THE EFFECT OF MOTION ON CLOCKS, MATTER AND TIME

THE EFFECT OF MOTION ON ATOMIC CLOCKS

We have seen throughout this book that for observers in motion relative to each other, time does not slow down (or dilate as the term used in special relativity). In the previous chapter on the effect of motion on light clocks, we considered a clock which used light pulses reflected between two mirrors to mark the passage of time. But what happens to real clocks such as atomic frequency standards? Several experiments have been performed which confirm that these clocks do indeed slow down, and by the same amount predicted by special relativity. This is considered a great test success for relativity, but it is actually easily explained by the radiation continuum theory.

Einstein probably never imagined that we would one day have clocks sensitive enough to measure time dilation effects for velocities much less than the speed of light, say the speed of commercial aircraft. But such is now the case. In the twentieth century, we have developed clocks which are accurate to within one second in millions of years. What this actually means is that they are stable to within billionths of a second per second. It is this accuracy which makes tests of the so-called relativistic time-dilation possible. One of these timepieces is known as a cesium clock. This clock basically uses the fact that a certain frequency of energy applied to a cesium atom will cause it to enter an excited state. The input frequency is tuned by constantly striving for the highest quantity of atoms in a beam of cesium atoms being elevated to the excited state. This is accomplished, as in figure 6-1, by passing a beam of cesium atoms horizontally through a cavity of microwave energy, which is constantly tuned to the frequency which the beam of atoms needs to see. If the quantity of excited atoms drops, the microwave frequency is altered until the number of excited atoms is again at its peak. This tuned frequency then becomes the mechanism for keeping time in the clock. Since frequency is cycles per second, then time is seconds per cycle, and counting cycles is equivalent to counting time. If the cesium atoms were stationary, they would require a certain frequency to enter the excited state. However, in a cesium clock, we are dealing with a moving beam of atoms, moving left to right in figure 6-1 at some well defined velocity. As the atoms move through the microwave cavity, this motion causes them to require a Doppler shifted frequency to become excited, the shift in frequency being proportional to their velocity. For this reason, the velocity of the cesium beam is well controlled, and the actual frequency of the clock is tuned to the required frequency for this motion, which is actually slightly lower than it would be for stationary atoms.

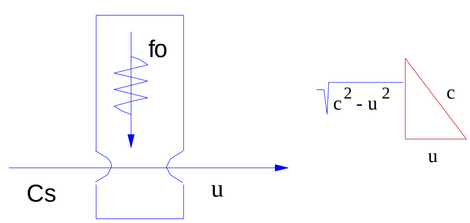

Figure 6-1 *Because of the aberration effect, an atomic clock using a moving beam of cesium atoms must be tuned slightly lower than the characteristic frequency of that atom.*

To obtain a clear image of the tuning of this clock, imagine the microwave frequency as moving top to bottom as shown in figure 6-1. In chapter four we indicated that there is a difference in Doppler effects from light which is *actually* perpendicularly incident, and that which *appears* perpendicularly incident to the observer. In the case of the cesium clock, we are dealing with the former effect, where the beam of cesium atoms becomes the observer. Due to aberration, the cesium atoms experience radio energy striking them at an angle related by the Pythagorean theorem to the velocity of the atoms and the initial component velocity of light. Since, from the figure, this initial component velocity is less than c, the resulting frequency which the cesium atoms see is higher than the frequency of the source. By carefully controlling the velocity of the cesium atoms through the microwave cavity, it can be calculated what the frequency is that they require, and this becomes the time unit of the clock. Since the atoms receive a higher frequency than that emitted by the source, the actual time tuning frequency emitted from the source must be set lower than it would be if the cesium atoms were stationary. This lower initial frequency, after being shifted higher by the aberration effect, becomes the proper tuning frequency for the cesium atom. If we set the velocity of the moving beam of atoms to higher and higher values, the frequency of our tuning source must be set to correspondingly lower and lower values.

From the above, we see the first impact of motion on the "local time" of a moving observer. The cesium atoms, when in motion relative to the stationary frame of the microwave cavity, require a lower frequency to enter an excited state than would a stationary atom in the same cavity. These moving atoms, in their own inertial frame of reference, are susceptible to the same frequency as would be a stationary atom. However, since the clock is generating a lower frequency to excite the atoms, it appears that "time has slowed sown" for the moving cesium beam. Once again, it is clear that time has not been affected in any manner, but the Doppler effect has changed the required frequency for the moving atoms.

In order to fully develop the effects of motion on an atomic clock, we will consider the case of moving atoms and frames of reference a little further. Imagine two cesium atoms, side by side in space, with one of the atoms soon to be placed in motion to the right at some fixed velocity. We desire to know the proper frequency required to cause each of these atoms to enter an excited state. We know that a given atom at rest requires a frequency of about 9 GHz (9 x 10^9 cycles per second) in order to enter this state. This corresponds to an energy level equal to Planck's constant times this frequency. Now, if we allow one of the cesium atoms to acquire a fixed velocity, we will effectively have already supplied an amount of energy equal to the kinetic energy of the moving atom. This acquired kinetic energy is equal to one-half the mass of the atom times its velocity squared. We would thus expect that we need supply less additional energy to cause this atom to enter an excited state, and it is fairly easy to determine the value of this reduction in required energy.

In our reference frame, we can express the total energy of the moving atom as the sum of its rest energy and its kinetic energy. To transform this energy to the reference frame of the moving atom, its rest frame, where it has no kinetic energy, we simply subtract the kinetic energy term from the energy we see in our frame. This is a Galilean transformation, of the type we have seen before in the treatment of Maxwell's equations, and not a Lorentzian transformation such as we see in the special theory of relativity. Since any mass quantity and its associated kinetic energy would transform proportionally, we can derive an energy conversion formula by taking the ratio of the energy in the moving atom's reference frame to the energy measured in our reference frame. We know that this conversion takes the form of a proportionality constant due to the principle of equivalence. If such were not the case, then different energies would transform differently, and the moving atom could become aware of its constant velocity by measuring the differing degrees to which energy levels of some items change compared to their rest energies. A little algebra reveals that this proportionality ratio is equal to one minus one-half the velocity of the atom squared divided by c^2. Therefore, the energy required to cause this atom which has been placed in motion to enter an excited state is reduced by the same ratio.

Thus we see that an atom which has been placed in motion is susceptible to a lower frequency than an atom which remains stationary for any initial rest frame of reference we choose. Note that the stationary atom does not need to be actually present. Further, the actual nature of the presumed rest frame is not important. In other words, we do not need to presume the existence of any preferred, absolutely and universally stationary frame of reference. The energy required by any cesium atom which has been accelerated out of our reference frame and is now moving uniformly with respect to our own will be less than that required by an atom which remains stationary in our reference frame, as measured in our reference frame. What we must be careful to do then, when building and testing actual atomic clocks, which must be calibrated and synchronized, is to make certain that they are all calibrated and synchronized in the same reference frame prior to starting the test. This reference frame will then become the common rest frame for all clocks in any experiment we wish to perform. It does not matter if this reference frame is experiencing motion relative to any other reference frame we may wish to consider. It may even be that this reference frame is in motion relative to the frame in which we, the experimenters, reside. All that is important is that all clocks are synchronized in the reference frame defined as their common reference frame. As we shall see shortly, if we do not invoke this requirement, it becomes impossible to determine which clock has slowed.

Note that in determining the degree to which the moving clock slows we did not need to consider the direction of motion. This slowing was based only on the relative velocity of the clocks. Thus we have shown that, as measured from the reference frame of the stationary clock, the moving cesium clock requires a different frequency than the stationary clock by the same factor, no matter which direction the clock is moving. This factor is normally denoted by one over gamma, or γ^{-1}. It is extremely important to realize that time does not actually slow down due to this motion. Since cesium atoms of a given velocity require a specific frequency to reach the excited state, so atoms

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accelerated to a different velocity relative to the first require a different frequency, as measured in the reference frame of the first, shifted to the red according to the magnitude of the velocity by the factor γ^{-1}. Since the frequency is lower, it takes more time for a fixed number of cycles to occur. With seconds in these clocks being defined as the length of time required for a specific number of cycles to occur, the moving clock slows down--more physical time is required for a given "second" to pass in the moving clock.

The effect of this motion is real in that a device on the moving clock counting "ticks" of frequency will count less ticks in a given amount of "time" (defined by the stationary clock-- "proper" time) than will the stationary clock. It does not matter whether the tick accumulator for the moving clock is on that clock or remotely located with the stationary clock, as it is simply a counter. Counters count integer occurrences independent of the motion involved, except for the practical problems noted in the next paragraph. The continuum of the speed of light does not affect the operation of a mere counter. What changes due to the motion is the frequency required by the moving cesium atom, and the counter on that clock will count less ticks, each tick being defined as one cycle of frequency.

