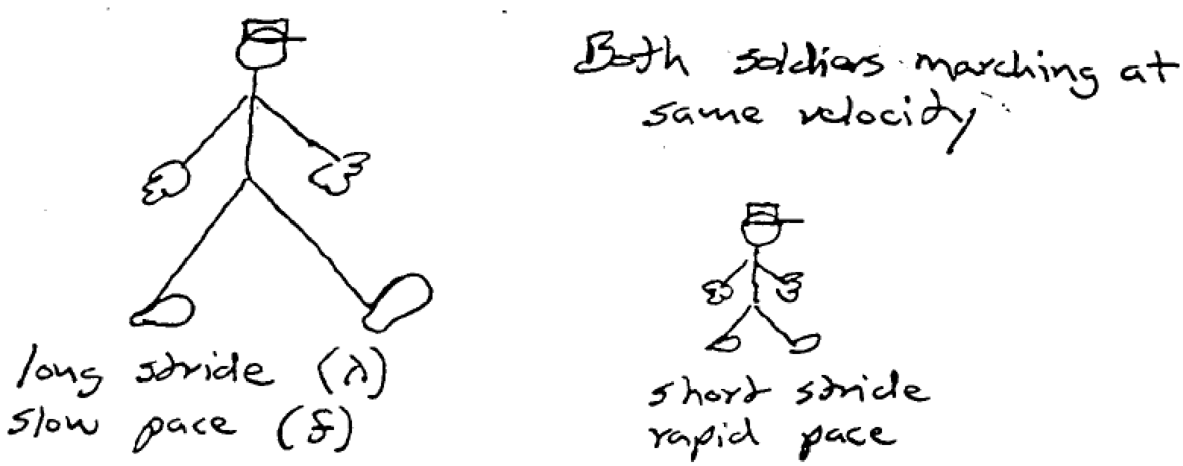

Figure 2.9. Velocity depends on both the frequency and the wavelength.

<u>Light as a measuring tool</u>

The speed of light affects our measurements. It would seem irrelevant, at first thought, but in fact the speed of light determines our very capacity to <u>make</u> measurements. For example, when you measure the length of some object, a railroad car, for example, light carries information to our eyes comparing the ends of the car to the grid marks on our measuring stick. It turns out that in any measurement, with any measuring device, the speed of light is the absolute limit to the rate at which information can be transmitted.

When an object is moving at slow speed, any measurements made on that object are completed by nearby observers before the state of the object – its position, for instance – can change very much. At high speeds, however, an object can change its state, e.g. its position, during the course of the measurement. Because it takes light some time to cover the distance moved by the object during the time interval in which the measurements are made, the measurements differ from those we would obtain with the object at rest.

Consider, for example, how our measurement of the length of a railroad car would be affected if the car was traveling rapidly down the track. We lay an extended ruler along the track and stand at the zero mark. A friend stands up the track, a car's length away. At the instant the front of the car reaches the zero mark, we flash a light signal, the fastest possible means of communication, and our friend measures the position of the end of the car against the ruler. In the time it takes our light signal to travel down the track, however, the end of the car has moved a bit farther down the track, so our friend measures the car a bit shorter than it is at rest.

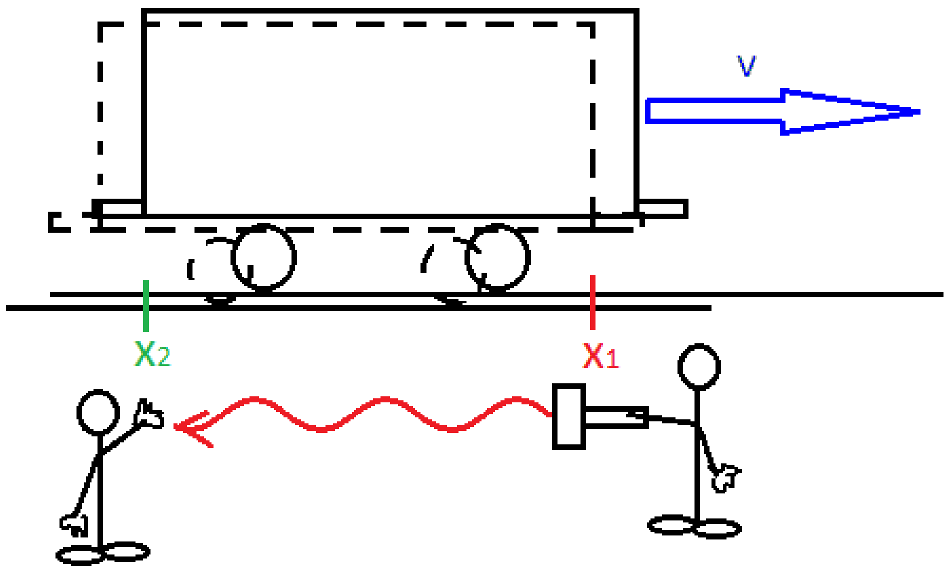

Figure 2.10. When the front of the moving boxcar is at position x_1, you send a light signal. In the time it takes a light signal to reach your friend, the end of the boxcar has moved to position x_2, so you measure the boxcar shorter than it actually is.

