A Model of Light

Having spoken of the rays of the sun, which are the focus of all the heat and light that we enjoy, you will undoubtedly ask, 'What are these rays?' This is, beyond question, one of the most important inquiries in physics.

Leonard Euler

At the turn of the twentieth century, a revolution occurred. Thousands of years of slow and steady progress in understanding the nature of physical laws had led many physicists to conclude that their work in the theoretical realm was nearly finished. Albert Michelson declared at the University of Chicago 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." Yet it was Michelson himself who had planted one of the seeds of the revolution six years earlier in an experiment he performed with Edward Morley. Almost simultaneously new discoveries were made concerning the nature of atomic structure, electricity, magnetism, and the energy and velocity of light. Attempts to correlate these discoveries led to the special and general theories of relativity and laid the foundation for quantum theory.

Relativity theory proved very difficult for most people to understand. It was thought in the early days of the theory that there were perhaps only a handful of individuals alive who could comprehend it fully. A *New York Times* headline in November 1919 proclaimed, "A book for 12 wise men" in an article on relativity. As difficult as the special and general theories were, they quickly gained dominance as a description of the way the universe is. The success in predicting the deflection of starlight by the sun as well as an anomalous advance in the perihelion of Mercury's orbit, were initial triumphs of the theory. In fact, it was the experimental verification of the deflection of starlight by the sun during a solar eclipse in 1919 that made Einstein an instant celebrity to the general public. The graphic demonstration of the famous equation $E = mc^2$ over Hiroshima and Nagasaki made the implications of the theory dramatically accessible to the lay person. The explosions in Japan not only closed the Second World War but also seared the concept of relativity as a fundamental axiom in the minds of a generation of scientists in the fifty years to follow.

Despite the almost universal acceptance of the special and general theories of relativity, there is a problem—Einstein was wrong. Beginning in the 1920's, the field of Quantum Mechanics began to dominate physicist's attempts to understand the basic workings and nature of the physical world of which we are a part. Einstein was very uncomfortable with the precepts of this new theory, stating at one point that "God does not play dice," referring to the probabilistic nature of the rules governing the physics of the quantum. He collaborated with Podolsky and Rosen on a thought experiment that demonstrated the foolishness (or incompleteness) of the theory. This experiment is referred to as the EPR paradox. Einstein's conclusion from this hypothetical situation was that the theory of quantum mechanics, though not necessarily completely wrong, is at best incomplete.

Recent advances in experimental tools have allowed tests of the EPR paradox to be performed, most notably by Alain Aspect at CERN in 1982. The results of the experiment are quite striking. Either the notion of what we call reality is false, and the ideas of physical objects, sequenced events, history, dogs and planets are meaningless; or special relativity is incorrect. Specifically, that portion of special relativity that deals with the velocity of light being an absolute limit to the speed of objects or information transfer must be false. In short, the model of light proposed by Maxwell, Lorentz and Einstein, though not necessarily completely wrong, is at best incomplete.

Einstein developed the special and general theories of relativity to reconcile the amazing mathematical derivations of Maxwell's electromagnetic theory with the experimentally observed properties of light and gravity. The Michelson and Morley interferometer experiments demonstrated that light has an apparent constant velocity independent of any particular frame of reference. Lorentz and Einstein took this one *observable* characteristic of light, and, treating it as an *absolute* characteristic developed a theory by which clocks in motion slow down, lengths contract in the direction of motion, and velocities of objects do not add in a common sense way. Combining this new model with Newton's laws of conservation of energy and momentum then required also that mass increases with velocity. This set an upper limit on attainable velocities at c, the "speed of light," since reaching this speed would require infinite energy. Generalization of the special theory of relativity to the case of free-fall in a gravitational field resulted in the theory that gravity curves space and time. The end result of all these adjustments is a universe that is not only counterintuitive, but is practically inconceivable to the layperson.

The weakness in the foundation of Einstein's theories lies in the assumption that the observed or measured invariant velocity of light represents an actual behavior of the light itself. This observed characteristic forms the

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basis for Einstein's second postulate: "The velocity of light is constant from all inertial frames of reference and is independent of the motion of the source." We begin by modifying the second postulate to more precisely state: "The *observed* velocity of light is constant from all inertial frames of reference and is independent of the motion of the source." In order to understand the distinction, we must develop a model that obeys the modified second postulate (with the word *observed*), but violates the original. Our initial approach is to consider the case of an idealized rubber band.

At Rest In All Frames Of Reference

If you place a cup on a table, the cup will remain there, at rest, until some outside force, say a cat, moves it. Even if the table moves, the cup may remain at rest in its place on the table. The cup will appear stationary to you whether you are seated at the table, or running past the table in any direction. The reason is that you are using the room you are in as a point of reference for you and for the cup and table. When you move, you are aware of your motion with respect to the room, and your mind takes this into account in determining that the cup is not moving. Such accommodating reference frames cannot always be found. We have all had the experience of pulling into a parking space and coming to a complete stop, only to slam on our brakes as the movement of the car next to us caused us to think we were rolling forward. In this case our mind used the adjacent car as a stationary reference frame and judged our motion relative to it. When the stationary reference moved, which it was not supposed to do, we reacted.

Imagine sitting in a train, looking out a window at another train adjacent to you on a parallel track. Suddenly your train begins pulling away. If the motion is smooth enough, it is impossible for you to tell whether it is the other train moving or your own. All you know is that in your reference frame, the other train is moving. The speed you assign to the other train depends on the relative velocity between you and that train. Imagine another passenger on a third train on the other side of the one adjacent to you. That person will assign a different velocity to the middle train if its own velocity does not match yours. With no external reference frame we can only judge motion relative to ourselves. If the velocity of the third train is not equal to yours, it is practically impossible, except in error, for that passenger in the third train reference frame to assign the same velocity to the middle train as you assign in yours. This said, we now propose an experiment in which this assignment *is* possible. The experiment involves several passengers traveling at different speeds who will each assign a velocity of zero to an object outside their windows.

Suppose we take a piece of clear elastic, very resilient and pliable, and one foot in length. We fasten one end of this elastic to a pole, and stretch the other end to a distance of one thousand miles. While it is stretched to this length, we place a faint white line every foot from the pole to the thousand-mile point. The elastic then looks like that in figure 1-1. Once we have completed marking the elastic, we allow it to return to its original one-foot length, still anchored at point *O* on the pole.