There are practical effects which must be considered if the tick counter for the moving clock were to be placed at the location of the stationary clock. If the moving clock is keeping time by generating a specific frequency, then we could notify the stationary clock of the time (number of ticks) by simply transmitting the frequency to the stationary clock. The problem here is that we must account for the motion induced Doppler shift caused by motion at an arbitrary angle of incidence as described in chapter four. Thus the received frequency has two sources of distortion. The first component is the Doppler frequency shift due to the motion of the source (moving clock) at an arbitrary angle of incidence. The second is the actual slowing of the clock in motion as described above, the so-called relativistic time-dilation effect. If the first effect is calculated and removed, we will be left with the actual rate of slowing of the moving clock, and we can therefore count the "slowed ticks" of that clock. As an example, we could use a radio signal to transmit the sound of a bell from the moving clock to the stationary clock at the end of every minute as timed by the moving clock. Since the transmitter, or moving clock, is moving away from the receiver, we would have to tune our receiver to a lower frequency to overcome the motion induced Doppler shift and pick up the signal. Once we locked on to the signal, we would find that the sound of the bell occurs at intervals greater than one minute. This is because the moving clock is running slow compared to the stationary clock, and therefore takes longer than one minute by our clock to record what is an elapsed time of one minute on its own clock. Note that we have determined which is the moving clock by our choice of the way in which we accounted for the motion induced Doppler shift. We have subtracted out the Doppler shift in such a way as to place everything in our frame of reference, sitting with the stationary clock. The importance of this point will become more clear in the next section in which we discern the methodology for determining which is the clock in motion, and therefore which clock should be expected to run more slowly.

It is obvious from the analysis above that time itself has not slowed down, but that the moving clock runs more slowly due to its being placed in motion. The reason the clock slows down is due only to the principle of conservation of energy and the principle of equivalence. If we were to perform the clock experiment using a mechanical pocket watch, the so called time dilation effects may not occur. There are practical problems associated with this. First, the limited accuracy of pocket watches would require very large velocities in order to obtain observable results. Secondly, at such high velocities, the full physics behind the mechanical nature of clock springs (which are made up of electromechanically interacting atoms and electrons) would have to be considered. It may well be that the interaction of the atoms would be affected in a similar manner as the microwave energy and cesium atoms above, and the spring coefficients would change such that the effect on the watch would indeed be one which would slow it down by the factor γ^{-1}. Recall that in the example using light clocks in chapter five, no slowing of the clock occurred. This is primarily because the light clock had no frequency dependence on the light which was keeping the time. Such a clock could be built, physically, by using a photo-detector such as a charge coupled device (CCD) used in video cameras, in place of the bottom mirror. Each light pulse which reflected off the top mirror and struck the photo-detector would cause the clock to emit another light pulse toward the top mirror. The clock would keep count of each pulse striking the photo-detector, and time would be measured as number of pulses. If the round trip time from the source to the mirror to the photo-detector was set at one microsecond (10^{-6} seconds), then each click of the detector would indicate the passage of one microsecond as well. Presumably, time as measured with such a clock could be the same whether the clock was set in motion or remained at rest, absent an analysis of the complete physics of all the electronics and devices in the clock.

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ESTABLISHING THE REFERENCE FRAME FOR DETERMINING CLOCK MOTION

The determination as to which clock should slow down in a system of moving clocks depends on the choice of the observer as to which clock is the stationary one. If this were not the case, then, in any system of two clocks, each would assume itself stationary and insist that the other must be running slowly. If both clocks ran slowly there would be no disagreement as to the elapsed time in any experiment, and the idea of clocks in motion running slowly would be meaningless and untestable. Any scheme to relate the time of one clock to that of another requires defining which clock is stationary. The assumptions used to transform the velocity of the "moving" clock to the reference frame of the "stationary" clock will then lead directly to the result regarding which clock has slowed. We will first look at the situation where all clocks are constructed and calibrated in the same reference frame, and later study the results if the clocks are constructed or calibrated in different reference frames.

Consider the case depicted in frame A of figure 6-2. In this figure, Alice has a long rod connecting an electronic sensor to her clock. The sensor will send a signal to her clock as soon as Bob crosses the sensor. The length of the rod is fixed, and Alice knows exactly how long it will take a pulse to travel from the sensor to her clock. If Alice waits for a signal from the sensor before she starts marking time, she will be able to accurately mark the time it takes Bob to travel from the sensor to her location, this time being the elapsed time since receiving the signal plus the time it took the signal to travel the length of the arm. Bob begins marking time as soon as he crosses the sensor, and is therefore able to accurately time his trip from the sensor to Alice's location on his own clock.

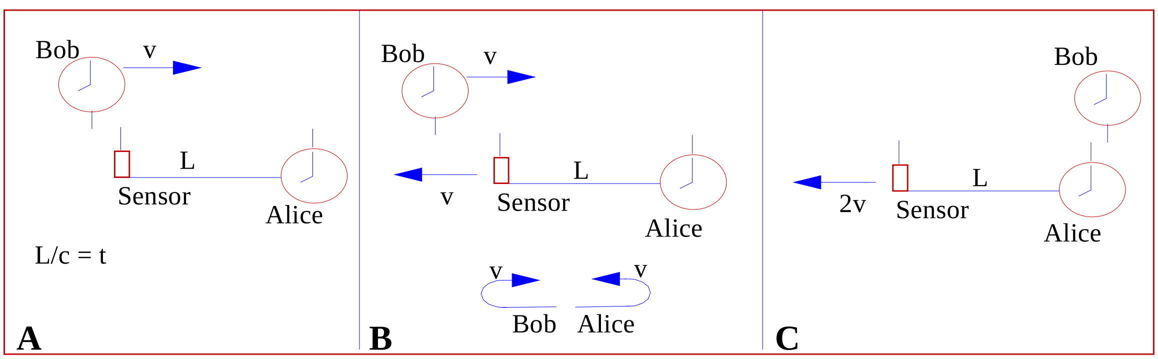

Figure 6-2 Depending on the decision as to which clock is stationary, the moving clock can always be determined to have slowed.

If both clocks are constructed in the same place and synchronized, then set in motion in equal and opposite paths as shown in frame B, each clock will experience equal slowing with respect to their mutual rest frame. Alice and Bob will each reach the same final velocity as measured on their own respective clocks. Each will also see the other moving past at twice this velocity, just as two cars, each at twenty miles per hour, will pass each other at forty miles per hour. The reason that the two clocks are in such good agreement is that they have each experienced the acceleration required to attain their current velocities, and each therefore agrees that their velocity is the same with respect to their common point of construction, or their common rest frame. If each clock records the elapsed time of the test on a piece of paper, and then each clock is decelerated to return to their common point of origin, the clocks will be synchronous, and the time each recorded for the test will be the same.

In the above, each observer was aware of its own velocity. Suppose, though, that neither is capable of determining its velocity, and therefore each assumes itself to be stationary. In frame C, we view the same test as in frame B, except that Bob claims himself to be stationary, and declares his clock's measured time to be the "stationary" or "proper" time of the test. Furthermore, since Alice is then moving at twice the velocity indicated in the previous example, Bob concludes that Alice should measure a shorter test time on her slower running clock. Since Alice actually records the same test time as Bob, he concludes that at the start of the test Alice's clock must have been running fast. Her clock was also running fast by just the right amount that after slowing due to its motion it recorded the same test time as Bob. From Bob's perspective, the way to verify this is to reverse Alice's motion

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such that she becomes stationary with respect to Bob and the two clocks are in the same reference frame. Since Alice considers herself to be at rest, she agrees with Bob that this new motion will cause her clock to slow from its current time unit by the appropriate factor. When this test is performed, and Alice is in Bob's reference frame, moving in the same direction at the same velocity, we find that the two clocks are in synchronicity. However, since Alice's clock has slowed due to going from "rest" to this new speed, it must have originally been running fast, such that the slowing due to this motion exactly offsets the initial excess rate of the clock, and it now runs synchronous to Bob's clock. This is exactly as Bob said it should be.

But we know the two clocks were constructed initially at rest and keeping the same time. So what actually happened? Alice's and Bob's clocks were initially synchronous. As we saw in frame B, each was placed in motion at the same speed such that each clock slowed identically. Bob's clock maintains this slower time for the entire test. In reversing Alice's direction, however, her clock is first decelerated to its original time unit, where it is now in the rest frame in which it began its journey, and is therefore marking "proper" time. Next her clock is accelerated to the same test speed in the direction of Bob's motion, where it again is slowed by the same amount, and the two clocks again agree. The fact that Bob claims not to have slowed at all is simply due to the decision to place all measurements of time in his frame of reference. Note that no "absolutely stationary" frame of reference has to exist to accommodate these changes in velocity and clock rates.

In the above example, where Bob assumed himself to be stationary, we could just as easily have said that Alice assumed herself to be stationary. Hence, either observer can make the claim that the other was moving. It is the choice of the way in which they account for the induced motion which allows them to deduce that the other clock was the one in motion, is the one which had slowed, and was therefore initially calibrated to run fast.

The following points apply to all clocks based on the principals discussed in these sections on the effect of motion on clocks (remember that it was shown with the pocket watch that perhaps all possible clocks behave in this manner):

1. Identical clocks constructed in the same manner which are stationary with respect to each other will keep the same time.

2. If two identical clocks are set in motion such that the magnitude of velocity with respect to their rest frame is identical, though the direction may be arbitrary, then each will experience the same slowing due to their velocity relative to the rest frame, and each will therefore keep the same time.

3. If each of the two clocks above is returned to its rest frame, the two clocks will still mark the same time.

4. If one of the moving clocks declares its frame to be the rest frame, ignoring the acceleration it has undergone, it will conclude that the other clock is calibrated to run initially fast by a factor that allows it to measure the same elapsed time in its frame after slowing as the so-called "stationary" clock does in its frame.