In familiar, everyday circumstances, the time required for light travel during measurement is insignificant, but over astronomical distances (and, as we'll see, at extremes of velocity and extremes of gravitational fields) the speed of light cannot be ignored. The Io clock cited in Chapter 1 provides a primary example.

Knowing that the speed of light affects our measurements, it became important to determine if the speed of light itself varied. Would the measured speed of light change if the source of light was moving? What if the observer was moving? Or what if the medium through which the light traveled, such as air or water or the vast realms between the galaxies, was moving?

Despite James Clerk Maxwell's mathematical demonstration that light could be a self-propagating electromagnetic wave, many physicists (including Maxwell himself) believed light must have a medium through which to propagate. Since water waves require water, and sound waves require air for propagation, light, they reasoned, must also require some medium. They hypothesized a "luminiferous ether," permeating all space, which served as the medium for light.

In effect, the ether fulfilled Newton's notion of absolute space: it provided a frame of reference through which everything else moved. The paths of galaxies, stars, planets, light – all the bits and pieces of the Universe – could be measured in reference to the ether.

American physicists Albert Michelson and Edward Morley studied this question with an elegant apparatus, now known as the Michelson interferometer, that could measure minute differences in the speed of light along two different paths. If there is an ether which propagates light, Michelson and Morley reasoned, it should be possible to detect Earth's motion through it. Since the Earth orbits the sun, the sun orbits the galactic nucleus, and the galaxy itself moves through space, Earth presumably moves with considerable net velocity through the ether. (Earth's orbital speed alone is about 67,000 miles per hour.) Just as we can feel air flowing past a moving car if we stick our hand out the window, we should be able to detect the flow of ether – the ether "current" – past Earth.

The Michelson-Morley Experiment

The following analogy illustrates the logic by which Michelson and Morley sought evidence for the ether:

Imagine a ferry boat on a lake. The boat shuttles between three towns, and the central boat dock, in town A, is located four miles from each of the other two towns.

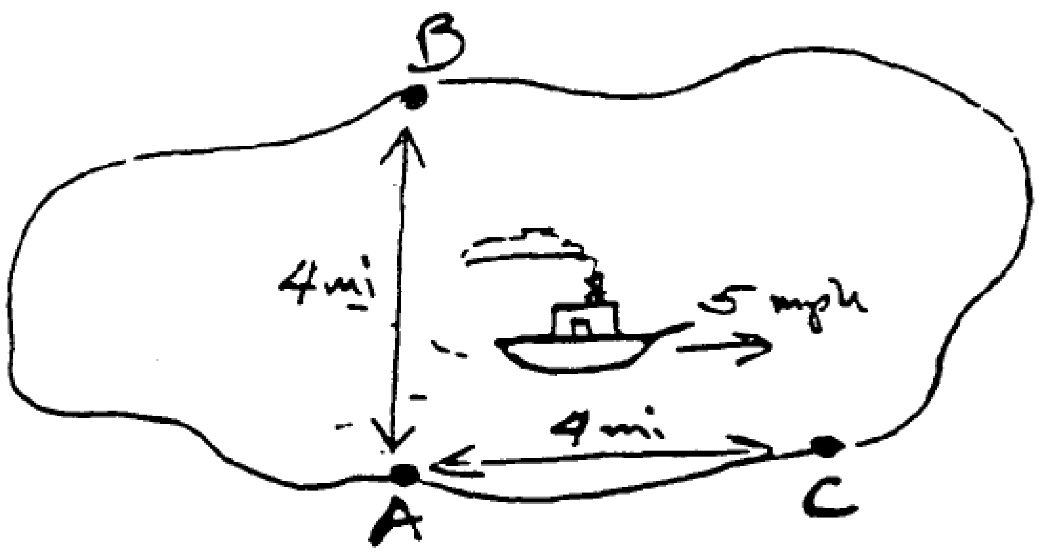

Figure 2.11. Ferry boat shuttling between towns on a lake.

The boat travels five miles per hour. On a calm day, with no wind, how long does it take the ferry to travel from town A to town B and back, or to make the round trip A to C and back to A? Obviously each round trip takes the same time: 4/5 of an hour one way, 1 and 3/5 hours round trip.