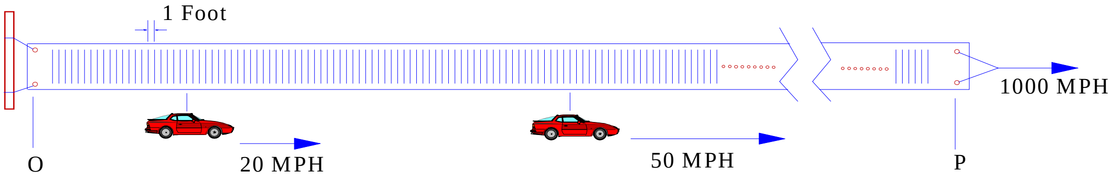

Figure 1-1 Each automobile will remain adjacent to a specific, mark on a piece of elastic stretching alongside them as long as they maintain a constant velocity

An important point about the way that an elastic material stretches is that any two points on the elastic always maintain the same relative separation. For example, if we place marks dividing the elastic into thirds, then as it is stretched these marks will continue to delineate three equal sections, as in figure 1-2. An implication of this is that each point on the elastic has a unique, unchanging speed as the elastic is being stretched. Thus if we pull the end of the elastic at three feet per second, the other marked sections will be traveling at one foot per second and two feet per second, respectively. These ratios of velocity and spatial separation hold for any combination of points on the elastic. In addition, for whatever speed the end of the elastic is moving forward, a unique point can be found somewhere on the elastic that is traveling at any speed we choose between zero and the speed of that end. In the example of figure 1-2, suppose one end is anchored while the free end is moving at three feet per second. If we wish to find a point traveling at two feet per second, that point will always be located at two-thirds of the distance from the anchored end to the moving end.

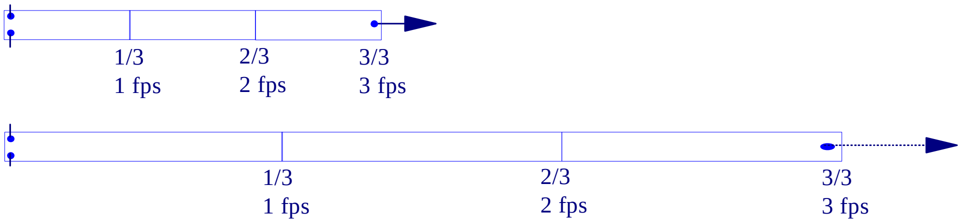

Figure 1-2 As a piece of elastic is stretched, all points maintain their same velocities and relative separations.

Referring again to figure 1-1, suppose we take the loose end of the marked elastic and begin pulling it forward at a velocity of one thousand miles per hour. At the same instant, two automobiles driven by Alice and Bob pass the starting pole, traveling in the same direction as the stretching elastic. Alice, in the first auto, is traveling at twenty miles per hour, while Bob, in the second, is traveling at fifty miles per hour. Further, each automobile is carrying a camera and pointing it directly at the elastic stretching alongside. We assume a very low light level, such that a long time exposure is required to obtain any detail in a photograph taken by either camera. Any object not exposing the same surface of the photographic plate for at least twenty minutes will not appear in the photograph. Thus any object that is in motion at even a very slow speed would, with sufficient light, appear only as a faint blur on the photographic plate. But, with the low light level we a using, any image moving with respect to the camera will not expose the plate long enough to be detected, and will not appear on the photographic plate at all. Each automobile begins a time lapsed photo thirty minutes after passing the starting pole, and allows the exposure to continue for thirty minutes.

After the experiment is complete and the photos are developed, Alice and Bob each have a photo containing one distinct white line and nothing else. The reason for this is as follows: Given an elastic with one end stationary and one end moving forward at one-thousand miles per hour, a unique point can be found on the elastic whose velocity corresponds to any given value between zero and one-thousand miles per hour. Further, an automobile traveling at twenty miles per hour and passing the pole at the same instant the elastic commences being stretched will remain adjacent to the very point on the elastic that is also traveling at twenty miles per hour for the duration of the trip. Since there is a white line on the elastic at this point, this line will appear to be stationary with respect to the camera in the car, and will therefore appear as a distinct white line on the photographic plate.

Since each of the marks on the elastic are separated by one foot when the elastic has attained its one-thousand mile length, their separation will be much less than one foot at the start of the test. Each auto turns on its camera exactly half way through the test and therefore when the elastic is stretched to five hundred miles. At this time, the separation of each of the marks is six inches. Over the time of the rest of the test, this separation of the marks will increase to one foot. The mark initially six inches in front of the line traveling at twenty miles per hour will be traveling slightly faster than the automobile. Over the duration of the test, this line will continually increase its separation until it is one foot in front of the twenty miles per hour mark. Having moved forward six inches with respect to the twenty miles per hour mark, it will therefore not expose any one point on the photographic plate long enough to produce an image. Likewise, the line initially six inches behind the twenty miles per hour mark will be traveling slightly slower than the automobile, and will also fail to expose any one point on the plate long enough to make an image. The same is true for all other lines in front of or behind the twenty miles per hour mark. Thus Alice's photographic plate will have only one white line corresponding to the twenty mile per hour mark, and no other images. This reasoning also holds for Bob's automobile traveling at fifty miles per hour, and considering the fifty miles per hour mark.

When the experiment is over, Alice will conclude that the event she photographed was the release of an object with a faint white line at rest from her frame of reference (traveling at twenty miles per hour). Bob will conclude the event was the release of an object with a faint white line at rest from his frame of reference (traveling at a velocity of fifty miles per hour). If the experiment is repeated with many automobiles, all traveling at different velocities, the drivers will, after a time, conclude that the event was the release of an object with a faint white line exhibiting the unique property of appearing to be at rest from all frames of reference. In reality, the event was the release of, for all intents and purposes, an infinite stream of faint white lines, traveling at all velocities from zero to one-thousand miles per hour. The problem is that, due to the nature of the observer, only that aspect of the event remaining at rest with respect to the observer can be detected.