5. If the "moving" clock of point 4 is then brought into the "rest frame" of the "stationary" clock, the two clocks will be synchronous. Since the "moving" clock will obviously have experienced acceleration to do this, the "stationary" clock will take this as proof that initially the "moving" clock was indeed running fast.

Effect number five above is actually a result of first slowing the "moving" clock to its actual rest frame, and then accelerating it to the frame of the presumed "stationary" clock. Either of the clocks can declare itself the "stationary" clock, and obtain consistent results as to the error in initial adjustments of the other clock and the magnitude of its slowing. Either clock may also declare itself to be moving at any arbitrary velocity, and still obtain consistent results. Thus the choice of "proper" time depends on the choice of stationary clock, in the absence of initial calibration data. As we shall see, one of the more famous tests of the slowing of clocks was based on the assumption of a "proper" rest-frame clock ideally situated at the center of the earth. Of course this clock didn't exist, but it provided an arbitrary "stationary" clock marking "proper" time against which to measure the other test clocks.

Is there a way that Bob could convince himself that Alice's clock was initially running fast without actually translating her to his reference frame? The answer is yes and no. In each of the clocks, we are generating a specific frequency tuned to the cesium atom. This same frequency can be used as a radio signal. By backing out the red-shift

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caused by the motion between the clocks, Bob can determine the actual frequency which Alice transmitted, and thus, determine if her clock is tuned to run fast.

Bob claims that Alice is moving away at a constant velocity, and, therefore, the frequency he receives will be red-shifted by a clearly defined value due to that motion. Since he claims Alice's clock is initially fast, then the Doppler corrected frequency he receives should be higher than that which he would receive if her clock were properly calibrated. When the test is carried out, though, Bob actually receives the frequency associated with a properly calibrated clock. Thus Alice's clock is keeping the correct time. At this point, Bob cannot claim himself to be stationary. He knows that he has undergone an acceleration equivalent to Alice, and that is the reason that both clock's are in agreement. That is also why Alice's clock will still match Bob's when it is translated to his frame. The two frames are equivalent as far as the measurement of time units are concerned. Thus Bob would be able to determine if Alice's clock actually was running initially fast, but in this case, it was not. This allows us to add one more note about clocks in motion:

6. If we pass a light signal of a known frequency between the clocks while they are in motion, we can use the Doppler shift to determine whether one or the other or both clocks are in motion with respect to their common rest frame.

The above point does not imply that there is any type of preferred rest frame such as the aether concept provided by Lorentz. A common rest frame simply refers to the common frame of construction or calibration of the two clocks. The reference frame in which the two clocks experience no relative motion and are also synchronous is their common rest frame. But what happens if there is no common rest frame for the clocks?

We saw in the previous section that in any system of two clocks in references frames moving at a constant velocity with respect to each other, each will record the other's clock as running slowly. Suppose Alice and Bob each construct and calibrate a clock in the respective reference frames in which they reside, approaching at some fixed velocity. Alice and Bob would each feel confident that their own clocks are correct, and that the other's is experiencing slowing due to motion. Assume that the clocks to be used are cesium clocks of the type described earlier. In a cesium clock, we can control the time unit of the clock by adjusting the velocity of the cesium atoms through the microwave cavity. If we slow this velocity down, the required tuning frequency will increase and, therefore, the clock will speed up. Alice and Bob each construct and calibrate their clocks by an identical set of plans and procedures, thus the two clocks are identical except for the reference frames in which they reside. Alice uses her clock to send a signal to Bob, and Bob sends an equivalent signal to Alice. Now, since each observer knows the value of their velocity relative to the other, each can fully account for the motion induced Doppler shift, and therefore determine the effective rate of the other's clock. In this example, both Alice and Bob determine that the other's clock is ticking at exactly the same rate as their own! What happened to the slowing of clocks due to motion? The answer lies in the careful consideration of reference frames.

We have seen that clocks in motion slow down only when placed in motion relative to the rest frame in which they were constructed or calibrated. Since each of these clocks remains in its rest frame, each will record the passage of time accurately. Recall that when a clock slows down due to being placed in motion, this has no actual effect on *time* itself, but only on the recording of time by that clock. The rate of the clock placed in motion becomes lower. Now Alice could argue that Bob's clock should be running slow, and that the reason it is not is that he has calibrated it improperly. For example, he may have set the velocity of his cesium atoms at too low a value, thus his clock would run fast. In fact, since all his clocks should be running slow, the clocks he used to establish the velocity of his moving atoms would be slow, and, therefore, he would calibrate the speed of the atoms to a correspondingly low value. This low velocity of cesium atoms would actually cause his clock to speed up by the identical amount which the motion of his reference frame would slow it down--therefore Bob's clock is ticking at the same rate as Alice's. Bob, of course, can make the same arguments regarding Alice's clock. Now we will see how the reference frames compare.

We will place Alice and Bob on two identically long trains on parallel tracks, heading toward each other at *very* high speeds, as is illustrated in figure 6-3. Each observer is in the front of its respective train, and carries two identical, synchronized clocks. These clocks are constructed in such a manner that for every second which passes on the clock, one mark is made on a ticker tape. Thus the elapsed time of any experiment can be determined by simply counting the number of dots on the paper. As the trains pass each other, each observer tosses one of its clocks onto the passing train. When the last car of the passing train is along side the observer, each then stops the tape on the clock which was tossed to them and tosses it back to its original train. We will assume that each of the clocks which

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remained with Alice and Bob in their "stationary" frame of reference recorded a time of one-hundred seconds for the trains to pass each other. After walking to the back of their respective trains and checking the clocks which were placed in motion on the passing train and then returned, each finds that these clocks recorded only ninety seconds. Now that these moving clocks are back in their initial rest frames, it is found that they are each once again marking the correct time.

Alice and Bob had each already concluded that the other's clock was initially running fast. This, reasons Bob, is why Alice recorded one-hundred seconds on her clock, while his clock, traveling with her, recorded only ninety seconds. Alice reasons the same way concerning the clock she gave to Bob. This seems fine, but an apparent paradox quickly arises if we follow things a little further, exposing the fallacy of this line of reasoning.

When Bob tossed his clock onto Alice's train, it slowed down due to that acquired motion, but then sped up again upon returning to Bob's frame of reference. The clock which Alice kept with her on her train, which is also in motion with respect to Bob, kept time at a faster rate than Bob's moving clock. If Bob were to bring this clock into his frame of reference, so that, as far as he is concerned, it is no longer moving, it seems that this clock should speed up by the same amount that his own clock did when brought to rest. However, we have already seen that Alice's clock, when brought into Bob's reference frame, slows down. How can this be--that one moving clock, when brought to rest, speeds up, while another slows down? To answer this, we return to a statement made in the previous section--all clocks in a given experiment must be calibrated in the same reference frame, which then becomes their common rest frame. In the above example, the clock which appeared to slow down when brought to rest was actually being placed in motion from its rest frame, thus it was slowing due to this acquired motion--the rest frame of this clock was not the same as the clock to which it was being compared.

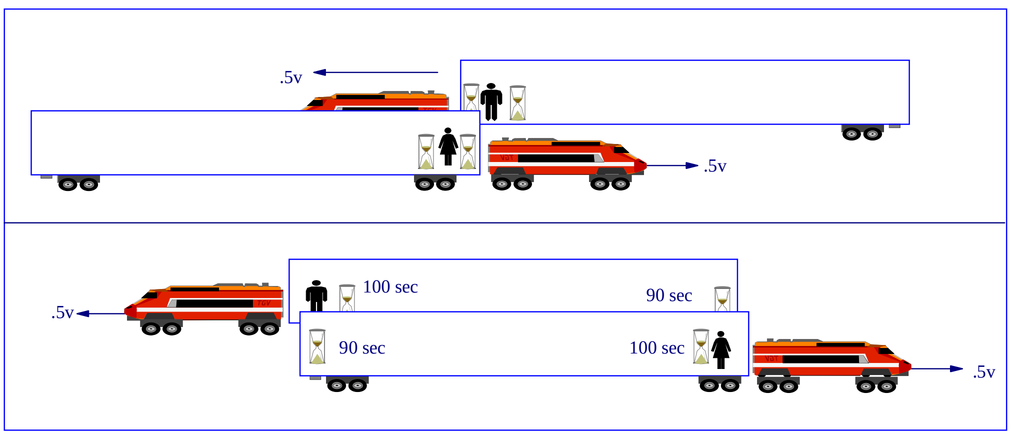

Figure 6-3 *A clock in motion will slow down only if that motion is due to an acceleration out of the inertial frame in which that clock was initially calibrated.*

Alice and Bob constructed and calibrated identical clocks by identical means in two different inertial frames of reference, and found them each to be marking proper time. The reason for this is that a cesium atom is susceptible to a specific frequency. In fact, the cesium atom is used to define that frequency, rather than the other way around. As these clocks are placed in motion, they slow down due to a change in state from the reference frame in which they were calibrated. In other words, it is not enough simply to be in motion with respect to a given reference frame. The clock must actually have been placed in motion with respect to its rest frame of calibration. It is this non-inertial change in reference frames which causes the clock to slow. In order to achieve its final velocity, the clock must be accelerated, and the slowing actually occurs during this acceleration process. Once the clock is no longer accelerating, and is moving at a constant velocity in an inertial manner with respect to its original rest frame, it will not continue to slow down, but will run consistently at whatever low rate it has achieved. Thus, when Alice tosses her clock into Bob's reference frame, it slows down.

