Chapter 22

RELATIVITY
(FOR THE HUMOR OF IT!)

A.) The Michelson-Morley Experiment:

1.) Difficulty #1--Newtonian physics and inertial frames of reference:

a.) An inertial frame of reference is an unaccelerated (i.e., constant velocity) frame of reference.

b.) Newtonian physics is predicated on the assumption that fixed (inertial) frames exist. N.S.L. expressly states: "In an inertial frame of reference, objects in motion tend to stay in motion, objects at rest tend to stay at rest . . . etc."

c.) Fixed frames of reference are not easy to find. The Sun will not do--it's moving through space. The surface of the earth will not do--it is both rotating about its own axis and orbiting the sun.

i.) If you will remember, using N.S.L. on long-range projectile problems (i.e., projectile motion covering several miles) does not yield the correct touch-down position unless a fictitious force (the coriolis force) is included in the analysis. Why? Because the earth is not an inertial frame of reference--the earth is spinning.

d.) As Newtonian physics is based on the existence of inertial frames, early theoretical physicists spent a considerable amount of time mulling over where at least one such frame might be found.

2.) Difficulty #2--Light (a wave) moving through the vacuum of space:

a.) Young's experiment in 1801 established to the satisfaction of all that light is a wave.

b.) A wave is a disturbance that moves through a medium.

c.) Light travels 93,000,000 miles from the sun to the earth through a vacuum.

d.) The problem: If light is a wave disturbance, and a wave disturbance needs a medium to move through, what is the medium light uses as it passes through the nothingness of space?

3.) Scientists of the 1880's had an ingenious solution for both problems. They assumed that there exists an underlying stuff, a kind of fixed under structure, upon which space is built. This under structure was called ether after a similar idea from ancient Greece.

a.) The supposed existence of ether satisfied the inertial frame problem; the ether was assumed fixed;

b.) Ether also explained the wave through a vacuum problem; ether was the medium.

c.) In short, everybody and his or her mother believed that the ether existed . . . it had to for physics to work!

4.) The infamous Michelson-Morley experiment was designed to prove what was believed to be the obvious in the 1880's: that ether exists. The experiment was based on the following reasoning:

a.) Light travels at a fixed velocity relative to the ether ($3\text{x}10^8$ meters/second, or 186,000 miles/second).

b.) As the earth is moving through space, hence is moving relative to the fixed ether, the earth must be experiencing a kind of ether wind blowing against it.

i.) Explanatory example: Assume you are driving 35 mph in a car on a windless day. You put your hand out the car's window and feel wind against it. The appearance of wind is the consequence of your motion relative to the still air outside the car.

An ether wind against the moving earth is a similar situation.

c.) Light traveling in the direction of the earth's motion should appear to have slowed yielding a measured speed (relative to the earth) that is less than $3\text{x}10^8$ m/s.

i.) Explanatory example: You are driving your car at 35 mph in a wind that is blowing 30 mph in the same direction you are traveling. When you put your hand out the window, you will feel a breeze, but it won't be a 35 mph breeze; it will be a 5 mph breeze.

d.) Likewise, light traveling in the direction opposite the earth's motion should appear to have sped up yielding a measured speed (relative to the earth) that is more than $3x10^8$ m/s.

e.) <u>Bottom line</u>: If ether exists, the speed of light (relative to the earth) will vary depending upon the direction of the light beam. Michelson and Morley's experiment was designed to show this variability.

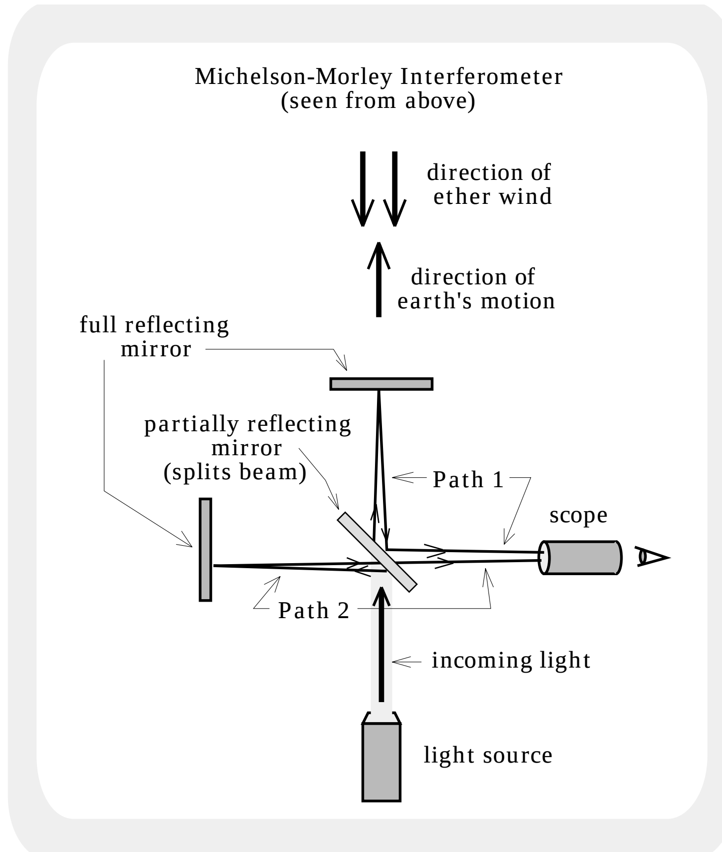

FIGURE 22.1

5.) The experiment did not actually measure the speed of light for various beam orientations. Instead, it used an interferometer mounted on a flat, horizontal table to observe interference fringes produced by two superimposing light beams. As seen from above, the device is shown in Figure 22.1. An explanation of the device and experiment is given below.

a.) A light source shines a ray of light on a half-silvered mirror. The mirror splits the ray. Half the light follows Path #1 while the other half follows Path #2 (see sketch). Path #1 and Path #2 are the same total length.

b.) Assuming the earth's motion is as pictured in Figure 22.1a, the light traveling along Path #1 will be affected by the ether wind more than will the light traveling along Path #2. As such, the time required for each ray to reach the viewing scope will differ.