The important point to remember in the above experiment is that the obvious conclusions to be drawn from a set of measurements are not necessarily an accurate description of the system itself. We may develop a model of a system based on a set of observations, and this model may work quite well at predicting future observations made of a similar system under similar circumstances. However, the model is not the system itself, and when future observations produce results inconsistent with the model we have developed, it is the model which must be modified or abandoned in favor of reality, not the other way around.

A Constant Velocity for All Frames of Reference

Suppose now we repeat the above experiment with the following changes. The light requires only one second to expose the plate. Each automobile is a train, fifty feet in length. The camera is propelled from the back of the train towards the front at a velocity of ten miles per hour (Alice and Bob's trains are still assumed to be traveling at velocities of twenty and fifty miles per hour, respectively). The plate is exposed for the first second of the camera's trip down the length of the train. Once again, everything the camera sees that is not stationary with respect to itself will be a blur on the photographic plate, too faint to be observed. This time, since the camera is moving at ten miles per hour with respect to the train, we have created a device that will record only objects that are moving at ten miles per hour with respect to the train. Thus, for a train moving at fifty miles per hour, an object must travel at fifty miles per hour plus ten miles per hour or sixty miles per hour in the same direction as the train in order to be recorded. In this manner, each train rider knows that the apparatus will record only objects that are traveling at ten miles per hour with respect to the velocity of the moving train. Clearly, from the above arguments, Alice will conclude the event produced a glowing object traveling at ten miles per hour as observed from her frame of reference (traveling at twenty miles per hour). Bob will conclude that the event produced a glowing object traveling at ten miles per hour with respect to his frame of reference (traveling at fifty miles per hour). If the experiment is repeated with many trains, the common conclusion will be that the event was the release of an object exhibiting the unique property of an invariant velocity of ten miles per hour for all frames of reference.

Next imagine that we replace the camera in the above examples with a device that can only detect motion at the speed of light, c, relative to itself. The fast moving end of the elastic will need to move forward at a speed not less than c plus the velocity of any potential observer. For the time being, let us agree with Einstein and state that no observer will be traveling faster than c. This being the case, the elastic must be pulled forward with a velocity of at least two times c in order for all possible experimenters to record the white-line phenomena. When the experiment is performed by many people, all traveling at different speeds, they will undoubtedly come to a common conclusion—the event appears to be the release of an object that travels at the speed of light, c, from all frames of reference.

Imagine the experiencing and photographing of elastic bands as described in the first two experiments to be a common occurrence. Then if the true nature of the elastic and markings were not known, physicists would be pressed to devise a theory for an object that remains at rest or is slowly moving when measured from all inertial frames of reference. This problem would be a little harder than the one Lorentz faced when developing his transformations, since in this case, for any observer at a given velocity, other observers can be found traveling both faster and slower than the object being observed. In Einstein's theory, nobody and no object was found to be traveling faster than c, and so the possibility of these objects could be, and was, omitted. Our last example with the elastic band produced an event—the recording of a single white line on a photographic plate—that appears to travel at the speed of light, c, from all reference frames. We have the advance insight of knowing exactly the true nature of the stretching elastic band, so we are not fooled into thinking that the "obvious" conclusion to be drawn from the evidence on our photographs is the correct one. However, if we had not known in advance the nature of our experimental setup, what appears to us now as a far-fetched conclusion would seem very plausible indeed.

As the next chapter will show, it is important to consider the context of Lorentz's work. Faced with the results of the Michelson-Morley experiment and with the incredible success of Maxwell's equations, Lorentz had to find a way to reconcile the two. The Lorentz transformations allowed the preservation of the form of Maxwell's equations in any inertial frame of reference (a frame traveling in a straight line with a constant velocity with respect to another frame) while still supporting the results of the Michelson-Morley experiment. This experiment had shown that the "medium" of light propagation (the aether) was not dragged along by the earth in its motion about the sun. The Lorentz transformations, developed as a means to reconcile the unexpected results of the Michelson-Morley tests, predict that lengths should contract and clocks should slow down for a reference frame in motion. These transformations imply an invariant c for all inertial frames of reference, because they were developed under the assumption of an invariant value for c. However, they do not force c to be invariant. In other words, the actual motion of light is not controlled by the equations Lorentz chose to model it, any more than a red light physically stops a car from crossing an intersection. Einstein used the Lorentz transformations to formulate his second postulate—that c is a constant independent of the motion of the source. The acceptability of this postulate was improved because the required Lorentz length contraction could apparently be interpreted to apply for all electromagnetic phenomenon. Since matter is electromagnetic in nature (composed of electrons, etc.), the supposed Lorentz contraction should apply to all matter. We will later demonstrate that the Lorentz length contraction is merely a result of the particular transformations chosen to preserve the form of Maxwell's equations, but is not a necessity for all allowable transformations of the same, nor does it represent an actual physical effect of motion.

The Radiation Continuum Model of Light

We shall find in what follows that the velocity of light in our theory plays the role, physically, of an infinitely great velocity.

Albert Einstein, 1905

In ancient or pre-scientific societies, light was considered predominantly as spiritual in nature. In the ninth century, the Islamic philosopher al-Kindi proposed that "everything in this world produces rays in its own manner...Everything that has actual existence in the world of the elements emits rays in every direction, which fill the whole world." From early time to the current day, the nature of light—spiritual, particle or ray—has been debated, with one idea prevailing for a time, only to fall to another. In 1611, Galileo wrote that when a substance was reduced to its most indivisible constituents, light would be created. Newton in *Optiks* returned to al-Kindi's rays as fundamental units of light in his first definition "By Rays of Light I understand its least Parts." Even so, he went on "Are not the rays of light very small bodies emitted from shining substance?" Newton had thus seized upon the idea of a dual particle-ray nature of light. Michael Faraday in 1846 returned to the ray theory, giving it more of a flavor of waves on a pond "The view I am so bold as to put forth considers, therefore, radiation as a high species of vibration in the lines of force." In 1864, after unifying electric and magnetic theory and developing the equations governing the waves of electromagnetic radiation, Maxwell concluded that "light is an electromagnetic disturbance propagating through the field according to electromagnetic laws." Arthur Compton demonstrated that light "photons" can be made to bounce off electrons in the same manner as billiard balls on a pool table. Current theory holds with Newton that light exhibits both wave-like and particle-like behavior, depending to some extent on the methods chosen to observe it. In fact, under quantum theory, it is precisely the means chosen to observe light that determines whether it is in that particular instance a wave or a particle.