Now suppose that Alice decides to trick Bob. She knows that his clock will speed up when returned to his reference frame, so when he tosses the clock to her, she quickly recalibrates it to the same rate as her own clock and immediately tosses that clock to Bob rather than tossing one of her own. She thinks it will be funny when Bob gets

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this clock back, and finds that it speeds up so as to record approximately one-hundred ten seconds for the trip rather than ninety. Unfortunately for Alice, this is not what happens. As soon as she recalibrated the clock, her reference frame became its rest frame. When she tossed this clock back to Bob's train, its rate slowed such that it would record only ninety seconds, just as if Alice had tossed one of her own clocks. As soon as Alice made an adjustment to the clock, she changed the nature of the experiment. In the original experiment, Alice was a completely passive observer, thus she could observe the rate at which the clock was ticking without impacting its nature. As soon as she became non-passive, and made a change to the system by her observations, her intrusion caused a change in the experiment which could not be undone. Even if she had adjusted the clock back to the original slow rate at which she had found it, the clock's rate would still slow when tossed back to Bob's reference frame--he would find a clock ticking slow by twice the amount as would normally be expected due to the velocities involved. He would also know immediately that Alice had sabotaged the experiment by her prank.

This effect is not unique to saboteurs of atomic clocks. One of the basic assumptions in the field of quantum mechanics is that simply making an observation of a system alters the system. We will address this in more detail in chapter ten when we consider the case of Shrodinger's Cat. However, it would appear from the above example that the quantum theorists are not entirely correct. When Alice observed the system in a passive, or non-obtrusive, manner, she was able to extract information--in this case the rate of the clock--without altering the outcome of the experiment. However, when she made her observation in an obtrusive manner, changing the rate of the clock and then returning it to its original rate, the experiment was irrevocably altered. The reason the quantum physicists don't distinguish between obtrusive and non-obtrusive observations is that every observation they make is of the obtrusive form. This is due to the nature of the items they are measuring. Quantum physicists study photons and elementary particles, none of which can be individually discerned or measured by the naked eye. All observations in these experiments involve electromagnetic detection or perturbation of the items under consideration, which, by their nature are obtrusive observations, and thus result in apparent paradoxes such as we see in chapter ten concerning double-slit photon experiments. Every time we make an obtrusive measurement in an experiment, that marks the start of a whole new experiment. In the case of Alice and the clock recalibration, that act ended the original experiment and began another, the results of which are easily predictable and consistent with other experiments of the same type.

Do we know that we can make a passive observation of a system without affecting it? The answer would appear to be yes, and it may be fairly simple to demonstrate. If we send a cesium clock on board the space shuttle, calibrated on earth, it will slow down due to the extreme velocity of the shuttle. Actually the effect is better demonstrated on a more linear trip, such as an Apollo moon mission, and the slowing of clocks on these missions has, in fact, been verified. If we now construct or perhaps simply recalibrate an identical clock on board the shuttle, using the exact procedures used on Earth, this clock should be found to be ticking slightly faster than the clock which was carried from and calibrated on Earth--the clock which was accelerated out of its rest frame. We must bear in mind however, that the shuttle astronauts, and any equipment which they carry with them, actually came from the same common rest frame as the earth clock. Therefore it may not be possible for them to construct and calibrate such a clock that is independent of the history of their origins. We could imagine that all the electronic tools they need for this task will be constructed and calibrated during this mission as well, but then, how do we know that the tools were calibrated to match those in the rest frame of the earth? Very careful attention to such details would be necessary for such an experiment.

The Mossbauer Effect and the Rotor Doppler Experiment

As we saw in chapter four, in relativity theory, the Doppler shift experienced due to perpendicular motion is a consequence of time dilation--the presumption that time slows down for a moving observer. A classic test of this effect was performed in 1960 by Hay, Schiffer, Cranshaw and Englestaff. Their experiment made use of the fact that a receiver on the rim of a rotor will experience a purely transverse or perpendicular velocity relative to an emitter at the center of the same rotor. Since the emitter is effectively "spinning in place," it is safe to assume that it is "stationary", while the receiver is in motion with a constant transverse speed, this speed being equal to the rate of revolution of the rotor times the radius of the rotor itself. Actually, the receiver is also undergoing constant acceleration, as it is constantly changing directions in its path around the circle, and a change in direction is, by definition, an acceleration. However, this acceleration should have no effect on the outcome of the experiment, and

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the fact that it did not was actually counted as further support of the special theory. However, we are here concerned only with the perpendicular or transverse Doppler effect. It is important to note that, although the receiver has a constant transverse velocity with respect to the transmitter, as far as the Doppler effects are concerned, there is no motion between the source and receiver in either the transverse or radial direction. The setup here is similar to the Doppler analysis of the Michelson-Morley experiment in chapter five. Since, in the frame of the apparatus itself, the source is always pointed directly at the receiver, there is no relative motion, and thus no Doppler shift.

In order to understand the significance of this test, we must again realize that a receiver can be used as a clock. A receiver tuned to a specific frequency can use that frequency as a basic unit of time. If that frequency then shifts to the red, or slows down, the "clock" will slow down by the same amount. Alternatively, we could state that if the receiver's clock slows down, then it will measure a received frequency as being higher than it actually is. If a process is expected to occur once per second, and our clock slows by one-half, the process as measured by our clock will appear to have speeded up, such that it is occurring twice per second. It is difficult to conceptualize why the tuning of a receiver should represent an actual change in the passage of time, any more than changing the dial on a radio would affect the passage of time. However, in relativity theory, it is not the change in frequency which affects time, but rather the slowing of time which causes the shift in the received frequency. The higher frequency detected by the receiver is due to the idea that time has slowed down in its frame of reference.

It is easy to see that the Doppler effect due to any motion along the line joining the receiver and transmitter would dwarf the effects of clock slowing for all speeds except those approaching c. This is because the Doppler effect is proportional to one over c, while the clock slowing is proportional to one over c^2, a tremendously smaller number. For this reason, an ordinary transmitter and receiver would not work. The Doppler effect due to the motions of the atoms involved in the experiment along the line of transmission would outweigh the clock slowing effect being measured. In other words, the expected experimental error would be greater than the results to be obtained, given the relatively low velocities of the actual experimental setup. Fortunately, Rudolph Mossbauer discovered that he could trap a particular radioactive isotope of iron, Fe^{57}, in a specific lattice such that the motions of the nucleus itself could be made to be insignificant. The effects eliminated included the recoil effect from emitting a photon, as well as oscillations caused by thermal fluctuations. So important was this discovery to theoretical and experimental physics, that Mossbauer was awarded the Nobel Prize in 1961 for this work. By exploiting the "Mossbauer effect," the rotor Doppler experiment was carried out and confirmed the slowing of the clock of the moving receiver to within an error of a few percent.

While the results of this experiment were seen to be a direct confirmation of time dilation for a moving source, it is clear that RCM theory predicts an identical shift in the rate of the moving clock. This shift is due entirely to the effect of motion on atomic clocks addressed in that section, and is obtained without invoking any effect on the passage of time for a moving observer.

Clocks in a Gravitational Field

Having seen in chapter four that frequencies shift to the blue (higher frequency) when brought into the presence of a gravitational field, it is natural to question what happens to a clock or any time-measured process in the same field. There are many considerations in this analysis, just as in the case of analyzing clocks in motion. We must be careful to establish the appropriate rest frame for "proper" time, and then determine how we are going to determine the rates of one clock vice another, or, more fundamentally, how we are going to determine the degree to which the frequency has shifted in the first place. Let us begin by examining the case of a signal passed from a clock deep in a gravitational field to one outside the field. We will use a highly stable oscillator as our clock, and let the frequency of the source represent the time unit of the clock. Each cycle of frequency in this respect will equal one unit of time. We know from the analysis of the gravitational red-shift and the Pound-Rebka experiment that the frequency received by the clock outside the field will be shifted to the red from that emitted by the source, as measured with that clock. Thus if an observer located with the receiver is using an identical frequency source to time the received signal, he will obviously notice that the frequency generated by his clock is higher than that which he receives. Thus each "tick" of the received signal will be longer than the "ticks" on his own clock. From his point of view, the clock in the gravitational field must have slowed down. Similarly, for a signal going the other way, there will be a blue shift in the transmitted signal, and an observer with the clock in the field will observe that the "ticks" of the other clock are occurring faster than his own. He will conclude that the clock outside the field is running

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faster than his own. If the two frequency sources are slowly brought together, either in the field or far removed from it, they will generate identical frequencies. What we have to decide is, did the clock inside the field slow down, or did the frequency decrease as it climbed out of the field. Clearly, only one of these effects occurred, otherwise the frequency would be shifted twice--once due to being generated at a lower frequency by a slower clock, and again by being gravitationally red-shifted as it climbed through the field. This is, of course, not what we observe.