Note 1: This time difference will exist only if the ether exists.

Note 2: A superficial look may lead you to conclude that the transit times for paths A and B should be the same. This is not the case. To see this, consider the following example: A boat capable of traveling 10 m/s on currentless water makes a round-trip that takes it 100 meters upstream, then back to its starting point (see Figure 22.2a). Will it take the same amount of time for the boat to make the trip if there is a 6 m/s current on the river (see Figure 22.2b)?

The temptation is to notice that the boat will move more slowly when going against the current but will go faster when going with the current, concluding that the speed difference will average out and the elapsed round-trip time will be the same for both scenarios.

In fact, that is not the case as the period of travel for each path is not the same. To see this, consider the following numerical example:
In currentless water, the elapsed time for each leg is 10 seconds (t = d/v yields 100 meters divided by 10 m/s, or 10 seconds per leg). The total time for the trip is 20 seconds. In water moving at 6 m/s, the boats effective speed moving upstream is 4 m/s. It takes (100 m)/(4 m/s) = 25 seconds to make the first leg of that trip. Without even taking the second leg into account, the times are obviously not the same.

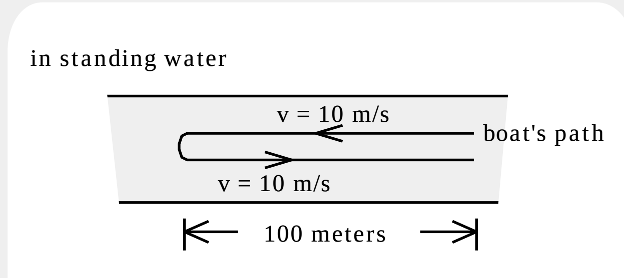

FIGURE 22.2a

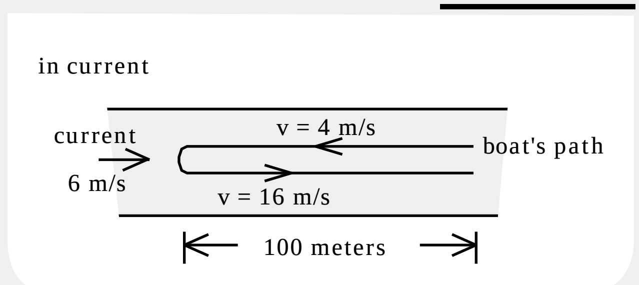

FIGURE 22.2b

c.) Because one ray will take more time to reach the scope than the other, there will be a phase shift between the two rays. When they re-combine, this will produce interference fringes like the ones shown in Figure 22.3a.

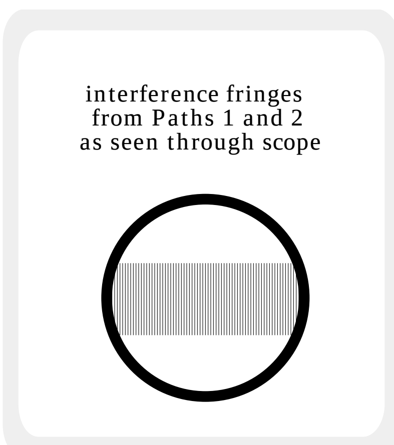

FIGURE 22.3a

d.) The Michelson-Morley experiment hypothesized that if the interferometer was rotated to the position shown in Figure 22.3b, the time variations between paths #1

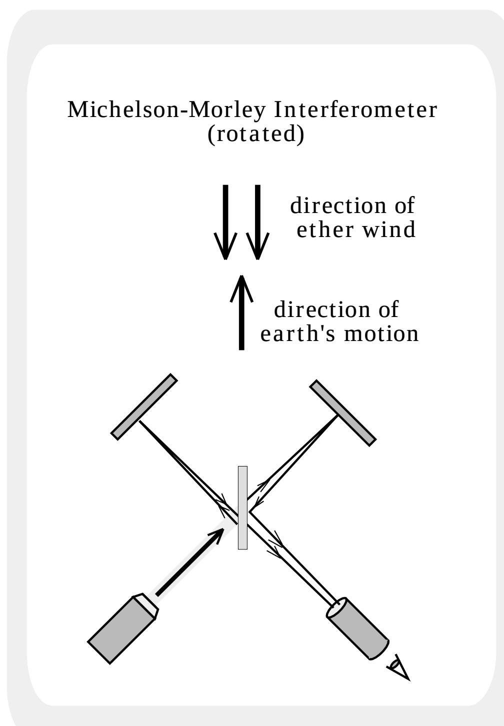

FIGURE 22.3b

and #2 would change, changing the phase shift between the rays. That, in turn, would make the interference fringes shift relative to their initial positions.

In other words, if the interference fringes were observed to move as the interferometer was rotated, it would imply that the speed of light was different for different path orientations. This, in turn, would indirectly verify the existence of ether.

e.) To the absolute horror of physicists around the globe, the fringes didn't budge when the experiment was executed. The speed of light was, evidently, the same no matter what the orientation of the light's path.

Put another way, the speed of light seemed to be the same no matter what frame of reference was used for the measurement.

f.) The end of the story is mildly amusing. Michelson and Morley were given a fair chunk of money to re-do the experiment. They bought the best interferometer money could buy, placed it on a concrete slab that was, itself, floated in a pool of mercury, and with the greatest of precision got the same results.

According to their findings, the measured speed of light did not change from one constant-velocity frame of reference to the next.

6.) The Michelson-Morley experiment started out as an exercise in proving-the-obvious; that ether exists. Its results were devastating. It meant that the accepted theories of light were badly flawed and, to add insult to injury, it meant that the theoretical underpinnings of Newtonian physics (the required inertial frame of reference) probably did not exist.

Physicists tried all sorts of maneuvers to save the ether theory, but it wasn't until a man named Einstein came along that things were finally rearranged into a coherent whole.