At about the same time that Maxwell was deriving his equations, the observable speed of light was experimentally measured to be approximately 300,000 kilometers per second (km/sec). Since this velocity was shown to be the same from all inertial frames of reference, Lorentz and Einstein proposed that the dimensions of space and time are dependent upon the relative motion between the observer and the thing being observed or measured. With this theory we instantly run into the problem of developing a model and confusing it with the reality of the thing being modeled. Lorentz and Einstein had concluded from the available observations that the speed of light itself was exactly c in all frames of reference, without adequately considering the role of the observer in making the measurements.

In quantum theory, the observer is all-important. Any book one reads on the subject raises the issue as to whether anything exists on its own accord without the presence of a conscious observer to give it substance. This hardly seems like a question for physicists. As children we all came across the question "If a tree falls in the forest and no one hears or sees it, was it ever really there?" However, in trying to understand some of the perplexing implications of quantum theory, one is often left to ask questions such as this. As the chapter on quantum theory will demonstrate, this is not a shortcoming of the theory, but is instead a result of continually trying to reconcile quantum mechanics with the theory of relativity. And at that, it is mainly relativity's second postulate—the absolute constancy of the speed of light—that produces all the dilemmas.

The speed of light in a vacuum was determined by making physical measurements (observations) on light itself, and on the electric and magnetic properties of materials in the case of radio energy. The speed of light was not predicted from any application of first principles, nor has any analysis of the observed data yielded any explanation as to why the velocity should be strictly c instead of any other value. The role of the observer appears to be of utmost importance in the determination of *any* physical quantity in the realm of quantum theory. Clearly the only means by which the velocity of light has been specified is through the analysis of physical measurements, yet the velocity of light is stated as an absolute quantity, independent of any observer or any preferred frame of reference.

Based on the analysis of the previous sections, we are ready to propose what we will call the radiation continuum model (RCM) of light. In this model, light does not radiate from its source at a constant velocity of c. Rather it emanates in the same manner as a piece of elastic, anchored at the source, with one end pulled forward at a constant velocity C, with the upper case C denoting a velocity that is potentially much greater than c, and is very probably infinite. This being the case, there will be a component of the light that is traveling at any speed we pick in the range from zero to C. As important a characteristic of this model of light, and of living and electro-mechanical observers, is that only that component of light that is striking the observer at a relative velocity of c in the observer's frame of reference will be detected. Because of this, as in the case of the "device" described earlier that detects only motion at ten miles per hour in its frame of reference, we are left with the conclusion that the observed velocity of light is invariant for all inertial frames of reference. That is to say that regardless of our velocity, any light we perceive will appear to be striking us at approximately 300,000 kilometers per second (km/sec).

As an example, choose an event such as an instantaneous burst of light from a satellite at a fixed location in space. We choose a satellite so that we may speak of distances and motion relative to the satellite and distances and motion relative to the "event" as synonymous. When one tries to discuss motion relative to an instantaneous event, the concepts of "motion", "location", and "event" become blurred in a strict interpretation of the terms. If we choose one observer, not in motion relative to the satellite, that observer will detect that component of the burst of light that is traveling at the velocity c with respect to the source. Another observer, moving away from the satellite at a velocity of $0.2c$, will detect that component of the burst of light that is traveling at a velocity of c in that observer's frame of reference. From the satellite's frame of reference, this component of the light burst must leave at a velocity of $1.2c$. To illustrate this, imagine that you want to throw a football so it passes a receiver at ten miles per hour. If the receiver is running away from you at six miles per hour, the ball must leave your hands traveling at sixteen miles per hour in your frame of reference. To reach another receiver running at only three miles per hour, you would need to release the ball at only thirteen miles per hour in your frame of reference.

One of the more significant implications of the radiation continuum model of light is that it allows a more intuitive "Galilean" structure of space and time. By Galilean, we mean that the laws of electromagnetic radiation would conform to Galilean transformations, just as Newton's laws of motion do. Under such a transformation the concepts of space and time are absolute. This does not require that there is some preferred rest-frame against which all motion is measured. It simply means that agreements can be reached as to the simultaneous occurrence of distant events, and that transformations from one observer's point of view to that of an observer with a different velocity are straightforward and consistent with our everyday experience. For example, consider two rockets traveling toward each other, each at a velocity of $0.4c$. Following the tenets of special relativity and the Lorentz transformations, the two rockets would be approaching each other at a combined speed of only $0.7c$. Under a Galilean transformation the rockets will approach each other at $0.8c$, just as two cars speeding towards each other at fifty miles per hour each will collide at one-hundred miles per hour. The effect is the same as if one car were parked and the other hit it head on at one-hundred miles per hour. This is the transformation we use in our day to day experience. We are concerned only with the relative velocity between objects in physical measurements. The frame of reference of the observer is irrelevant to the outcome of the experiment and to the damage ultimately inflicted on each car.

Now, without specifying an upper limit on the speed of light C, we have developed a model of light as a rubber band anchored at its source and moving forward through space at all speeds from zero to C. There is no obvious reason to set a bound on C at any value short of infinity. In fact, we will show later on that the value of C is most likely infinite. One might argue that an upper limit of infinity on C would imply infinite energy. While this is strictly the case, it must be realized that only an observer moving away from the source with infinite velocity could detect this component, and this is a very unlikely scenario. Additionally, the frequency of the light at an infinite velocity would be shifted all the way to zero due to Doppler effects, and a zero-frequency signal contains zero, not infinite, energy. It will be shown later that the important consideration along each point on the light wave is the photon's momentum, which remains constant for all velocity components from zero to *C*. From here on in this book, the meaning of *c* shall be taken to be a speed of 300,000 km/sec, as measured with respect to a specific source or observer, and should not be considered synonymous with the phrase "the speed of light." Instead, light is henceforth considered to travel at all speeds from zero to some as yet undetermined upper value *C*, such that *C* is much greater than *c* and is less than or equal to infinity.