Imagine a photon in free-fall entering a gravitational field. We have seen how the frequency of this photon, as measured in the field with "local" clocks, will be increased or shifted to the blue. The photon, however, must be unaware of any change in its frequency, or it would become aware of its presence in the field--the principle of equivalence prohibits this. What this principle basically states is that if you are in free-fall (not being accelerated by a rocket or being held in place by a floor), you can not tell the difference between floating freely in space or falling toward a gravitating body such as the sun. No experiment you might perform would provide you with any knowledge as to which state you might be in, as the results of any experiments performed would be identical in either case. You could state that if you are in free-fall toward the earth, the kinetic energy you feel when you strike the earth would be ample evidence that you were in a gravitational field. However, the same effect would be felt if the earth were hurtling toward you instead.

Now, the photon, upon entering a gravitational field, or "well," acquires excess energy, much the way a ball dropped from a tower gains energy as it falls toward the ground. Borrowing again from the results of chapter eight, we can express the energy of a photon as mc^2 or as Planck's constant times c divided by the wavelength. Thus an increase in energy can be viewed as an increase in effective mass, or conversely as a shortening or "bunching up" of the various wavelength components. A visual representation of this is when smoothly flowing traffic suddenly comes upon slowing due to rubbernecking a stalled vehicle across the road. The traffic slows, and the cars which had a comfortable, even spacing now become bunched up as they pass through this area. Upon leaving the congestion, the cars once again resume their original, spread out configuration. Recall that a single photon is made up of a continuous stream of wavelengths, each associated with a particular velocity component. The slower components have shorter wavelengths. Now, if a photon component traveling at c with a particular wavelength finds itself bunched up so that that wavelength is now smaller, the photon will slow itself down such that, in its frame of reference, its frequency remains unchanged. Alternatively we can say that since the photon's speed at any point is equal to its frequency times its wavelength, and its wavelength has shortened, its resultant speed will be reduced as well. Likewise, a component initially moving somewhat faster than c, with an initially larger wavelength, will find that as that wavelength is bunched up, its speed reduces the appropriate amount. So it is with all components along the entire length of the photon continuum. Thus, in the photon's frame of reference, its frequency remains unchanged, as required by the principle of equivalence.

If the photon has managed to keep its frequency the same in its own frame of reference, then why does an observer situated deep within the gravitational field see a blue-shifted frequency? To see this, imagine a hydrogen atom far removed from the gravitational field. It will generate or absorb light or radio energy at a specific frequency, 1420 MHz (1420 megahertz, or one billion, four hundred and twenty million cycles per second). In fact, we use these emissions to *define* what 1420 MHz is. If any other source of producing energy at this frequency gives a value above or below this one, we assume the hydrogen atom to be correct, and the other source to be incorrect or shifted in frequency. Now, if we carry our hydrogen atom into the gravitational well, the resulting change in energy will cause the atom to generate and absorb a lower frequency than that which we saw outside the field. However, due to convention, we still use this lower frequency as a definition of 1420 MHz. Suppose another hydrogen atom generates a photon well outside the field, and that this photon then falls into the field, where we compare its frequency to one generated by our own hydrogen atom. What we find is that the photon has managed to keep its frequency unchanged, as measured locally by itself at each point along its journey, but upon reaching us, we have a new, lower definition of 1420 MHz. Thus when we compare the frequency of the photon to our definition, we find that it is higher--the frequency has been blue-shifted compared to an identical source inside the field. If we now build a clock based on the frequency required to tune these atoms, we will have to supply energy at this lower frequency to which the atom is now sensitive. Thus when we compare this frequency to one generated far removed from the field and sent to us, we will measure the incoming frequency as being blue shifted, even though to the photon itself it has not changed. Likewise, since our clock is tuned with a lower frequency, it will accumulate less time than a clock outside the field. When this clock is carried back outside the field after some duration, the elapsed time on this clock will read less than the elapsed time on a proper clock which never entered the field in the first place, even though the two clocks will be ticking synchronously once they are brought together.

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From the above, it is clear that when we speak of the frequency shift in a gravitational field, we are speaking of the frequency as measured in "local time." This is almost inherently obvious. If the sun absorbs the characteristic frequency of sodium emissions, it is absorbing the frequency as measured locally, and the emissions themselves are at a frequency as measured locally. Clearly the frequency absorbed cannot depend on the value of some clock (calibrated frequency) far removed from the place of absorption. Likewise, when we are measuring velocity, we are doing so using local time. Thus, if we are concerned with a velocity of c, this velocity is c as measured with the local clock of the observer in the gravitational field, not a clock far removed from the gravitational field.

This locality of measured time, frequency and velocity becomes important when we desire to transform the results of "local" experiments to a "proper" observational reference frame far removed from the gravitational field. A given velocity measured with a slow-running local clock would appear slower as measured with the faster-running proper clock. Since the velocity of light is "observer" dependent, then we must consider c as recorded using local time. Transforming this velocity to proper time results in a lower value for c, to the same degree as the local clock compared to proper time. This point becomes very important when we determine the delay in the time it takes a light signal to pass near the sun, which we do in chapter eight.

Suppose the above arguments illustrating the constancy of the photon's frequency in its own frame were not correct, and that the observed frequency of a photon actually increased for some reason other than clock slowing, such as conservation of energy in a volume alone. Let us further assume that we have tested the gravitational slowing of clocks by placing one clock on a tower and measuring the elapsed time. We find that the tower clock accumulates more hours than the clock at the base, in keeping with our predictions. We now send a signal from the tower clock to the base clock. As stated earlier, this signal would be shifted twice. Once because the tower clock was ticking fast, and thus generating a higher frequency, and again as this higher frequency fell through the gravitational field and became blue shifted. The clock would generate a blue-shifted frequency due to ticking fast, which upon being received would be blue-shifted even further due to gravitational blue shift, exactly doubling the effect. This is not the effect we see. The received frequency is affected only once. This was demonstrated over a short distance in the Pound-Rebka experiment, and over a much greater distance sixteen years later using a rocket, whose length, coincidentally, was almost exactly the height of the tower used by Pound and Rebka at Harvard.

The Scout D Rocket Experiment

On June 18, 1976, an interesting experiment was performed to test the gravitational red-shift and the slowing of clocks due to motion, or "relativistic time-dilation." The experiment was a joint venture of Bob Vessot at Harvard University and NASA. The basis of this experiment is quite simple. Take two identical and synchronized atomic clocks. Place one of these on a rocket while the other remains "at rest" on the surface of the earth. Use the frequency of the clock on the rocket as a radio signal which will be sent to earth and compared with the rest clock. The received signal will be shifted due to the motion induced Doppler, the gravitational red-shift and the motion induced time dilation. Simply add up all these effects, and verify that the observed shift matches the predicted value.

In reality, of course, things are not as simple as this. As we saw in chapter four, the Doppler effect would be the predominant factor, overshadowing the other two effects, and, of course, the other two effects are what we desire to test. Uncertainties in the exact position of the rocket and its velocity at all times would make it practically impossible to determine how much of the shift was ultimately due to Doppler alone. Fortunately, a device called a transponder saved the day. A transponder simply takes a received frequency, amplifies it, and retransmits it with more power. This is the basis for the commercial satellites relaying television signals to your cable provider. The application of the transponder to the experiment is straightforward. We use the ground based clock to send a signal to the rocket, which is then immediately amplified and retransmitted to the ground. At the same time, the clock on the rocket transmits its signal, indicating the rate at which it is ticking. The signal sent from the ground is shifted by the Doppler effect, the gravitational shift (toward the blue, since the rocket is higher in the field than the earth clock), and by "time dilation" due to the relative velocity of the earth clock and rocket. After being reflected and received back at the earth clock, this signal will be further shifted by the Doppler effect, such that the total effect is twice that seen on the one-way trip. However, this time the signal will be gravitationally red-shifted as the signal falls back through the field, thus the gravitational effects will cancel. Additionally, since the transmitter and receiver are both the controlled by the ground based clock, the time dilation effect experienced by the transponder will also vanish, as

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there is no relative motion between the earth based transmitter and the earth based receiver--they are the same device. Therefore, for this two way signal, the only shift in frequency is due to Doppler, and the effect counts twice. By subtracting the received signal from the transmitted signal and dividing by two, we have the exact contribution of the Doppler shift at the instant the rocket clock transmits its signal. The final step is to take this value of the Doppler shift, subtract it from the measured shift in the signal sent from the rocket itself, and we are left with the residual change due only to the gravitational red-shift and the motion induced slowing of the clock.

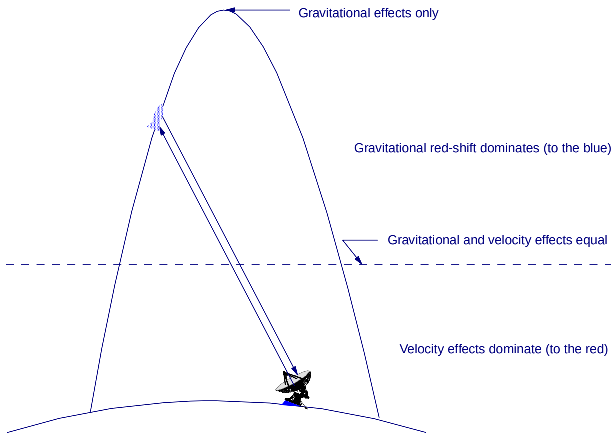

Figure 6-4 As a rocket moves from launch to apogee, first velocity effects, then gravitational effects, dominate in their effects on on-board clocks. This order is reversed as the rocket heads for splashdown.