B.) Einstein's Special Theory of Relativity:

1.) Einstein made three assumptions:

a.) If ether cannot be experimentally observed, assume it does not exist;

b.) The laws of physics work the same in all stationary or constant-velocity frames of reference; and c.) The measured speed of light is the same in all constant-velocity frames of reference (frames that are apparently stationary fall into this category). That is, the speed of light <u>does not depend upon</u> the constant-velocity frame in which it is measured.

2.) Commentary on the first two assumptions:

a.) <u>The first assumption</u>--that ether does not exist--is a direct consequence of the Michelson-Morley experiment. It was a bold step, letting go of the theoretical mechanism that explained light's ability to travel through a vacuum--a step many physicists of the day were not willing to take. Einstein said, Enough. If ether cannot be experimentally observed, there is no reason to assume it exists at all.

b.) <u>The second assumption</u>--that the laws of physics work equally well in all constant-velocity frames of reference--was something with which even Newton would have agreed.

Consider:

i.) You are sitting in an airplane on the ground. You order tea. It arrives and what do you do? You pick up the tea pot, position it over the cup, and watch the tea follow a graceful, parabolic arc as it pours from the pot to the cup.

ii.) Two hours later the plane is at 35,000 feet. You decide to have tea again. It arrives. The fact that you are now moving 600 mph does not require you to position the cup some number of feet behind the pot so as to catch the liquid as it falls. All you need to do is repeat the movements you executed while pouring tea when on the ground.

iii.) In both constant-velocity frames of reference, the equations of physics are the same.

3.) Comments on <u>the third assumption</u>--the zinger: Einstein's third and considerably more exotic assumption was that the measure of the speed of light will always be the same in all stationary and constant-velocity frames of reference. This assumption also came as a direct consequence of the Michelson-Morley experiment. Although it looks innocuous enough, its presence within Einstein's theory suggests some very peculiar phenomena.

a.) For the sake of comparison, consider the following:

i.) A pitcher can throw a fast ball 90 mph. With a horizontal meter stick and timing device attached to you (Figure 22.4a shows the situation from above), you stand up to the plate. The pitcher lets loose; the ball approaches.

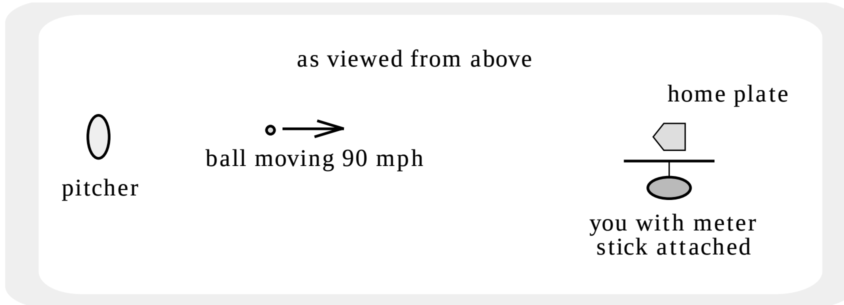

FIGURE 22.4a

ii.) As the ball passes the front end of the meter stick, the timer engages. As it passes the end of the meter stick, the timer disengages. How fast is the ball moving?

iii.) Relative to you, the ball travels 1 meter in a known time. Using the formula v = d/t, you can determine the velocity in m/s, then convert it to mph. Doing so yields a velocity of 90 mph.

iv.) Not being satisfied with so mundane an exercise, you try the experiment again with one difference. You run at the pitcher as he throws the ball (see Figure 22.4b). Assuming your running speed is 20 mph, the timer engages as the ball passes the front end of the meter stick; the timer disengages as it passes the end of the meter stick. How fast is the ball moving relative to you?

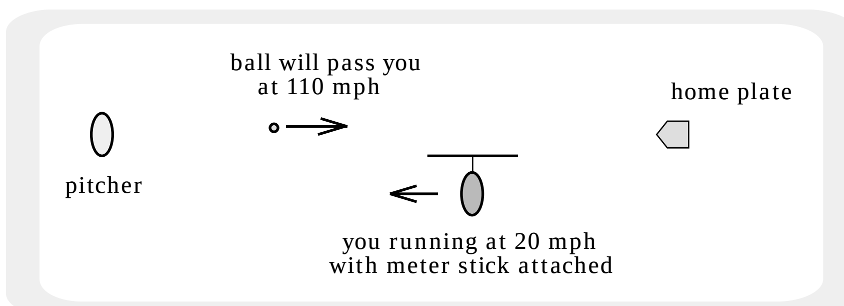

FIGURE 22.4b

v.) Relative to you (and the meter stick attached to you), the ball travels 1 meter in a known time. Using the formula v = d/t, you can determine the velocity in m/s, then convert it to mph. In doing the calculation, you calculate a velocity of 110 mph.

Note: This makes sense. Running toward the ball means it will pass you faster than if you were standing still or running away from the ball.

vi.) You try again by running away from the pitcher as he throws the ball. Relative to you (and the meter stick attached to you), the ball travels by you with a velocity of only 70 mph.

vii.) There is nothing dazzling here; in each case the apparent velocity of the ball, relative to your frame of reference, depends upon the relative motion between you and it.

b.) Taking Einstein's assumption into consideration, what happens when we do a comparable experiment using light?

i.) Assume you are sitting in a stationary space ship out in space. You radio a friend on the planet below and tell her to shoot a beam of light toward your ship. You have a velocity-measuring device similar to the one used in the baseball experiment (but with a much quicker timer), so as the beam passes through your ship (you have windows at both ends), your setup measures the speed of the passing light at 186,000 miles per second . . . the accepted speed of light.

ii.) Again, not being content with so ho-hum an exercise, you accelerate the ship away from the planet until its speed is 150,000 miles per second (I should probably mention how absurdly fast this is--our fastest military jets only go around three-quarters of a mile per second, and the space shuttle has a top-end of only 17 miles per second when in space). The beam catches up to the ship and passes through the velocity measuring device.