The illustration utilized earlier of the elastic band all bunched up at one point waiting to be stretched out can not be carried too far. One shouldn't think of a photon as being coiled up inside an electron waiting to get out. Rather, the photon is created at a point in time, according to a well behaved set of rules. The creation of this photon wave is simply (and loosely) conversion of "mass" energy into "photon" energy. Typically a photon is created when an electron in an atom drops from a high energy state to a lower one. A photon is also created during many processes of particle decay. In either case, the entire photon wave is created in an instant, in the same respect that the entire photon wave collapses in an instant, as described in the section on quantum effects. It must be noted that the photon thus produced shares many of the characteristics of the photon that was absorbed to send the electron to its higher energy state in the first place. This is what allows the well-observed group characteristics of light interaction with matter, such as angle of incidence equals angle of reflection.

Also a photon does not generally emit from a source in a straight line. It is often useful to think of a photon as emitting in a spherical volume from its source. Under special relativity, such an event produces an expanding spherical shell, with the radius increasing at a speed of *c*. Upon absorption of the photon by an observer, the entire spherical shell collapses in an instant. Under RCM, the photon energy expands in a spherical volume, with the outer edge of that volume expanding at *C*. As in special relativity, upon absorption by an observer, the entire spherical volume collapses in an instant. Special relativity envisions a spherical shell in place of a volume at the expense of Galilean concepts of the dimensions of space and time. RCM does not assume a unique velocity of light with respect to the source, and thus retains Galilean concepts of space and time.

The Invariance of the Speed of Light

The invariance of the speed of light was detected by Michelson and Morley (their experiment is discussed in detail later). What they discovered is that the speed of light appears to be the same whether the observer is moving toward the source, standing still, or moving away. Imagine trying to pass a truck that is moving twenty miles per hour faster than you. However, each time you speed up, the truck is still moving twenty miles per hour faster than you. If you slow down, stop or go into reverse, the truck is still moving twenty miles per hour faster than you. This is fairly easy to explain, as the truck you are following can simply adjust its speed to match yours. But what if your friend is in another car beside you and the truck is also moving twenty miles per hour faster than that car? Let us assume that you slow down while your friend speeds up. Now the truck will not be moving twenty miles per hour faster than both of you. It may be moving twenty miles per hour faster than you, but it will be moving less than twenty miles per hour faster than your friend is moving. It may even be moving slower than your friend. The speed of the truck is not invariant. It is dependent on the speed of the observer; in this case you or your friend, and you each observe a different velocity. Such is not the case with light. If the truck driver were to flash his brake lights at you and your friend, you would see the light pass you at a speed of *c*. Your friend would also see the light pass at a speed of *c*. Any theory of light has to support this unusual feature, as it was tested and confirmed by Michelson and Morley in 1887. As the previous example with the satellite showed, this is not a problem for RCM theory, though it posed all manner of problems for Maxwell and Lorentz with the assumption of a constant velocity of light. This experiment should not have posed any problem at all, except that Maxwell and Lorentz were both firm believers in the concept of the aether. The aether was postulated as a substance filling all of space that served as a carrier for electromagnetic waves. Even though in the special theory of relativity Einstein ultimately abandoned the aether concept, he retained many of the corrections to electromagnetic theory imposed by Lorentz and others in an effort to save the aether theory. We will discuss this historical path in detail later.

Despite the fact that the speed of light appears invariant under both RCM and relativity theory, there is a difference as to when and where observers in motion with respect to one another will actually see the light. In special relativity, two observers in motion with respect to each other will each observe an oncoming pulse of light at the same place *and* at the same time. It is this conclusion that causes problems in the analysis of the simultaneity of remote events, even though this simple concept has never been tested. This concept is a direct result of the second postulate—that the speed of light is a constant independent of the relative motion of the source and observer. Figure 1-3 illustrates a ray of light exhibiting the RCM property one second after its release from an explosion in space. The purpose is to illustrate when and where each of several observers will perceive the light under different conditions. We have three witnesses to the event. Alice is stationary with respect to the explosion's source. Bob is moving toward the source of the explosion with a velocity of .5*c*, while Carol is moving away from the source with a velocity of .5*c*. Consider first the case where all three observers see the flash at the same time. We wish to determine where they must each be located for this to occur. Alice, the stationary observer, is sensitive to that component of light leaving the source at a velocity of *c*. One second after the explosion this light will have traveled 300,000 km, and this then must be her distance from the explosion to see the flash at that time. Bob, moving toward the source at .5*c*, will see only that component of light traveling away from the event at .5*c* with respect to its source. The .5*c* velocity of this component added to Bob's .5*c* velocity will cause that component to have a relative velocity of *c* in Bob's reference frame. This component will travel 150,000 km in one second. Bob must therefore be this far away from the source one second after the explosion in order to see the light at the same time it is seen by Alice. Carol, moving away from the source at .5*c*, will see only that component of light traveling at 1.5*c* with respect to the source (moving toward her at a relative velocity of *c*). After one second this light will be 450,000 km from the location of the blast, and this must also be Carol's location at the time of interest.

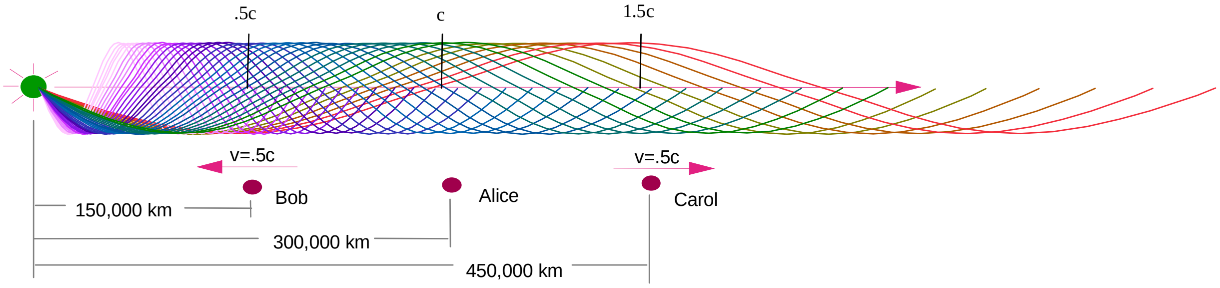

Figure 1-3 Observers in motion relative to each other will in general either be in different locations when they observe a distant event, and/or they will see it at different times.