Now imagine the ferry on a river. Again, the towns lie four miles apart, and the ferry cruises at five miles per hour. In this case, though, we must consider the effects of the current, flowing, say, at three miles per hour.

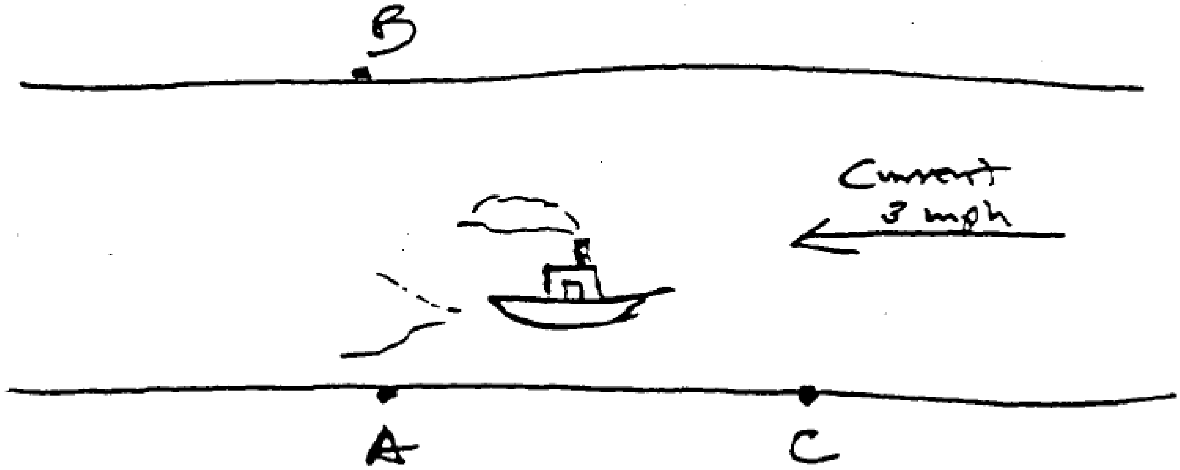

Figure 2.12. Ferry on a river. Now we have to include the effects of the current.

Now what are the round-trip times, A-B-A and A-C-A? First picture the ferry cruising upstream to C then back down to A. The net speed (relative to town A and the shore) on the upstream leg, 5 mph boat against a 3 mph current, is 2 mph. So it takes 2 hours to reach C. On the return trip, the current adds 3 mph to the boat's 5. The boat is now moving at 8 mph relative to the shore and takes only 1/2 hour to return to A. Net travel time to and from C is 2.5 hours. How does this compare to the travel time, across the river, from A to B and back?

To calculate the round trip time from A to B to A we need some geometry. To reach B from A, the ferry angles slightly upstream, or else the current will wash it down-river. If we calculate the upstream compensation needed to keep the ferry on line from A to B, we find in our example that the ferry's course forms a 3/4/5 right triangle. The ferry actually travels five miles, compensating for the 3 mph current, to reach a point four miles directly across the river. (See the demonstration, Moving Frames of Reference, at the end of this chapter.)

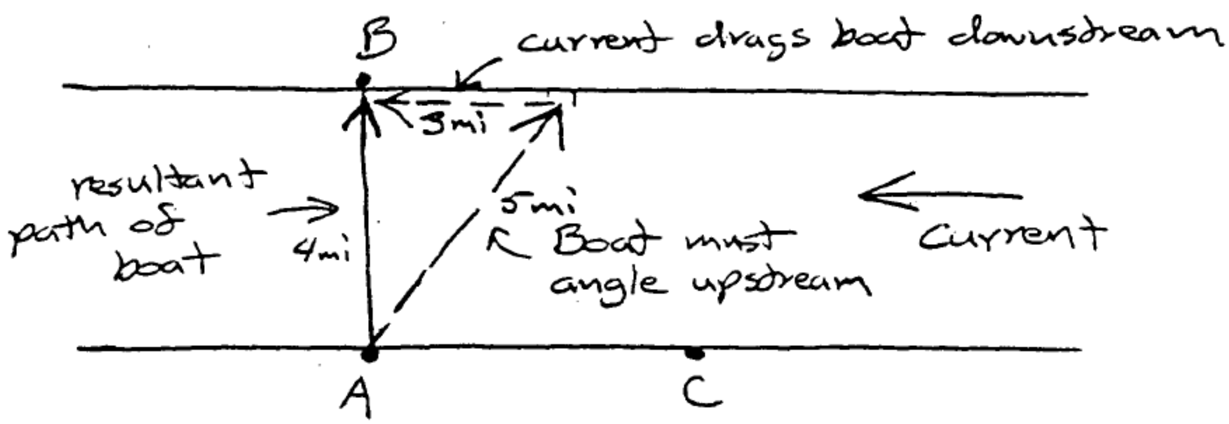

Figure 2.13. Geometry of theferry's trip across the river. Actual path of the boat is straight across the river, from A to B. To do this, however, the boat must angle upstream in order to compensate for the current.