As this is a lot like the baseball problem, common sense leads us to expect that the device will register a speed of 186,000 - 150,000 = 36,000 miles per second. But that is not what happens. The device measures the passing light at a speed of 186,000 miles per second.

iii.) You then turned the ship around so that it approaches the planet at 150,000 miles per second. As the light beam from the planet passes through your ship, you might expect its speed to measure 336,000 miles per second. Not so. What you find is that the speed of the passing light, relative to your moving ship, is 186,000 miles per second . . .

c.) Is Einstein's assumption strange? You'd better believe it is! Nevertheless, it has been experimentally confirmed. Contrary to all common sense, the measured speed of light will always be 186,000 miles per second whether you are traveling into the light beam, away from the light beam, or just standing still relative to the light source. Just as the Michelson-Morley experiment suggested, the speed of light will always be the same when measured in a constant-velocity frame of reference.

4.) Why? Einstein had a perfectly simple, straight forward explanation for this apparently mysterious behavior of light, but to understand it we need to take a quick look back at Newtonian physics.

a.) When Newton created his physics, he made certain commonsense assumptions--assumptions that both you and I would undoubtedly have made if we had been in his place.

b.) One of his first informal assumptions had to do with time. By time, we are talking about "a measure of the rate at which the moment passes." As far as Newton was concerned, time was universal--something that was constant and independent of all else.

i.) This isn't that unusual. Time doesn't appear to be running any faster in the mountains than it does at the seashore; time appears to run at the same rate here as it does there.

c.) Another of Newton's informal assumptions had to do with space. For Newton, space was a homogeneous, three dimensional void.

i.) Again, not a hard assumption to accept when you think about it. A void does seem to be the same in all directions (i.e., homogeneous), and space does seem to be associated with length, width, and height--three dimensions.

d.) Einstein's argument began by noticing that speed is simply the ratio of a spatial measurement (a distance traveled) and a temporal measurement (the time to travel that distance). Einstein then observed that the only way the speed of light could possibly be constant in all constant-velocity frames was if there existed a not-so-obvious relationship between spatial and temporal measurements. In plain English, he said that space and time are NOT independent of one another.

e.) Taking this a little further, Einstein noted that if time is not the universal constant Newton thought it to be, and if time and space are somehow related, the measure of the rate at which the moment passes must depend upon WHERE the measurement is being taken.

That, dear reader, is what gave Einstein the idea that real space is not a three-dimensional, homogeneous void, but rather a FOUR DIMENSIONAL entity whose fourth dimension is (gulp) TIME itself.

Put another way, Einstein's Theory of Relativity maintains that TIME IS QUITE LITERALLY A PART OF THE FABRIC OF SPACE. In physics, this real space is called either space-time or four-space.

5.) The mathematics of Relativity:

a.) Part of the reason full-blown Special Relativity (not to mention General Relativity) is not taught at the high school level is that Einstein's physics requires four dimensional math. Furthermore, the theory assumes a geometry that is non-Euclidean.

i.) You are familiar with non-Euclidean geometries, you just aren't aware of it. Spherical geometry, for instance, is the geometry of the earth's surface.

One difference between the two: In Euclidean geometry the sum of the interior angles of a right triangle is 180^o. In a spherical geometry the sum of the interior angles of a right triangle is greater than 180^o (see Figure 22.5).

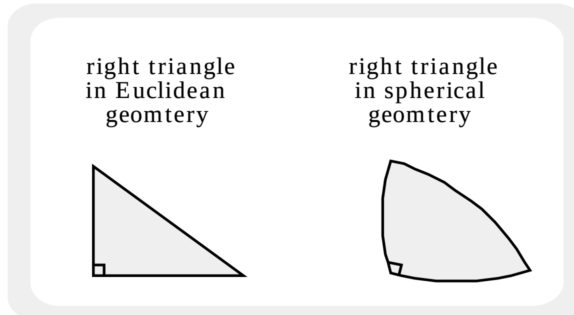

FIGURE 22.5

ii.) As a minor point of order: Relativity employs Minkowskian geometry and the mathematics is associated with what is called Riemann space.

6.) IMPORTANT TECHNICAL NOTE: When you or I measure a time interval, we position ourselves at a particularly convenient spot, use a single stop watch, start the watch at the beginning of the interval and stop the watch at the end. When dealing with an object that is moving at extremely high velocity, this approach doesn't work. Consider:

a.) A very fast moving rocket (velocity v_r) approaches an observer located at Point A. When the rocket is a horizontal distance L units from Point A (call this Point B) the rocket lets loose with a burst of light that is directed straight at the observer (see Figure 22.6).

b.) The observer starts her stop watch when the light burst arrives. She stops her stop watch as the rocket passes her. The time interval is Δt.

c.) If the observer calculates the rocket's velocity using the

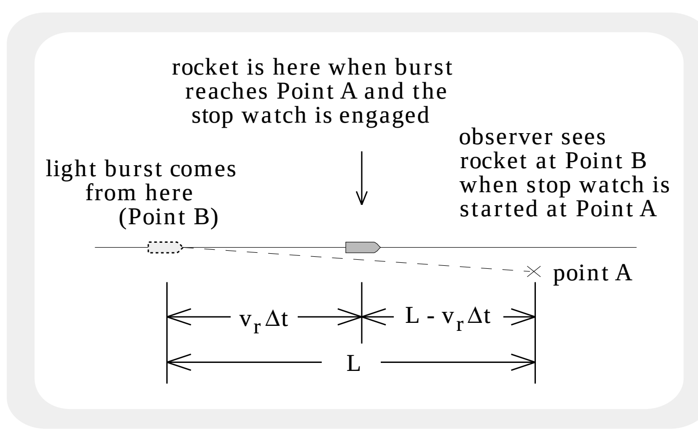

FIGURE 22.6

measured time interval Δt and the apparent distance traveled L, she will get an erroneous velocity result. Why?

d.) The problem is that when the stop watch is started, the rocket appears to be at Point B (the light's origin) even though it has traveled a considerable distance during the time required for the light to reach the observer. As such, the distance the rocket actually travels while the stop watch is running is not L but $L-v_r\Delta t$.