The rocket used was a Scout D rocket. It was sent on a sub-orbital flight to a height of one and one-half times the radius of the earth, and the test lasted for a total of two hours. Data recording began after the payload separated from the boosters, and was therefore in free-fall for the remainder of the trip. Figure 6-4 illustrates the path of the rocket on its flight from Virginia to a height of ten thousand kilometers, and finally to a watery grave in the Atlantic ocean. During the first few minutes of the flight, where the rocket had a velocity of several kilometers per second, the effects of relative velocity dominated over the gravitational effects, and the rocket clock registered as running slow. As the payload gained altitude, its velocity decreased, and the gravitational effects began to dominate. Since the clock was climbing out of the gravitational field, it would run faster than the clock which remained at rest on the earth, deep within its gravitational field. Three minutes into the data recording, the two effects were equal, and the earth and rocket clocks were beating the same. After that, the rocket clock was faster than the ground clock. As the rocket reached the peak of its climb, and readied for its descent, its velocity was effectively zero with respect to the earth clock, and the resulting frequency difference was due almost entirely to the gravitational red-shift. On its descent, the increasing velocity began to have an effect again. One hour and forty-five minutes into the flight, the earth and rocket clocks again agreed, and five minutes later the payload was lost to the horizon.

As we have seen in this chapter, both the gravitational effects and the velocity effects on the clocks used in this experiment are explained by the RCM theory as well as by relativity theory. The experiment is important for other reasons, though, relating to establishing the "proper" frame of reference for these clocks. In the section on the effects of motion on atomic clocks, we saw that the common rest frame of the clocks is simply that reference frame in which the clocks experience no relative motion with respect to each other, and in which they are synchronized with each other. In this experiment, the common rest frame is at the surface of the earth, deep within its gravitational field, and moving with the rotational velocity of the earth itself. This is clearly not the preferred reference frame of the aether as proposed by Lorentz, but is simply an arbitrary frame from which to make all our measurements. As with the theory of relativity, the idea of an absolute preferred reference frame has no meaning. We simply choose which frame we wish to be stationary, and transform all our observations into that frame. In this case we chose the moving surface of the earth. Therefore "proper" time became the time of a clock deep within the gravitational field, while "local time" was time as measured far removed from the field. Likewise, velocity effects were calculated as compared to the presumed stationary earth clock. By using the Doppler shift, calculated by the two-way signal, we were able to determine the velocity of the rocket relative to our "stationary" position, and then back out these effects, just the way Bob was able to declare that Alice was in motion in the section on establishing reference frames. If a

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passenger on this rocket had tried to claim ignorance about his acceleration, and declare instead that the earth had pulled away from him, he would have to claim that initially the earth clock was improperly calibrated. However, as soon as he verified the received values of the transmitted signals, he would be able to determine his mistake. This was also demonstrated by Alice and Bob in the section on establishing frames of reference.

While the Scout D rocket experiment chose an arbitrary rest frame which was partially at the center of a gravitational field and was also in motion both about a central axis (rotation) and a distant axis (solar orbit), there was still an actual clock at this location against which all effects were measured. In actuality, due to the non-linear motion of the earth, this location does not represent an inertial reference frame at all, as we will se in the next section. However, for the short duration of this particular test, the location could be considered as effectively inertial without noticeable effects on the outcome of the experiment. It is also possible to choose a hypothetical rest frame, at any point in space one desires. This rest frame may be within or outside of a gravitational field, and may or may not have a velocity relative to the experimental apparatus we are using. Furthermore, one does not even need an actual clock at this location. As long as the relative attributes of the location are known, all experimental results can be transformed into that reference frame, and the appropriate conclusions may be drawn. Such a hypothetical rest frame was the basis of comparison in another test of the slowing of clocks due to motion, and this test is the subject of the next section.

ROUND THE WORLD CLOCKS EXPERIMENT

In October of 1971, J. C. Hafele and Richard Keating performed a test of the effect of motion on clocks using cesium-beam atomic time standards and commercial aircraft. To a certain extent, this experiment also provided a test of the gravitational effects on clocks. Hafele and Keating realized that a clock on the surface of the earth was not at rest, nor was it moving with a uniform, linear motion. Due to the rotation of the earth, such a clock would be under constant acceleration, always changing direction to maintain its circular motion. Likewise, a clock located on a plane flying around the earth would not exhibit uniform motion relative to the earth clock. Since it would ultimately take off and land at the same point, say next to the earth clock, the airborne clock would obviously undergo accelerations and direction reversals relative to the earth-based clock. Since the experiment was to be a test of the time-dilation aspects of the special theory, which dealt with inertial reference frames (frames in uniform, linear motion with respect to each other), such circular motions could not be allowed. The way this problem was resolved is quite ingenious. Recall that in the rotor Doppler experiments, a transmitter on the outside of a rotor was compared to a receiver at the hub of the rotor. Since no motion occurred along the line joining the two, the transmitter could be considered as exhibiting only uniform, perpendicularly linear motion relative to the receiver. Thus Hafele and Keating would be in great shape as long as they could place a clock at the center of the earth, and make all comparisons relative to it.

Obviously one cannot actually place a clock at the center of the earth, so we must place a hypothetical clock there instead. In order to do this, we need a means of keeping time on this hypothetical clock. This is done by first assuming the truth of the effects we are trying to measure. By starting with a cesium-beam clock at the surface of the earth, we can calculate the velocity of this clock relative to an identical clock at the earth's center. For simplicity, we will assume the experiment takes place along the equator. At the equator the velocity of the ground clock is clearly equal to the circumference of the earth divided by twenty-four hours, since the earth completes one revolution per day. We can now assume that our ground clock is running slower than the clock at the center of the earth in proportion to the gamma value for this velocity, which is roughly one-thousand miles per hour. Thus we simply multiply the time measured on our earth clock by the inverse of this factor to get the elapsed time as measured on our hypothetical clock. Actually, this imaginary clock would also suffer gravitational effects, but these may be ignored. The only gravitational effects we need consider are those between the ground clock and the flying clocks, and we can measure and calculate these effects directly. We are now ready to perform the experiment.

The basis of the experiment is simple. We begin with three identical, synchronized clocks, one of which will remain at the same point on the earth for the duration of the test, and from which we will derive the time on our hypothetical earth-center "proper" clock. We place one clock on an eastbound aircraft, and allow it to fly around the world. We place another clock on a westbound flight, and allow it to also circle the globe. When all three clocks meet again at their point of origin, we compare the elapsed time on each of the clocks. For the moment we will ignore the gravitational effects. Consider first the earth based clock. At the surface of the earth, this clock is moving

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eastward at roughly one-thousand miles per hour relative to the "proper" clock at the center of the earth. Thus this clock will run more slowly than that clock by a factor proportional to gamma for that speed. Now, imagine that our planes fly at four-hundred miles per hour on average. The eastbound clock will then have a velocity relative to the "proper" clock of fourteen-hundred miles per hour. Clearly, this clock would be expected to run even more slowly than the earth based clock. So far, so good, but what about the westbound flight? This clock has a velocity with respect to the "proper" clock of only six-hundred miles per hour. It therefore should not be running as "slowly" compared to this clock as the earth bound clock is. In other words, the westbound clock should actually gain time, or run fast, compared to the earth bound clock. But how can this be? **

(** The answer is that the clocks were initially calibrated in a non-inertial reference frame. The rotation of the earth causes the clock to change velocity during the time of one clock cycle. This change in velocity causes the clock to be calibrated to run fast, assuming an IFR, but, since the clock continues to change its velocity by the same amount with each pulse, it slows by just the right amount with each pulse to be keeping what earth bound folks consider the correct time. When this clock is flown westward, it is indeed returned more closely to its inertial calibration frame, and the effects of having been calibrated to run fast in that frame become apparent—the clock speeds up to its proper rest-frame rate.)

Both airborne clocks are in motion relative to the earthbound clock, so shouldn't they each run more slowly? The answer is no, and the reason is the lack of uniform, linear motion--the three reference frames are not inertial. Only when comparing these clocks to the hypothetical clock at the center of the earth do we have inertial reference frames. The three frames experience increasing velocity with respect to this "proper" frame in the order of westbound clock, earth clock and eastbound clock. Thus the earth clock runs slower than the westbound clock, but faster than the eastbound clock. Before we review the results of the actual experiment, we must bring in the gravitational effects. Since the flying clocks are farther removed from the gravitational potential than the earth based clock, they would be expected to run a little bit faster as a result of this. For the eastbound flight, the motion induced slowing with respect to the earth clock would be expected to slightly exceed the gravitational blue-shift gain, and this clock would lose time. For the westbound flight, the gain due to the gravitational blue-shift would add to the motion induced gain, and this clock would accumulate quite a bit more time than the earth based clock.