Since the ferry travels five miles per hour, the crossing takes one hour. It takes the same time to return, so the total travel time, forth and back across the river, is two hours.

The round trip, then, from A to B to A takes two hours, while the trip from A to C to A takes 2.5 hours. Even though towns B and C are both located 4 miles from A, the travel times differ because of the effect of the current.

Two results are important here. First, when the current flows, the round trip travel times across the current and parallel to the current are <u>both</u> longer than when the water is still. Second, the time needed to travel across the stream is shorter than the time to travel parallel to it. This is in sharp contrast to the situation in still water where the round trip times are identical.

The arguments above can easily be extended to the case where the medium is at rest but the locations A, B and C are all moving in the same direction. For example, consider two planes launched from an aircraft carrier. Assume that the wind is calm but that the ship is moving through the water at a high speed in some specified direction. A plane which makes a 100 mile round trip perpendicular to the motion of the ship will take less time than a plane making a 100 mile round trip parallel to the ship's motion (that is, fly 50 miles from the ship and return). The situation is identical to the ferry boat on the river, but now the shore (with the carrier represented by town A) is sliding along an otherwise stationary body of water (the carrier is moving through still air).

In the actual experiment, Michelson and Morley used light as their "airplanes", the Earth as the "aircraft carrier," and the ether is analogous to the "still air". They compared the time for light to make a round trip perpendicular to Earth's motion through the assumed ether to the time required for light to make a round trip parallel to Earth's motion. The apparatus they used is illustrated below.

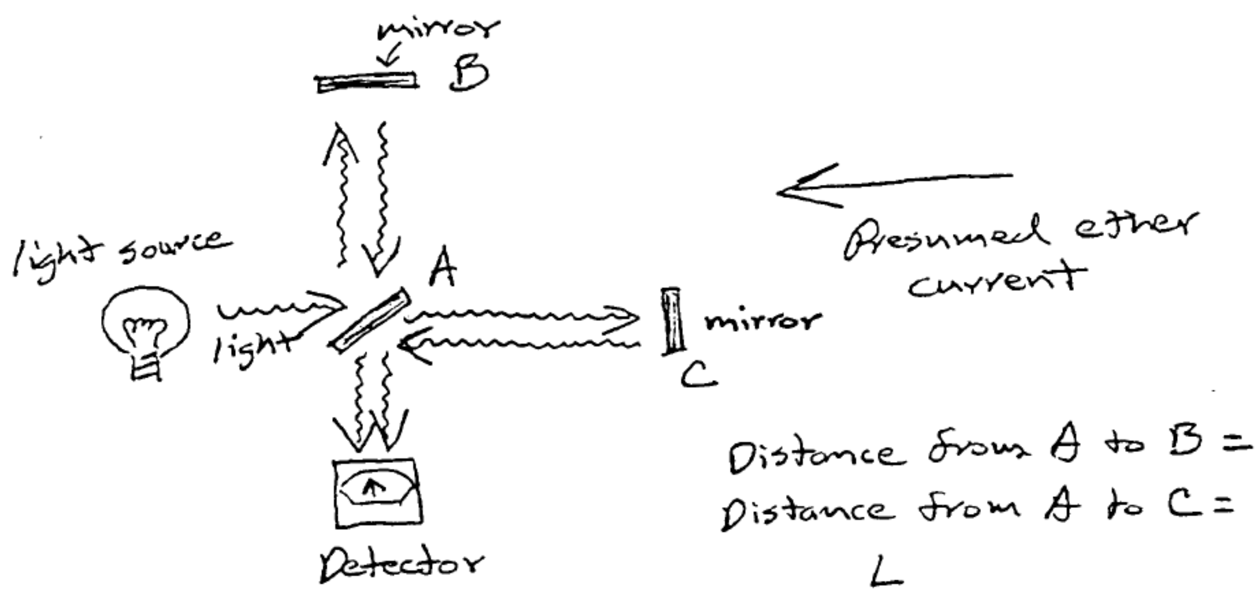

Figure 2.14. The Michelson-Morley apparatus. Light can travel either of two paths through partially reflecting mirror A: path 1) from A to B and back through A to the detector or path 2)

through A to C and back to A, then reflected to the detector. (As we'll see later, light actually follows both paths at once!)