To alleviate this light time delay problem, a different theoretical technique is used whenever time-interval measurements are required in relativistic problems. The approach is as follows:

i.) Set up a series of closely spaced, stationary (relative to your chosen frame of reference), synchronized clocks in space.

ii.) To measure how long it takes the rocket to get from Point B to Point A: As the rocket passes Point B, have the clock at Point B register that time. As the rocket passes Point A, have the clock at Point A register that time. At some later time, visit and record the times registered on both clocks. The difference between those two times will give you the time interval.

e.) As picky as this may sound, WHENEVER A TIME-INTERVAL IS MEASURED, it is always assumed that the measurement has been made using a set of synchronized clocks. Likewise, length measurements are always taken using a lattice of meter sticks set up side by side in the frame of reference in which the measurement is to be taken.

7.) One of the consequences of Einstein's assumptions is the phenomenon of TIME DILATION. Consider:

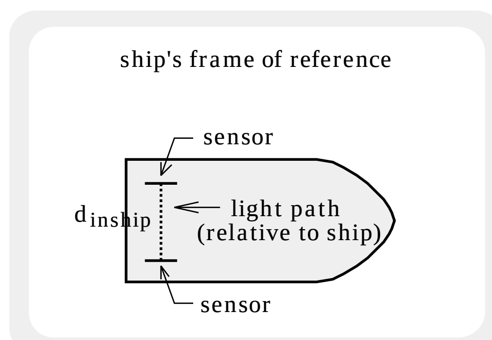

FIGURE 22.7a

a.) Two sensors are mounted inside a space ship that moves with velocity v relative to an inertial (unaccelerated) frame of reference (in this case, relative to space). When a photon of light passes from one sensor to the other, synchronized clocks inside the ship are used to measure the photon's transit time Δt_{inship} (see Figure 22.7a). Also, a lattice of meter sticks is used inside the ship to measure the photon's path-length (call this d_{inship}).

Put a little differently, a scientist inside the ship uses his clocks and his meter sticks to make the measurements.

b.) A second scientist floats stationary in space as the ship passes. She uses her synchronized clocks and lattice of meter sticks to measure the photon's path length ($d_{outside}$) and transit time ($\Delta t_{outside}$) in her frame of reference. That is, she measures the net distance the photon travels in her frame of reference using her meter sticks, and the photon's elapsed-time-of-flight using her clocks. This information is presented in Figure 22.7b.

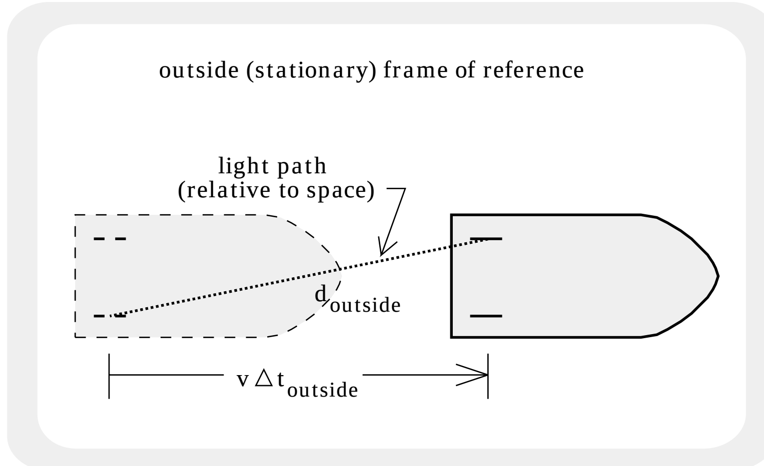

FIGURE 22.7b

c.) Notice that during the time interval $\Delta t_{outside}$, the ship moves a distance $v\Delta t_{outside}$.

d.) Manipulating the definition of speed ($v = d/t$) to get an expression for the distance traveled by the light as viewed from both frames of reference (i.e., $d = vt$), and remembering that in both cases the speed of light must be c (i.e., $3\text{x}10^8$ m/s), we can write:

$$d_{inship} = c\Delta t_{inship}$$

and

$$d_{outside} = c\Delta t_{outside}.$$

e.) Coupling these two equations with the right triangle shown in Figure 22.7c, we can write:

$$d_{outside}{}^2 = d_{inship}{}^2 + (v\Delta t_{outside})^2$$

$$\Rightarrow (c\Delta t_{outside})^2 = (c\Delta t_{inship})^2 + (v\Delta t_{outside})^2.$$

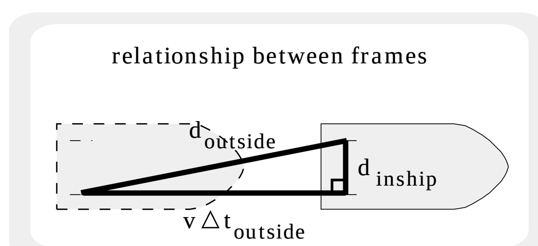

FIGURE 22.7c

f.) Manipulating this equation to solve for the time-interval relationship between the outside scientist's clocks and the inside scientist's clocks, we get:

$$\Delta t_{outside} = \Delta t_{inship} / [1- (v/c)^2]^{1/2}.$$

In other words, the transit time as measured in the moving space ship is different from the transit time as measured by the outside observer.

Examining the relationship suggests that the ticking of a clock inside the ship measured by an observer outside the ship will tick more slowly than will a clock outside the ship (if this isn't clear, the example below should help). The significance is even greater, though. In fact, not only will the clock seem to move more slowly inside the ship, EVERYTHING will seem to move more slowly inside the ship.

i.) There is an interesting example of this time dilation phenomenon that comes from the world of sub-atomic particles.

ii.) Cosmic radiation interacting with upper-atmosphere gasses produces radioactive particles called mu-mesons. A mu-meson has a half-life of around 1.5×10^{-6} seconds (that is, if 1000 are created at once, half will decay into something else within the first 1.5×10^{-6} seconds; half of the 500 left will decay in the next 1.5×10^{-6} seconds; half of the 250 left will decay in the next 1.5×10^{-6} seconds; . . . etc.).

iii.) Disregarding Relativistic effects, a mu-meson traveling at close to the speed of light will cover about 450 meters in one half-life. This means that if mu-mesons are created solely in the upper atmosphere, which seems to be the case, there should be very few found at sea level.