As might be expected, the actual experiment differed in many details from the ideal case above. The aircraft had to take off and land many times during their circumnavigation of the globe, as they were, after all, commercial aircraft. The flights also did not track smoothly along the equator, but changed latitude many times. Other factors which obviously changed were the direction, height and speed of the aircraft. Even so, by maintaining an accurate history of all these factors, the expected differences in elapsed time on each of the clocks could be calculated. For the eastbound flight, which took forty-one hours, the expected loss was forty nanoseconds, or forty billionths of a second. The actual measured loss was fifty-nine nanoseconds, well within the limits of experimental error. For the westbound flight, the clock was expected to gain 275 nanoseconds. The actual gain was 273 nanoseconds, obviously well within the limits of experimental error.

As with the Scout D rocket experiment, these results are completely consistent with both RCM theory and relativity theory, but they are also important for other reasons. We see again that the particular effects obtained depend on our choice of "proper" rest frame. In the case of the cesium-beam clocks, since the earth is undergoing acceleration, the earth based clock could not be considered to remain in the common rest frame of the three clocks. While it is true that every twenty-four hours this clock would return to that frame, and again be keeping "proper" time, during the remaining times of the day the clock would be in motion relative to that point and would therefore slow down. Therefore the *elapsed* time on the clock would be lower than the actual elapsed time in the actual rest frame of the clock. Note that we do not need to go to the center of the earth to see this. We can imagine a point in space above this clock's rest frame which does not move with the earth. The earthbound clock will move completely around the circumference of the earth in a twenty-four hour period, and will experience slowing to do this, before returning to our imagined point in space. If we now allow a plane to fly westbound such that it takes a full twenty-four hours to circumnavigate the globe, we see that this plane will actually be located right at our imagined space point for its entire trip. The earth will effectively turn directly under the plane for twenty-four hours. Thus the flying clock, while in motion relative to an observer sitting with the earth clock, is actually remaining in the rest frame of that clock for the entire trip. The flying clock will then keep "proper" time while the earth clock slows due to its changing velocity. This is why the westbound clock gains time, even without invoking a hypothetical clock at the center of the earth. The important point is that we cannot arbitrarily assume our own reference frame to be stationary

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or even inertial in any given experiment. We must always keep track of the accelerations we are undergoing, and take these into account in our calculations and in the way in which we establish the frame of reference for the moving or "effected" clocks.

The above discussion carries practical importance in experimental physics. *Science News* ran an article in their May 1, 1993 issue regarding a new atomic clock. The article stated that "this new atomic clock will neither gain nor lose a second in the next 1 million years." Let's consider this more closely. Imagine that this clock is established on the equator, which, as we have seen, has a velocity of one-thousand miles per hour with respect to the earth's center, or with respect to the north pole, which can be considered as stationary with respect to the earth's center. We will place a second, identical clock at the north pole, and see what happens. The gamma factor for the equator based clock will cause that clock to run more slowly than the north pole clock. At this velocity, the equator clock will lose a full second in less than 30,000 years. Over the course of 1 million years, the clock will lose more than thirty-five seconds, not counting the intrinsic one second uncertainty of the clock itself. While this seems to be a minor nuisance, one must realize that the clock is not intended to keep time for 1 million years. Its purpose is to provide an extremely accurate time *standard* over very short periods of time--this clock becomes the clock by which all others are calibrated. Unfortunately, in order to obtain a completely consistent time unit, one would have to specify the time of day, latitude and altitude at which the measurement is to be made in order to ensure that the clock is in its proper rest frame. As difficult as this seems, things get more complicated. The earth orbits the sun at a velocity of thirty kilometers per second, changing direction every six months. Sometimes this velocity will represent the rest frame of the clock, while six months later it will represent a velocity of sixty kilometers per second. If we average this velocity out to be an effective thirty kilometers per second for six months of the year, we see that the clock will lose a second in only seven years, or over forty hours in 1 million years. This effect must be taken into account when specifying the time of year at which to use the standard, or how the standard changes over the course of a year. Finally, we must consider the rotational orbit of our lonely solar system around the center of the Milky Way, and, should we happen to leave this galaxy during the next million years or so, the velocity of the Milky Way toward the great attractor. Synchronizing clocks for deep space travel can become quite complicated indeed.

The Equivalence of Gravitational and Other Forms Of Acceleration

We saw in the first section of this chapter that clocks placed in motion with respect to their rest frame or frame of calibration will experience slowing due to this change in state. We have also seen that clocks will slow down when placed in the presence of a gravitational field, or gravitational energy well. A look at the Scout D Rocket experiment and the round the world clocks experiment demonstrated that the effects are additive and independent--a clock entering a gravitational field will slow due to the strength of that field, but will slow even more as it acquires ever more speed during its descent. While this latter effect is attributed to a supposed slowing of time due to the relative motion of two reference frames in relativity theory, we have shown that it is in fact due to the excess kinetic energy acquired while the clock is being accelerated out of its initial rest frame.

It is important to realize that it does not matter how slowly we accelerate the clock. In the end, the kinetic energy acquired will be related to its final velocity achieved, no matter how long it took the clock to attain that velocity. Once that velocity is reached, the clock will continue to run at its new, slower rate, until returned to its initial rest frame. Now, if the slowing of the moving clock is due to a change in kinetic energy, and the slowing of a clock in a gravitational field is due to a change in gravitational potential energy, we should be able to derive similar equations for each effect. In fact, gravitational potential energy can be converted to kinetic energy quite simply. If we hold a ball over the edge of the Harvard tower, it will posses a certain amount of gravitational potential energy as compared to an identical ball at rest on the ground twenty-two meters below. If the ball is now released, this potential energy will be converted to kinetic energy as it acquires speed on its trip toward the ground. At the instant before the ball strikes the ground, all of that excess gravitational potential energy will have been converted to kinetic energy. The amount of kinetic energy gained will exactly equal the amount of potential energy lost. That we can so easily shift from potential to kinetic energy further supports the equivalence of these expressions, and would lead us to believe that the expression for clock slowing due to gravitational potential is in fact identical to the expression for slowing due to acquired motion, with the expression for gravitational potential energy in the former replaced by the expression for kinetic energy in the latter. This is, in fact, the case.

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Consider the case of the clock in a gravitational well. We were able to show that the time unit of the clock slowed by a factor proportional to the strength of the gravitational potential at that point in the field. In fact, the ratio of the slower time unit of the clock in the gravitational field to the "proper time" of a lock far removed from any gravitational fields is equal to the ratio of total energies experienced by an atom in these two situations. This ratio is independent of the actual mass or atoms considered, as it is the same for all mass energies. Thus the ratio of the inherent or rest energy of, say, a cesium atom plus the gravitational potential to the inherent energy of the cesium atom alone would be the same ratio we would see when comparing the rate of ticking of the two clocks. The reason this is so is that frequency and energy are linearly related, and, thus, a ratio of energies is equivalent to a ratio of frequencies. Since the time unit of the clocks is also linearly related to the frequency, then the ratio of energies is also equal to the ratio of time units.

In the case of a clock which has been brought from rest to some velocity, we showed that the degree of slowing was equal to the ratio of the inherent energy of the mass less the kinetic energy acquired to the inherent energy of the mass itself. Thus the expressions for gravitational slowing and slowing due to acquired motion are indeed equivalent. Beginning with the expression total energy over rest energy, we simply plug in the gravitational potential energy for the gravitational case, and plug in the kinetic energy for the case of a clock brought from rest to some velocity.

If accelerating an object to some velocity slows the clock down, then why doesn't a clock sitting on a table continually slow down. Such a clock is being held in place by constantly accelerating it under the influence of gravity. If we include both the gravitational and kinetic energy terms in one expression for clock slowing, we can see why this is the case. The rate of slowing of the clock will be given by the ratio of its inherent energy plus its kinetic energy plus the gravitational potential energy divided by its rest energy. Now it is easy to see that a clock sitting still on a table never changes its kinetic energy, and also never experiences a change in the gravitational potential energy at the point at which it sits. Therefore its rate does not change. In fact, the clock is not actually siting still at all. In addition to the gravitational acceleration, the fact that the earth is turning means that the clock is constantly being accelerated as the day wears on. A change in direction of velocity is an acceleration just as a change in speed is. This acceleration does have an effect on the clock, as we saw in the example of the round the world clocks experiment and in the analysis of highly accurate time standards. All during the day, the clock will change its rate of ticking until, twenty four hours later, it is once again in its initial calibration or rest frame.

THE EFFECT OF MOTION ON Matter And Time

My argument is that special theory of relativity time is not, in fact, time and thus that the special theory of relativity shows not that time is relative but merely that certain light-connectibility relations are relative. I shall argue that time...metaphysical time...is absolute.

Quentin Smith, *Language and Time,* 1993

It has been postulated in special relativity that, as an object attains great velocity, not only do clocks slow down, but time itself slows down, and distances contract. Let's look at the latter idea first.

In the section on establishing the frame of reference for moving clocks, one of the clocks had a sensor located a specific distance from itself. An accurate way to measure this length, in the rest frame of that clock, is to use the wavelength of the frequency generated by the clock as a standard unit of length. Clearly, at the initial setup, with both clocks stationary, they will agree on the length of the sensor arm. Now we accelerate Bob's clock through a series of maneuvers such that it eventually passes Alice at some velocity, moving from the sensor toward the clock. Using the wavelengths generated by the cesium atom as a reference, Bob will determine the length of the sensor arm. Since the cesium atom is now sensitive to a lower frequency due to being placed in motion, his "ruler" has effectively lengthened by the factor γ (lower frequencies imply longer wavelengths). Since his ruler is now longer, he will measure the sensor arm to be shorter than it was in his rest frame. Since Bob considers himself stationary, he concludes that the length of the moving sensor arm has been lessened due to its motion.