Light leaves the source (a bright bulb or, nowadays, a laser) and travels toward mirror A, a "half-silvered mirror" which reflects half the incident light toward mirror B and transmits half on to mirror C. On one path, light bounces off C back to A, where half is reflected to a detector. On the second path, light reflects off B back to A, where half is transmitted to the detector. The mirrors at B and C are adjusted so that the light beams traveling the two paths come together at the detector. Because light acts as a wave, an interference pattern will be produced by the superimposed beams. One can adjust the mirrors in the initial configuration such that the combined beams produce constructive interference at the detector. If the apparatus is then rotated 90° and the travel times remain the same, no change will occur in the interference pattern. However, if the travel times change when the apparatus is rotated, the interference pattern will change. A time difference equivalent to half the period of oscillation of the light wave (an incredibly small value of about 2×10^{-15} seconds) would produce a complete cancellation of the waves. Obviously the apparatus is extremely sensitive to any time differences between the paths.

Let's compare the light travel times along the different paths as the apparatus moves through the ether. Assume the apparatus moves left to right (along the direction A to C) through the ether at a speed v. (v = the speed of the Earth, and the apparatus, through the ether.)

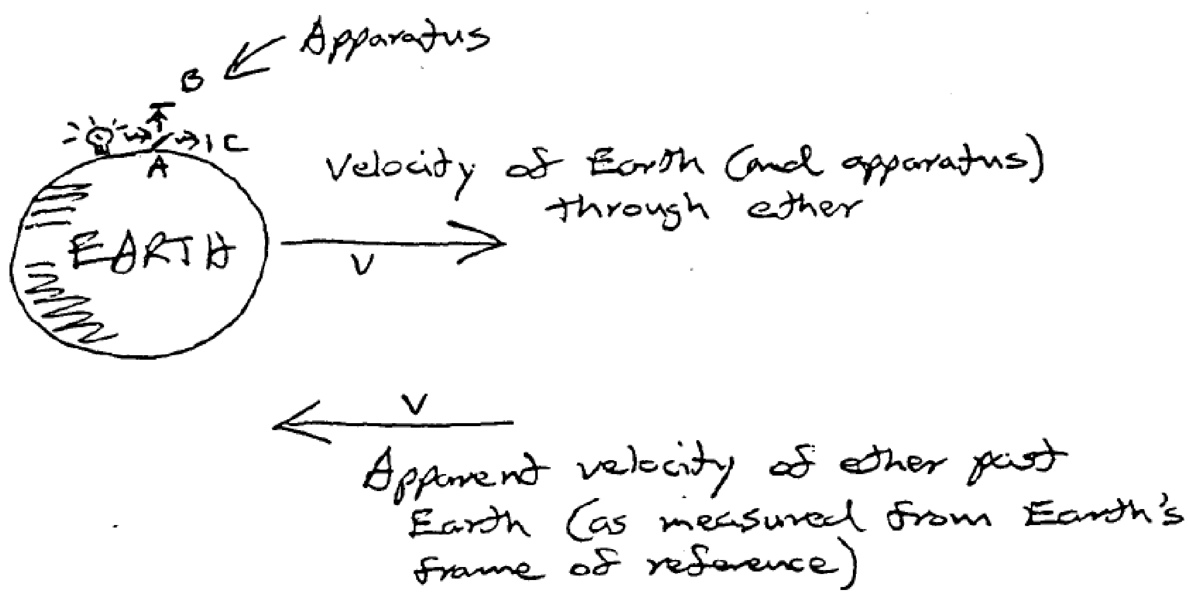

Figure 2.15. Motion of the Michelson-Morley apparatus through the (presumed) ether or, equivalently, motion of the ether past Earth.

First we calculate the light travel time from mirror A to C and back. While a beam of light travels from A to C, in time *t*, the entire apparatus, including mirror C, moves a distance *vt* relative to the ether.