What is peculiar is that, in fact, there are lots of them at sea level. The question is, "Why?"

iv.) Due to time dilation, mu-mesons can travel approximately 9 times further (relative to the earth) in one half-life than would be expected. That is, because they are moving at close to the speed of light (relative to the earth), their internal clock will read 1.67×10^{-7} seconds (that is, one-ninth of 1.5×10^{-6} seconds) during 1.5×10^{-6} seconds of Earth time.

As such, they are able to reach the earth's surface with impunity.

g.) Example: A chimpanzee sitting in a space ship moving at .8c (eight-tenths the speed of light) eats one banana every five seconds as measured by a Timex on the chimp's wrist. An observer in a stationary space ship uses his set of synchronized clocks and a chimp banana-eating counter to measure the chimp's banana consumption as the chimp's ship passes. If the observer watches for 15 seconds, how many bananas will the chimp eat in that period?

Solution: To do the problem, we need to know how much chimp time passes during the observer's 15 seconds. Using the relationship derived above:

$$\Delta t_{outside} = \Delta t_{inship} / [1- (v/c)^2]^{1/2}$$
$$(15 \text{ sec}) = \Delta t_{inship} / [1- (.8c/c)^2]^{1/2}$$
$$\Rightarrow \quad \Delta t_{inship} = 9 \text{ seconds.}$$

In 15 observer seconds, the chimp will eat 1.8 bananas.

h.) As can be seen by the example, time in the chimp's ship appears to have slowed down, relative to time in the observer's ship. This is not a trick. The observer will really see the chimp moving in slow motion. In fact, the chimp, the chimp's watch, the chimp's heartbeat, even the vibratory motion of the atoms in the chimp's body (assuming this could be measured), will all appear from the outside observer's perspective to be moving more slowly than normal.

The chimp, on the other hand, will not find anything abnormal about his situation. His clock will go tick, tick, tick as usual; his motion, as viewed by himself, will be as it always has been.

j.) Now, for the killer: We have already established that the observer in the other ship sees the chimp slowed down. Does that mean the chimp sees the observer speeded up?

The theory answers, "No!" We are again left with the question, "Why?"

i.) In the chimp's frame of reference, everything is normal. Because the laws of physics are identical in all constant-velocity frames, he doesn't know whether he is at rest or moving at .8c. Being an ego-centered chimp, he thinks he's the center of the world and all things revolve around him. In other words, when the chimp looks out the portal, he sees a ship passing what he believes is his stationary ship with a velocity of .8c.

ii.) In Relativity, no constant-velocity frame is preferred over another as the mathematics can not tell the difference between the two frames (everyone thinks it's the other guy who is moving). In short, the chimp will see the observer in the other ship SLOWED DOWN in the same way that the observer in the other ship sees the chimp SLOWED DOWN.

To understand how this can be, physically, we need to more closely consider the nature of four-space.

8.) Space-Time:

a.) Consider the following ANALOGY: A thin screen is backlit by a bright light. A book is placed between the screen and the light (see Figure 22.8a). What do you see when you view the screen from the side opposite the light source?

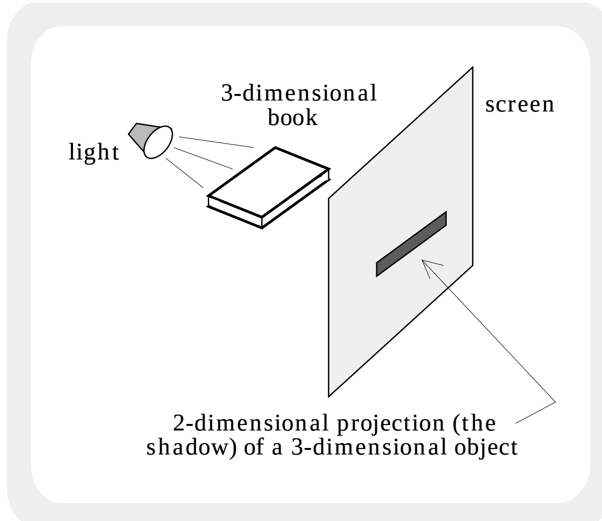

FIGURE 22.8a

You see the book's shadow as it is projected on the two-dimensional screen. That is, you see a two-dimensional projection of a three dimensional object. What is more, you see different projections as the book is rotated. As shown in Figure 22.8b, the projection can look like a rectangle, a diamond, or a line (assuming the book is thin).

THE BOOK DOESN'T CHANGE, BUT ITS PROJECTION DOES as the orientation of the book (relative to the light) is altered.

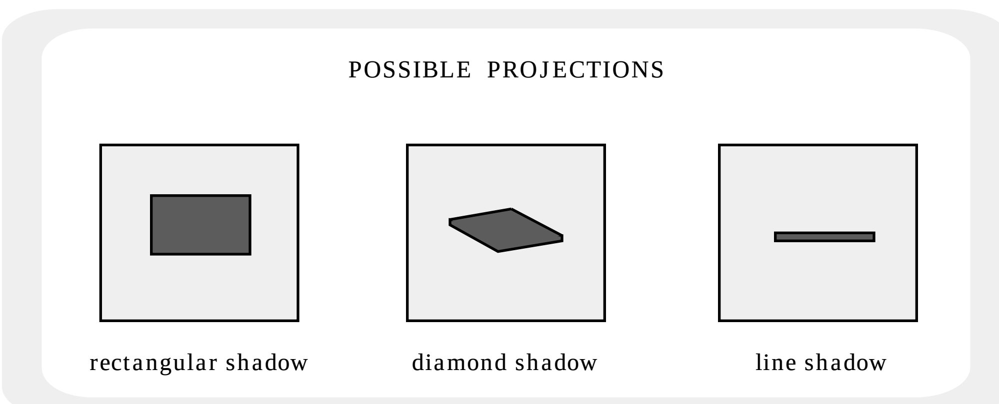

FIGURE 22.8b

b.) According to Einstein, space is really a four dimensional entity. That means that objects in space are really four-dimensional objects. Einstein maintained that when you measure a physical object, you are measuring a three-dimensional projection of a four-dimensional object. What is different about the two situations is that our book is purely spatial; Einstein's geometry includes time. That means the projection we are measuring is not only space related, it is also time related.

c.) Just as a change in the book's orientation can change the two-dimensional projection produced by the backlit screen, so can the three dimensional projection of a four-dimensional object also change.