Next consider the case where all three spectators see the explosion at the same location. We would like to know when each would see the flash. Let's assume we wish all three to see the event at Alice's location, 300,000 km from the source. We have already determined that Alice will see the light after one second. The light that Bob sees is traveling at .5*c*. It will take two seconds for this light to reach Alice's location. Therefore Bob would need to make sure that he goes flying past Alice exactly two seconds after the explosion in order to observe the light flash at that point in space. The light that Carol sees is moving much faster at 1.5*c*. It will take only two-thirds of a second for this light to reach Alice, and Carol must plan to be passing Alice two-thirds of a second after the explosion if she wishes to observe the flash where Alice is sitting. Thus each of the observers, Alice, Bob and Carol, can observe the same event, either at the same instant and at different locations, or at the same location but at distinctly different times. This marks the first major conceptual break with the special theory of relativity. This aspect may be the most testable difference, and it forms the basis of an experiment proposed in chapter eleven.

Why Is the Observed Speed of Light c?

One question that comes to mind in the radiation continuum model of light is: Why is it that we perceive only that component of light that is passing us at a relative velocity of *c*? The "we" in the question applies to humans, cameras, radios and even objects that will reflect light (although objects that reflect light themselves act as light sources, reflecting the component that strikes them at a relative velocity of *c* at all speeds from zero to *C*).

In order for light to be seen, it must interact physically with the eye, which in turn converts this interaction into electrical activity. Similarly, a radio wave, to be detected, must interact physically with an antenna to produce an electric current in it, which is in turn interpreted by the radio electronics to produce an audible sound. A physical object that is reflecting light must physically interact with the incoming signal in such a manner that some of the “photons” are repelled from the object, in the same manner as if the object were itself a source of light. Arthur Compton reported in 1923 of elastic collisions between “photons” of light and electrons, thus demonstrating that light does indeed interact on a physical level with matter to produce detection. In fact, photons are not actually reflected from a material. What occurs instead is that one photon is absorbed by an electron, which uses the photon’s energy to make a transition to a new energy level. That electron then releases the same amount of energy in the form of a new photon, as it relaxes to a lower energy state.

Electromagnetic theory involves the mathematical description and interdependence of the following four quantities or fields: the magnetic and electric flux density, B and D respectively, and the magnetic and electric field intensity, H and E respectively. Electromagnetic theory also defines the interaction of these fields with the physical world. James Clerk Maxwell published *Electricity and Magnetism* in 1873, in which he unified all known electromagnetic interactions through what are now known as Maxwell’s equations. Maxwell made predictions about electromagnetic wave motion, explained light in terms of electromagnetic waves, and calculated the speed of light. While all of this work is important, only a small part of it is the subject of this section.

When one takes the units of B, D, E and H in the ratio HE/BD, the resulting units are equivalent to velocity squared. The H/B term is considered the magnetic charge, while E/D is called the electric charge. While the dimensional analysis of the above ratio yields a velocity relationship to these quantities, this analysis alone does not specify a *value* for that velocity. Maxwell’s equations in and of themselves say nothing about the specific velocity of propagation of an electromagnetic wave, nor of the detectable velocity or range of velocities in any particular observer’s frame of reference. Maxwell knew this when he derived the equations, but the coincidental timing of early measurements on radio waves and the determination of the velocity of light encouraged the conclusion that the velocity implied by the equations and the velocities as measured were one in the same. In the physical world of which we are a part, we can use physical devices and measuring apparatus to determine numerical values of the above four quantities in various physical settings. When the results of the values obtained from measurements of the physical interaction of electric charges with the experimental devices are combined in the above ratio, the result is always the same—the velocity implied by the measurements is 300,000 km/sec, or *c*.

This conclusion that the speed of all electromagnetic propagation, including light, in free space, is *c* appeared acceptable to everyone at the turn of the nineteenth century, but one nagging question remained. In what frame of reference is the speed of light *c*? A train moving at eighty miles per hour in reference to the ground is only moving at sixty miles per hour in reference to another train coming from behind at twenty miles per hour. In this example, the Earth is considered stationary for all practical purposes, and is the preferred reference frame. When determining the muzzle velocity of a rifle, we are concerned only that a bullet leaves the rifle at one hundred miles per hour with respect to the rifle. The fact that a rifle moving at one hundred miles per hour can launch a projectile at two hundred miles per hour with respect to the Earth is not important, thus, in this example, the source of the projectile’s motion is the preferred reference frame. What, then, could be the preferred reference frame for this velocity, *c*, of light?

As mentioned above, early theorists suggested a background “aether” in which sat and through which moved all objects in the universe. This undetectable aether was presumed to be the benchmark on which the speed of light was based. Thus, to a moving observer, the perceived velocity of light would be greater than or less than *c*, depending on the observer’s velocity with respect to the aether, as with the slower moving train’s velocity with respect to the Earth as described above. Since velocities of all things on Earth are slow compared to the speed of light, and given the limited capabilities of measurement at the time, this relative change due to motion could not be easily detected. However, the Michelson-Morley experiment, described more fully in another section, tested the possibility of Earth’s motion through an aether background using interferometers. This test, performed over several seasons and equipment orientations, (along with several other experiments that eliminated the possibility of the Earth “dragging” a part of the aether with it as it moved) proved conclusively that there was no aether to use as a benchmark for light velocity measurements. The speed of light appeared to be *c* irrespective of the relative velocity of the source and observer. Other theories suggested that it was the velocity of the source that determined the velocity of light, the most notable of these put forth by the Swiss physicist Walter Ritz in the 1908. But studies of remote stars and galaxies and the odd disturbances that this concept would produce indicated that this was likely not the case.

Apparently the speed of light was *c* for all observers, no matter what their relative velocities, and no matter what the velocity of the source.

In the face of this experimental evidence for the invariance of the speed of light, a model had to be developed that allowed this to be possible. Beginning with the Lorentz transformation and ending with the theory of relativity, an interesting mathematical model was developed that allowed light to maintain this one, very confusing characteristic. Unfortunately, the whole structure of the universe had to change to accommodate this. Clocks in motion slowed down and rulers in motion shortened. The mass of a moving object increased without limit as its speed increased. And as objects approached each other at greater and greater speeds their combined velocities increased more slowly until, at a great enough speed (each at *c*), their combined velocities (measured with respect to the whole system) would still be only *c*, not 2*c* as one would intuitively suspect. Consider, for example, the case of two objects approaching each other, each with a velocity as viewed from a common rest frame of 0.9*c*. Their combined velocity under special relativity would be only .99*c*, not 1.8*c* as our common experience would indicate. It is interesting to note that if each of the two velocities exceeded *c*, then the resultant velocity under the relativistic transformation would become smaller and smaller as the component velocities increased. Of course Einstein's theory prohibits any object traveling faster than *c* so this event can not occur.