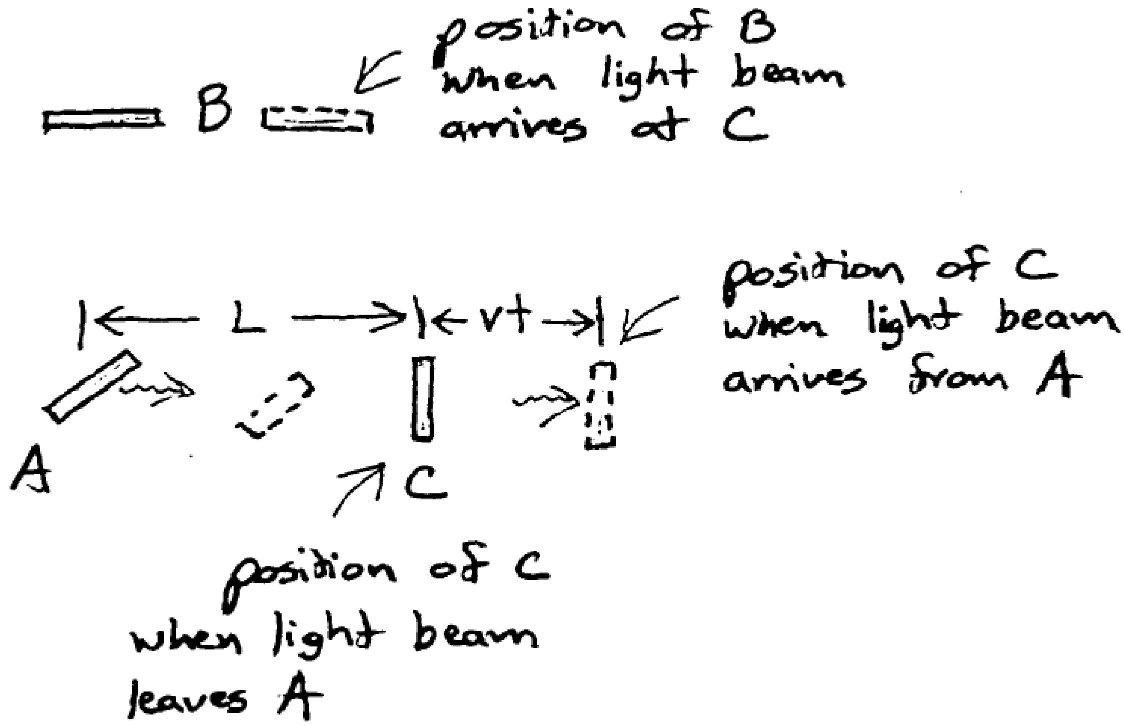

Figure 2.16. Change in position of the mirrors as the apparatus moves through the ether.

The light beam parallel to the "ether current" (i.e. parallel to the direction of Earth's motion) travels a total distance $ct_1 = L + vt_1$ (the distance between mirrors plus the distance mirror C moved during the time t_1). A little algebra gives us the travel time as

$$t_1 = \frac{L}{(c - v)}$$

where L is the distance from A to C, and c is the speed of light.

On the return trip, C to A, the light beam travels a (shorter) distance $ct_2 = L - vt_2$, since the apparatus, including mirror A, has advanced through the ether by a distance vt_2 in the travel time t_2. The travel time from C to A, then, is

$$t_2 = \frac{L}{(c + v)}$$

From these equations, we find the total travel time from A to C and back to A is

$$t_1 + t_2 = \frac{2L/c}{(1 - v^2/c^2)}$$

Now let's calculate the light travel time from A to B and back to A.

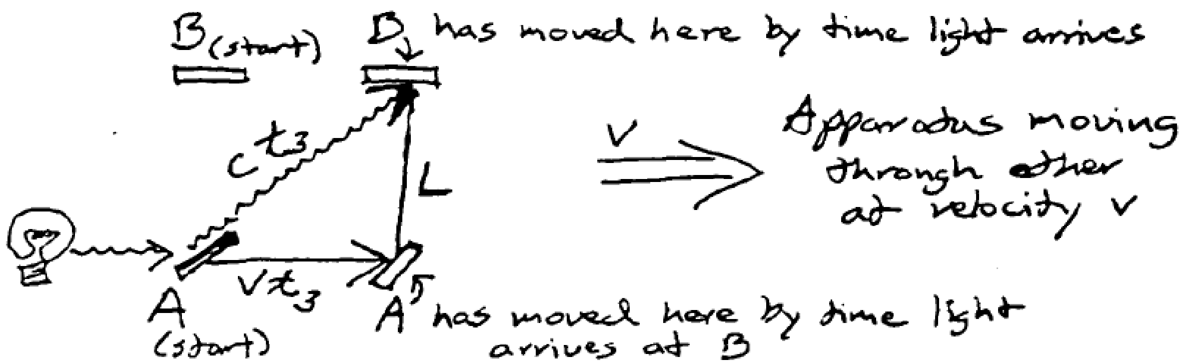

Figure 2.17. Path of light from mirror A to B as the apparatus moves through the ether.