According to Einstein, what changes your projection of another object is a high relative velocity. That has the affect of "rotating" the three dimensional projection of four-dimensional objects. In the case of the time axis, this rotation is measured as a slowing of time--as a time contraction.

d.) This physical contraction has another aspect to it. Specifically:

i.) Although the time coordinate appears to contract so time appears to move more slowly in the "other" ship (no matter which ship is the other ship), there is also an apparent LENGTH CONTRACTION in the direction of motion (see Figure 22.8c).

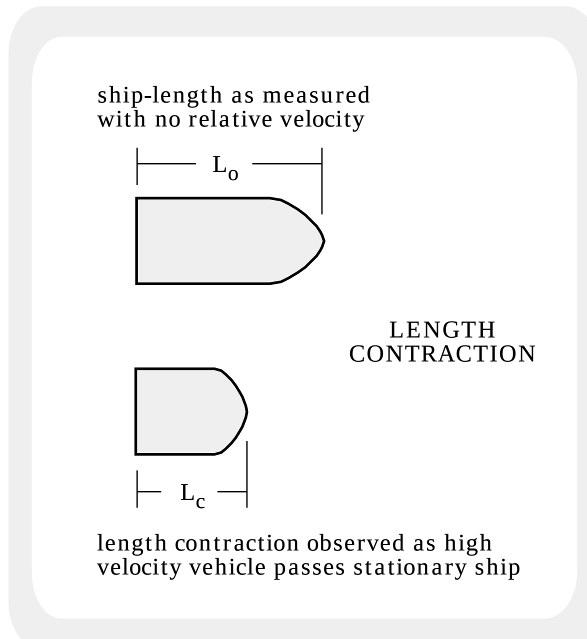

FIGURE 22.8c

ii.) Put another way, the observer will measure the chimp's ship as shorter than would have been the case if the two ships had been sitting side by side (the contraction occurs only in the direction of motion).

Furthermore, by the principle of reciprocity, the scientist's ship will appear length-contracted to the chimp.

iii.) This contraction is called the Lorentz-FitzGerald Contraction after a man named Contraction (a little physics humor . . . the real, true joke is that it is called the Lorentz-FitzGerald Contraction because it was derived by Poincare).

iv.) Without proof, the expression that relates the chimp's measure of his ship's length--I'll call this L_o--to the scientist's measure of the chimp's apparently contracted ship-length L_{contr} is:

$$L_o = L_{contr} / [1 - (v/c)^2]^{1/2}.$$

9.) <u>SPACE-TIME DIAGRAMS</u>: A useful way to visualize objects in space-time is with a space-time diagram. Because it is not possible to generate a four-dimensional graph on a two-dimensional piece of paper, we will simplify the situation by throwing out one spatial dimension.

a.) Assume you live in a two dimensional world (you can move right and left and forward and backward, but not up or down). Assume also that time is a part of the geometry of space. With these assumptions, the grid used to graph one's <u>position</u> in space-time will have three dimensions (that is, you will need two spatial axes and one time axis).

b.) Figure 22.9 uses such a coordinate grid to show the position of a stationary ant. Note that there is no variation in the x and y coordinates but there is motion along the time axis. That is because the ant never stands still in time--objects are always moving along the time axis.