All of the analysis performed by Lorentz missed an important point, alluded to earlier. Maxwell's equations do not insist on a specific velocity of propagation. They also certainly do not insist on a velocity that is independent of the frame of reference of the observer. It is the experimental means by which we measure or observe the speed of light or the ratio of H, E, B and D that results in a frame invariant velocity of *c*. The distinction here is critically important. As in the case of the expanding elastic in the previous sections, the equations of motion of the elastic had little or nothing to do with the results achieved by processing the film of the moving observers. The observers came away with an experimentally verified test of an object that was at rest or moving slowly from all frames of reference. While their observations demonstrated this, the elastic itself did not actually exhibit the properties recorded. The experimenters developed a model that explained their results, but that did not reflect the reality of the situation.

The principle of equivalence tells us that if we are in a uniformly moving reference frame, then any experiment performed in that frame should produce the same results as if performed in a "stationary" frame. Clearly, therefore, the ratio of Maxwell's four quantities in the manner above will result in a measured "velocity" of *c* in any uniformly moving frame of reference. Thus each of several observers in reference frames moving at different uniform velocities will each measure or observe the velocity of light from a distant source to be traveling through their apparatus at a velocity of *c*. As far as the speed of light is concerned, this restriction on uniformly moving frames of reference can and will be lifted as well. Clearly in relativity theory the restriction is not required, as the speed of light is absolutely invariant. In the RCM as well, the restriction is not required, as the observer simply becomes sensitive to higher and higher velocity components with acceleration away from the source. In both relativity theory and RCM, the Doppler effect (a change in frequency or detected energy due to a change in velocity) will play a role in either an accelerating or uniformly moving frame of reference.

From the above reasoning, it makes sense to state that the *observed* velocity of all electromagnetic propagation, in free space, is *c*. Thus two observers in motion relative to each other at any velocity will each see a beam of light passing them at the velocity of *c*. Since it is the same beam of light, that beam of light must have components of velocity (with respect to the source) of *c* plus the first observer's velocity (with respect to the source), and of *c* plus the second observer's velocity (with respect to the source). Since the source has no idea who its observers are, nor of their velocities, it must produce light in a radiation continuum, at all velocities from zero to *C*. In this manner, there is a component of that light which will pass any observer, moving at any velocity, at a relative velocity of *c* in the observer's frame of reference. This is the speed at which electromagnetic radiation is capable of interacting with the physical world, as demonstrated by laboratory measurements of light and the four electromagnetic properties of Maxwell. Any component of light not at this velocity relative to the observer cannot produce any physical interaction, and is therefore undetectable by any physical observer. Stated more concisely:

> Electromagnetic radiation propagates at all velocities from zero to some undetermined upper value *C*. As demonstrated by laboratory measurements, only that component of this radiation that passes a physical observer at a relative velocity of *c* in the observer's frame of reference can produce any physical interaction and hence be detected. All other velocity components of this radiation are undetectable by that observer, or by any other electro-mechanical device that is stationary in that frame of reference. Any observer in motion relative to the first observer will, in general, detect a

> different component of the radiation, that component being the one that has a relative velocity of *c* in its frame of reference.

Since light travels at all velocities from zero to *C*, no matter what our speed relative to the source, there is always a component of the radiation continuum that is passing us at a relative velocity of c. It is this component that is thus able to cause the physical interactions necessary to be detected. The end result is the appearance of light having the invariant speed of *c* from all frames of reference. It is interesting and comforting to note that the experimentally determined values of the fields in Maxwell's equations predict that our observed speed of light is equal to the square root of the proportionality constant between mass and energy as derived by Einstein (denoted by c^2). Of course this famous equation, $E = mc^2$, is not necessarily a consequence of relativity theory, but derives naturally from Max Planck's observations of light emissions from a heated object, as chapter eight will show. However, given this important relation, we can gain additional insight as to why it is that we perceive light only at the velocity indicated by the c^2 quantity. Since the conversion of radiant energy to mass energy can occur only if the ratio of the two is given by c^2, it would seem obvious that *c* is somehow related to the velocity at which matter can absorb or release energy in its own frame of reference. The simplest relation is that light must interact with matter at a relative velocity of *c* in order to be detected. The same holds true for all electromagnetic energy and for gravitational effects as well. Before we close this chapter, however, we must explore briefly how the relaxed second postulate of RCM theory resolves the confusion caused by Maxwell's equations when light was assumed to have a constant velocity of *c* independent of motion with respect to the source.

The Galilean Invariance of Maxwell's Equations

The key factor in the radiation continuum model of light is the relaxation of the constraints of Einstein's second postulate. This postulate states: "The velocity of light is constant for all inertial frames of reference, and is independent of the motion of the source." The principle of equivalence tells us that the laws of physics should remain invariant under any transformation of frame of reference. For example, if we drop a ball while standing still, it will fall straight to the floor. If we are on a train moving at a constant velocity of fifty miles per hour, and drop a ball, it will again fall straight to the floor. There is no experiment we could perform wholly inside the train, without looking out the windows for example, that would make us aware of our motion at a constant velocity. We can transform the results of our experiment to the reference frame of an observer on the bank. That observer will tell us that the ball dropped vertically at the proper speed according to the laws of gravity, but also continued moving forward at fifty miles per hour with the train—precisely the velocity it had before we dropped it. This type of linear transformation of physical laws is referred to as a Galilean transformation, and it is the type of transformation we are used to dealing with and make every day without thinking about it. If we are in a car going sixty miles per hour and we are approaching a car going only forty miles per hour, we instinctively make the Galilean transformation of velocity. This transformation implies that, in our frame of reference, the other car is effectively approaching us at twenty miles per hour. In this case we hit the brakes so that the other car does not effectively run into us. If one assumes the truth of the second postulate as stated, and also wishes to preserve the truth and reference frame invariance of Maxwell's equations, then one must adopt the Lorentz transformations, in which lengths contract in the direction of motion and time slows down for the moving object. If one attempts to use Galilean transformations and also adopt the Einstein's second postulate, it will not be possible to conserve the invariance of Maxwell's equations. The radiation continuum model simply adds one word to Einstein's second postulate as follows: "The *observed* velocity of light is constant for all inertial frames of reference, and is independent of the motion of the source." Through the use of the modified second postulate, making the observed velocity of light dependent on the observer, and adopting the radiation continuum model of light, it is a simple matter to show Galilean invariance of Maxwell's equations.