Again assuming the apparatus travels left to right through the ether, we see it moves a distance vt_3 while the light travels distance ct_3 from A to B. The geometry of the situation allows us to apply the rule of right triangles:

$$(ct_3)^2 = L^2 + (vt_3)^2$$

Solving for t, we find the light travel time from A to B is

$$t_3 = \frac{L}{\sqrt{c^2 - v^2}} = \frac{L/c}{\sqrt{1 - v^2/c^2}}$$

The travel time back to A from B is the same, so the total travel time A to B to A is

$$t_3 = \frac{2L}{\sqrt{c^2 - v^2}} = \frac{2L/c}{\sqrt{1 - v^2/c^2}}$$

Note that the argument <u>assumes</u> the existence of the ether. It assumes absolute, Newtonian space. Comparing equations for light travel times along the different paths, the experimenters expected to find a difference in the light travel times along the two paths:

$$t_1 + t_2 = \frac{2t_3}{\sqrt{1 - v^2/c^2}}$$

That is, the light travel time perpendicular to the direction of motion through the ether should exceed the travel time parallel to the ether current by the factor

$$\frac{1}{\sqrt{1 - v^2/c^2}}$$

(Heads up: we'll see this "gamma factor" shortly, in the equations of Special Relativity.)

The difference in times increases as the velocity of the apparatus increases.

Michelson and Morley constructed their apparatus so that it could be rotated with respect to the motion of the earth through the ether. After a few degrees of rotation the two paths are no longer exactly perpendicular and parallel to the earth's motion. The times taken to travel these paths will be altered and their difference will be less than the extreme values of the original orientation. This changes the amount of interference at the detector. The greatest change would obviously be produced by a 90 degree rotation, which simply exchanges the two paths. The shorter time becomes the longer and vice versa. Given the length of each path (11 meters in the original experiment), and the assumed speed of the earth through the ether (19 miles per second), the rotation should have produced a noticeable change in the observed interference pattern.

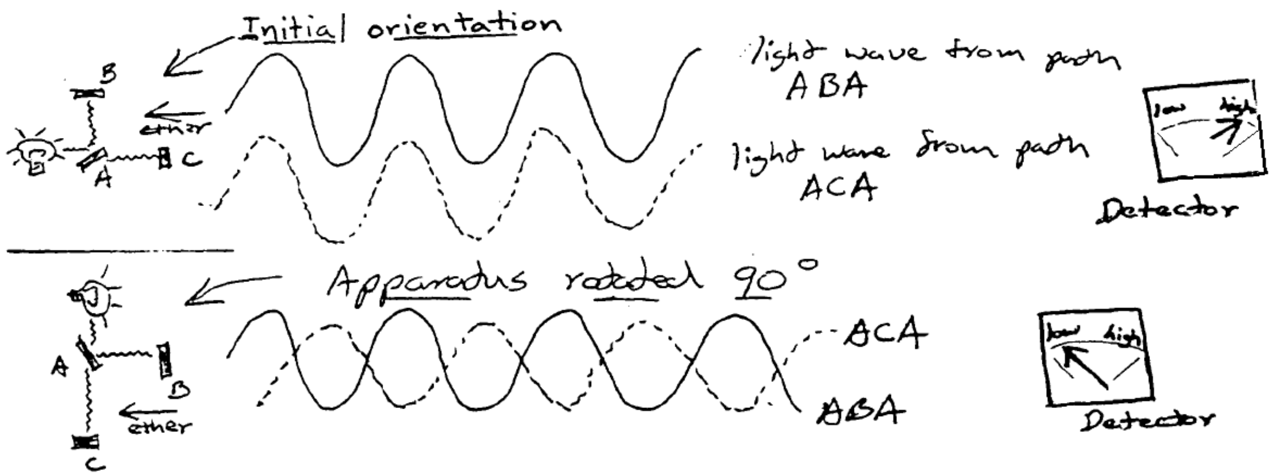

Figure 2.17. Change in the interference pattern as the apparatus is rotated, <u>if</u> there is an ether.

When Michelson and Morley performed the experiment, they found <u>no</u> change in the interference pattern when they rotated the apparatus. That is, there was no difference in the light travel times along the two paths. This came as a complete surprise. The results showed that even if the propagation of light is supported by the ether, it does not seem to provide a frame of reference from which to measure the speed of light. Once light enters the apparatus, the results seem to indicate that the moving apparatus itself provides the reference frame for measurement: even if the ether exists, it is superfluous. The notion of "ether" is excess baggage and can be dropped from a physicist's view of the world.

The null result (i.e. the failure to detect the effects of an ether current and, therefore, any substance with which to measure absolute space) shook the physics community. No absolute space, no absolute time – the Universe suddenly appeared a very slippery place.

<u>Newton's Principle of Relativity</u>

The loss of absolute space removes the foundation upon which Newton's laws were based. However, we do know that Newton's three Laws of Motion provide an effective means of analyzing nature. Almost every experience in our daily lives reaffirms these laws: If we throw a ball we can predict where it will go. When automobiles crash we can predict the damage. We obviously don't want to get rid of Newton's Laws. We need a new philosophical foundation to support them. This foundation is supplied by the Principle of Relativity.