Has the length of the arm contracted in his frame of reference? Not actually. If Bob had carried a rope with him, tested before he left to be the exact length of the sensor arm, he could unfurl the rope starting at the sensor and continuing on until he reached Alice. He would observe it to be the same length as the sensor arm. If he now

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measured the rope, traveling with him in his frame of reference, using his wavelength ruler, he would measure it as being contracted by the same amount as he measured the sensor arm to be. However, since the rope is stationary in his frame of reference, it should measure the original length, not the length contracted due to motion. If Bob was able to claim ignorance about his acceleration before, he would not be able to do so now. Clearly, the wavelength of the frequency with which he is performing his measurements has lengthened by the factor γ, causing everything he measures to be shorter than when he measured it in the initial "rest" frame. The change in the wavelength used to make the measurements is also not due to length contraction. Since he is using the frequency generated by his clock as his ruler, and the time basis or frequency of his clock has slowed, the wavelength has changed accordingly. Lower frequencies have longer wavelengths. It would now be obvious to him that he was traveling forth at a constant velocity, relative to the frame in which he initially made his measurements of the rope and sensor arm, causing his carefully tuned measuring rods to lengthen by the appropriate factor. This is a very important point. While measuring devices constructed in the manner of atomic clocks will have lengthened, causing the illusion of length contraction in everything measured, the lengths of the items being measured have not, in fact, changed at all. Once again, it is only when we use the propagation of a light signal to make our measurements that these effects occur. To paraphrase Quentin Smith, it is not length that is relative, but merely certain light-connectibility relations--in this case the relation between our defined unit of length and a unit of time on our moving atomic clock. If we use physical rulers, such as the rope above, the measurements are not changed due to the velocities involved. Since Einstein's second postulate insists that velocity has no effect on light, an actual physical contraction of length is required in relativity theory to account for the changes observed when measuring with light signals. In RCM theory, since we have different components of light for each observer, no physical length contraction is necessary. It is only when we use a light signal for measurements that the effects arise at all, and, with a knowledge of our velocity or the acceleration which produced it, these effects can easily be accounted for and eliminated.

Now to the matter of time dilation. It has been demonstrated that atomic clocks slow down due to an imparted velocity. It has also been proposed that perhaps pocket watches should also slow, though this has not been demonstrated. The real question is, do all atomic and molecular processes slow down. Consider the example commonly referred to as "The Twin Paradox." In this example, we have two twin brothers, each maintenance technicians, who have signed on to travel with two clocks A and B, and to maintain the clocks and the ships on which they respectively travel. Clock A is sent with its passenger on a long journey to the Andromeda galaxy at a velocity approaching the speed of light. Clock B and its technician (much to his disappointment) stay on Earth. The experiment continues for over fifty years, when, one day, clock A and its passenger return. Before the earthbound technician opens the door to greet his brother, he notices that the readout for clock B indicates that only eight years have passed. The earthbound technician (who has in fifty years grown very jealous of his traveling brother), claims he is too old and weak to be able to release the door latch, and leaves his brother in the capsule, which sinks to the ocean floor.

Thus an important question remains unanswered. Was the returning brother 50 years older than when the experiment began, or only eight years older as the clock suggested? Since Congress blamed NASA for not rescuing the capsule, they refused to fund another such experiment, and so other means have been used to postulate an answer. One of these methods involves elementary particles called muons. These particles, when left stationary in [our] rest frame, have a half life of about 1.5 microseconds (μs). What this means is that these particles spontaneously decay all the time (into electrons and other particles), but with a predictability such that if you had a cupful now, half of them would decay in the next 1.5 μs. In the following 1.5 μs, half of those remaining would decay, leaving you with one-quarter cup of muons. The process by which these particles (or any particles for that matter) decay is not entirely known, though the existence of the so-called "weak-force" is often postulated to explain this form of beta-decay. The weak-force is thought to break subatomic particles into electrons (beta-particles) and other minor particles. What is known is that if you increase the velocity of these muons (from our rest frame) to some high velocity, their half life will increase by the factor γ.

Thus it would appear that the muon's life has been extended by the same factor that a clock traveling with them would have slowed. Based on this, one could conclude that one of the twin technicians was forty-two years younger than the other when he died. This is certainly a vote in favor of all atomic processes slowing down, but not necessarily. Our only experience with measuring the lifetime of muons comes from measuring their decay at or near the surface of the Earth. One possibility may be that the mechanism of decay is external. Thus the properties which are abundant or well-tuned in our rest frame become scarce or improperly tuned as the particle's velocity is increased, in much the same manner as mass appears to increase with velocity when measured by purely electromagnetic means. In this case the means of measuring mass--the result of a magnetic force--has less and less

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effect on the particle as its speed increases relative to the field itself, as will be shown in chapter eight. A second possibility is that the cause of decay may be internal, requiring a transfer of forces inside the particle in a manner similar to the cesium clock (though not necessarily frequency tuning). Then, as with the clock, the decay of the moving muon will take longer than the decay of a stationary one, as the moving clock ticks more slowly than the stationary one. Of course a third possibility is that the mechanism of decay cannot be modeled completely in either manner. A neutron has a half-life of only about 620 seconds, yet when bound in the nucleus of an atom may exist for extremely long times without decay. In this case there is some mechanism that allows it to change its half-life other than by changing its velocity.

When one considers the first two possibilities above regarding the life of a muon, it is at once apparent that time has not slowed down (as it was shown with the clocks), but that the mechanisms for decay have been skewed by a factor allowing a longer life (on average) for each particle. If this is the case, then, atomic processes of all types may slow down in this manner, and it is not unlikely therefore that molecular ones do so also, though it is not guaranteed. If a neutron behaves differently in a bound state than when free, atomic processes in bound atoms may occur differently than for free atoms as well. Hence we are left with uncertainty as to the apparent physical age of the returning twin.

In the third possibility however, where the muon's internal forces cannot be modeled as a man-made clock, we may have a dilemma. If enough were understood about the nature of this decay, perhaps an internal "clock" mechanism could indeed be modeled in such a manner as to show why the decay slows. But, again, this phenomenon might be constrained only to the slowing of the decay of unbound subatomic particles, and hence it may be invalid to extrapolate this same slowing process to molecules and traveling twins.

Most importantly, however, it must be stressed again that time itself has not slowed down. Only the arbitrary units of measure with which we choose to mark time have slowed, whether atomic processes, frequency changes or molecular reactions. The distinction is important. In the relativistic model, clocks slowed down because time itself slowed down. No "mechanical" description could be provided as to why the clocks slowed, and, if it was, the effect would be additive. The clock would slow due to time dilation, and again due to the "mechanical" process. Though the effect is hard to distinguish because time is not tangible, it is exactly the same as explained for "length contraction" above. The means of measuring length was skewed (in this case the wavelength of the frequency of the time standard), but as was shown with the rope, length itself was not contracted. In the same manner, the means of measuring time (atomic processes) may have become skewed, but time itself remains unaffected. Quentin Smith has argued at length and quite successfully in *Language and Time* from a philosophical standpoint that "metaphysical time is the only time in the actual world and that it is the only time in any possible world in which there is time." William Lane Craig writes in *God and Real Time*:

> I find it surprising that anyone reading Einstein's 1905 paper can think that Einstein *demonstrated* that absolute simultaneity does not exist and that time is therefore relative to a reference frame. One who...rejects Einstein's definitions would regard these relatively moving observers as deceived due to the nature of their measurements, which fail to detect true time. In a real sense he would not regard Einstein's theory as a theory about time and space at all, but...as "a system of hypotheses about the behavior of light rays, rigid bodies, and mechanisms, from which new results about this behavior can be derived." Trapped in our locally moving frames, we may be forced to measure time by devices which are inadequate to detect the true time, but that in no way implies that no such time exists.

In Einstein's special theory of relativity, time, distance and mass are all relative quantities, depending on one's velocity and frame of reference. Simultaneity of distant events becomes a meaningless concept. So far to this point we have shown that time and distance are not relative quantities, but appear so only when trying to determine their nature by virtue of the transmission and reception of a light signal, and one obeying Einstein's second postulate at that. In chapter eight, we will dispense with the increase in mass due to velocity, for much the same reasons. We have also demonstrated that the simultaneity of distant events is in actuality the same as one would intuitively predict--in the words of Quentin Smith from chapter three, "Simultaneous means simultaneous and nothing else." The special theory is simply wrong on these counts. RCM theory, on the other hand, presents an intuitive, self consistent alternative, in keeping with all observable characteristics of *measurable* time as well as all the philosophical characteristics of *metaphysical* time. We have further shown that the gravitational red-shift, the first "test" of the general theory of relativity, actually has nothing to do with relativity at all. Having laid these foundations, we now turn to the two remaining classical "tests" of the general theory of relativity--the anomalous

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advance in the perihelion of mercury's orbit, and the deflection of a light ray grazing the sun. We will begin, not surprisingly, with another look at the gravitational red-shift.

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