In order to illustrate the difference between Galilean and Lorentzian transformations, imagine travelers in two sets of reference frames. One of these frames, K, is stationary with respect to the source of a burst of light, while the second, K', is moving along the X axis to the left at some fixed velocity. We place each observer at the origin of its own frame of reference. This situation is depicted in figure 1-4.

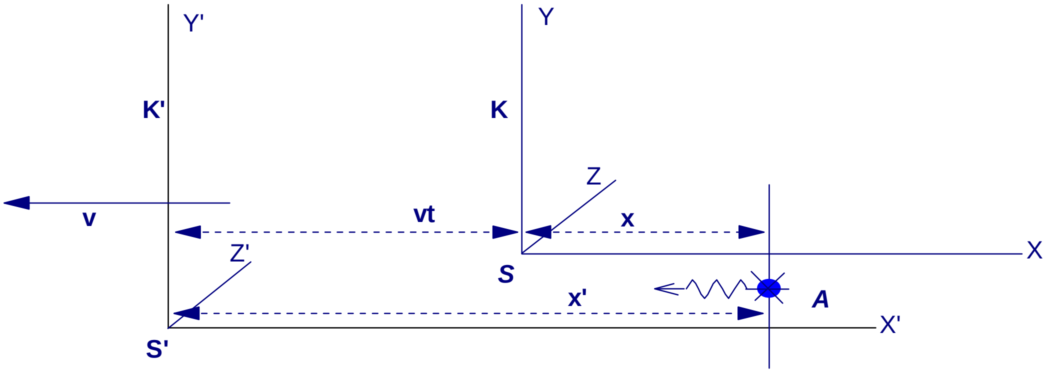

Figure 1-4 An example of two reference frames in motion with respect to each other along the x axis under a Galilean transformation

In the radiation continuum model, where light takes on all velocities from zero to *C*, the component of light as seen by an observer in any particular frame of reference has a relative velocity of *c* in that frame. Therefore, the component traveling at *c* in the moving system will have a velocity in the non-moving system of *c* plus the moving system's velocity. In figure 1-4, consider the source of a flash of light, which is some distance from the origin of the stationary system. If at the time of the flash the two systems had their origins together, and the moving system has been traveling for a given amount of time, its origin will now be at a distance equal to its velocity times this time beyond the origin of the stationary system. The distance to the source as measured in the moving system is thus equal to the distance measured in the non-moving system plus the distance covered by the moving system itself. This is the only shift required in a Galilean transformation. Without going into its derivation, we will simply state that under a Lorentzian transformation we must slow down time and shorten lengths along the axis of motion. The formulas contracting length and slowing time are related to the square of the velocity of the moving system, and, of course, to the fixed velocity of light. In the Galilean transformation, time is absolute, and there is no transformation required in this coordinate. Thus the time as measured in the moving system is the same as the time measured in the stationary system.

We have expressed the distance to the source of the flash from the origin of the moving system in terms of the distance in the stationary system and the velocity and time of motion of the moving system. This is similar to saying that in order to measure the distance from 42nd street to 49th street, you would have to know how far down Broadway a person had walked, or what time of day the measurement was made. It would be helpful if we didn't require the elapsed time to determine a value for this measurement in the moving frame. The two quantities, time and distance, should be independent. Now, in order to express the distance in the moving system in terms of measurements made in the stationary system using a Galilean transformation, consider a light signal traveling in both frames, which initially have their origins coincident, as before. We know that the moving system sees light leaving the source at a speed of *c* plus its own velocity. If we imagine two cars that leave from the same point and travel for one hour, one car at twenty miles per hour, the other at fifty miles per hour, the faster auto will have gone fifty miles while the slower will have gone only twenty. We can express the faster auto's distance as equal to the slower auto's distance times the ratio of the velocity of the faster auto to that of the slower one. This relation will obviously hold no matter how long or for what distance the autos travel. Thus if we have two components of light, we can also state that the distance traveled by the faster component in the moving system will be equal to the distance traveled by the slower component in the stationary system times the ratio of the respective component light velocities in each frame of reference. This is of course a much simpler transformation than the one proposed by Lorentz, and it is exactly the transformation we would normally use in, say, determining the distance traveled by a ball thrown on a train as measured by someone standing on the bank. It is a simple matter to show that the form of Maxwell's equations remains invariant under the Galilean transformations above when one replaces the velocity of light in the moving system with c plus the velocity of that system. This is done explicitly in Appendix A.

The importance of the imposition of the modified light principle of RCM over the light principle of relativity theory cannot be over stressed. Lorentz was faced with the results of the Michelson-Morley interferometer experiments that were designed to test the velocity of the earth through the aether. Michelson and Morley expected to obtain different velocities of light for various orientations of their light beams, depending on whether the light was traveling parallel to or orthogonal to the motion of the earth and the aether locally. What they found instead was no variation. The velocity c was a constant, independent of the observer’s motion relative to the supposed aether. Lorentz was simply trying to obtain a method for achieving a Galilean frame invariance of Maxwell’s equations given the result that c took on a constant value in all inertial frames of reference. He discovered that by scaling the quantities of length and time in the moving system by his squared velocity relations, the desired invariance was achieved. He was not initially interested in the physical significance, if any, of these transformations, and thought of them instead as a mathematical nicety. Einstein developed the actual second postulate addressed above later, partially as a result of Lorentz’s treatment of Maxwell’s equations. Clearly, if the constraint of a constant c that is not frame dependent is relaxed, then the Lorentz treatment is not required. Einstein’s special relativity has a fixed velocity of light combined with a continuum of different standards of length and time. RCM has fixed standards of length and time with a continuum of light speeds as measured with respect to the source only. A look at the sequence of events and discoveries leading up to the idea of a fixed speed of light will aid in the understanding as to why this apparently needless restriction was imposed. This is the subject of the next two chapters.