The Principle of Relativity states that the laws of physics are the same as seen by any observer moving at constant speed in a straight line. More abstractly, the mathematical form of physical laws is invariant from one coordinate system to another if the systems are moving at constant speed in a straight line relative to each other. The numerical value of a measurement may vary from one frame of reference to another, but there must be a means of assembling various measurements such that they describe the same physical phenomena. If two cars collide on a highway, all drivers who witness the collision must agree that it actually took place, even though the speeds of the two cars before the collision may have been measured differently by a witness moving toward the collision from the north compared to a witness moving from the south.

These are not new ideas. In fact, Galileo had employed the Principle of Relativity a century before Newton in his work entitled *On the Two World Systems.* There he developed a method for predicting the motion of projectiles (e.g., cannon balls) which relied on the fact that steady linear motion of a piece of apparatus (e.g., a cannon on board a steadily moving ship) would not affect its operation. He claimed, for instance, that a stone dropped from the top of the mast of a ship would fall to the base of the mast regardless of whether or not the ship was moving. You can test this yourself by dropping a small stone to the ground from shoulder height while you are walking or running. The stone will hit the ground right near your feet, exactly as if you were standing still.

We witness the Principle of Relativity in our everyday experience. It is evident, for instance, when one flies in an airplane at constant speed in smooth air: the trajectory of coffee poured from pot to cup within the airplane is the same as if the coffee was poured at the breakfast table back home. The observed parabolic shape of the trajectory is fundamental to trajectories (near the Earth's surface).

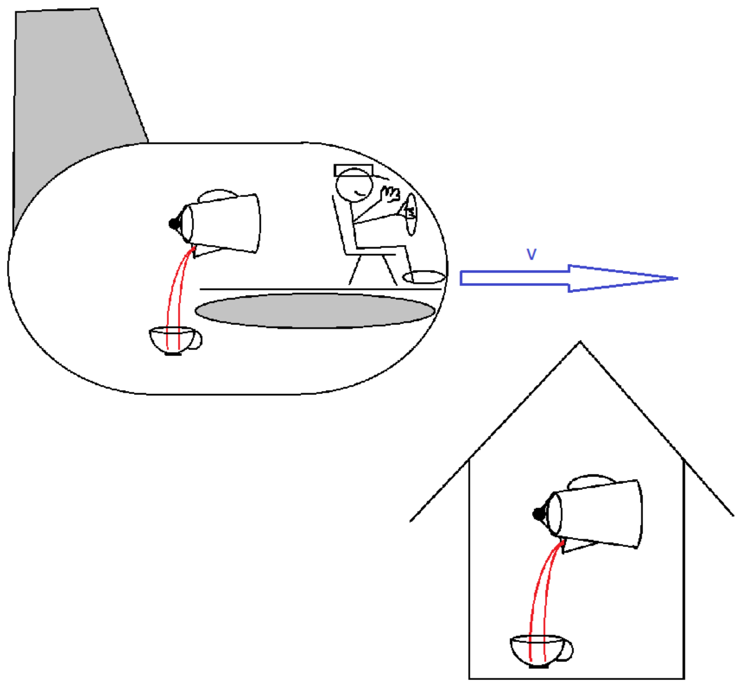

Figure 2.18. Laws of physics are the same for systems in uniform motion (constant velocity) as they are for systems at rest.

A car radio, to cite another example, works the same as the radio on the desk at home, even though the car is traveling down the highway at 55 mph. The natural laws which govern the behavior of electrical devices such as radios are independent of the speed at which those devices travel.

There is a logical inconsistency between the notion of absolute space and time and the Principle of Relativity. On the one hand, the Principle of Relativity implies that an observer traveling at uniform velocity cannot determine he is moving without looking outside his frame of reference, since all the laws of physics are the same in any inertial frame. On the other hand, the concept of absolute space and time implies a fixed frame of reference against which absolute motion can be measured.

Of these two concepts, the notion of absolute space and time fails experimental test, and the Principle of Relativity survives. It is one of the basic facts of Nature. In the next chapters we will trace the myriad implications of that Principle as discovered by Albert Einstein.

In this chapter we have described in some detail the evidence contradicting Newton's ideas of absolute space and time, especially the Michelson-Morley experiment, and we introduced the Principle of Relativity as an alternative basis for physical law. In the next chapter we shall trace Einstein's logic in developing the special theory of relativity and, in so doing, explain Michelson and Morley's unexpected results.