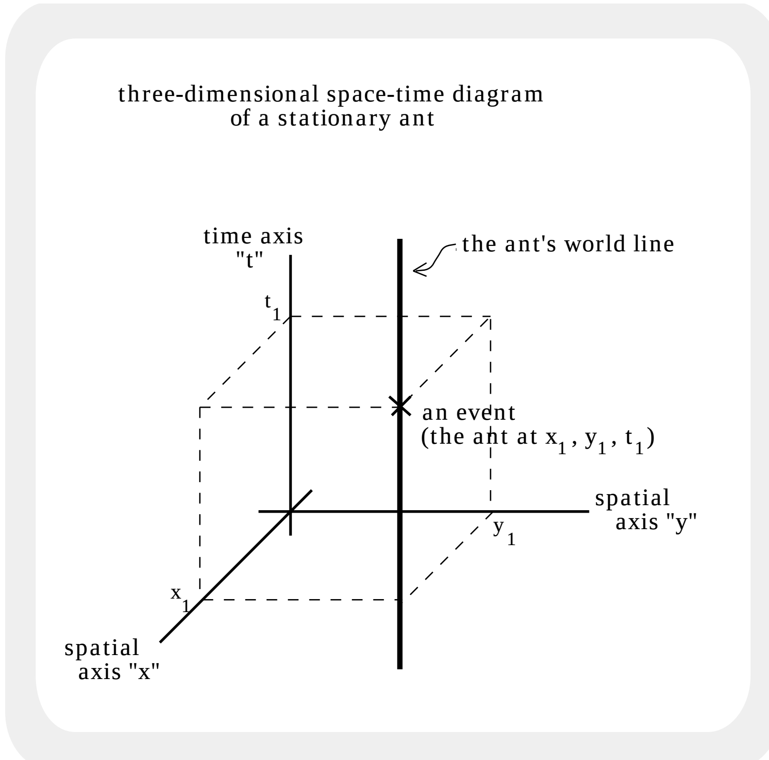

FIGURE 22.9

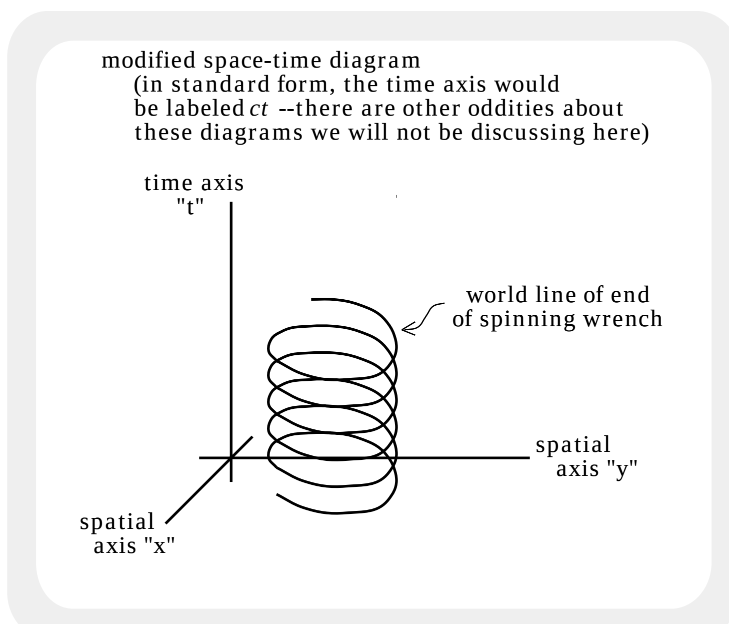

FIGURE 22.10

Note: The modified space-time diagram shown in Figure 22.10 is not standard. If you are interested in learning more about real space-time diagrams, get the book SPACETIME PHYSICS by Taylor and Wheeler.

c.) An object's WORLD LINE defines the object's motion in space-time. A particular point on a world-line is called an event (see Figure 22.9).

d.) Figure 22.10 (previous page) shows the world-line for a point on the end of a spinning wrench in the x-y plane.

10.) SIMULTANEITY: One of the consequences of Einstein's physics is that there is no certain way of telling whether two events that happen far apart occur at the same time.

11.) Simultaneity Example #1: A 20 meter long pole is accelerated to .9c. It approaches a 10 meter long barn (see Figure 22.11). Will the pole fit completely into the barn?

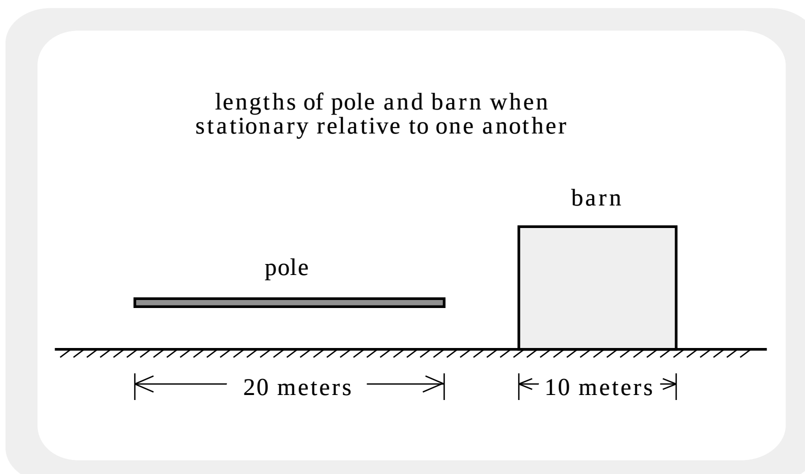

FIGURE 22.11

SOLUTION: Whether the pole fits depends upon the frame of reference from which you view the problem.

a.) From the frame of reference of the barn (i.e., with synchronized clocks and a meter stick lattice in the barn's frame of reference), the pole will length-contract by:

$$L_{\text{pole in poles frame}} = L_{\text{pole in barn's frame}} / [1 - (v/c)^2]^{1/2}$$

$$\Rightarrow \quad L_{bf} = L_{pf}\,[1 - (v/c)^2]^{1/2}$$
$$= (20\text{ m})\,[1 - (.9c/c)^2]^{1/2}$$
$$= 8.7\text{ meters.}$$

From the barn's frame of reference, the pole's length is 8.7 meters. What this means is that if someone standing at the front door were to slam that door shut just as the rear end of the pole entered, there would be an instant after the front door closed before the front end of the pole came

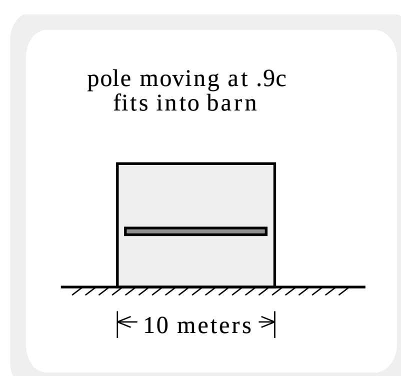

FIGURE 22.12a

crashing through the barn's rear-wall window. Put another way, the pole will fit inside the barn (see Figure 22.12a).

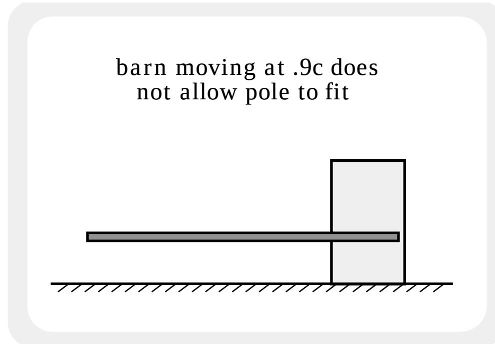

FIGURE 22.12b

b.) From the frame of reference of the pole (i.e., from the view of an ant riding on the pole--an ant with its own synchronized clocks and lattice of meter sticks): From this frame, the ant and pole are stationary while the barn approaches at .9c. As such, the barn length-contracts as shown in Figure 22.12b.

The math in this case follows:

$$L_{\text{barn in barn's frame}} = L_{\text{barn in pole's frame}} / [1 - (v/c)^2]^{1/2}$$

$$\begin{aligned} \Rightarrow \quad L_{pf} &= L_{bf}\,[1 - (v/c)^2]^{1/2} \\ &= (10\text{ m})\,[1-(.9c/c)^2]^{1/2} \\ &= 4.35\text{ meters.} \end{aligned}$$

From the pole's frame of reference, the barn's length will be 4.35 meters and the pole will not fit into the barn (see Figure 22.12b).

c.) So which is it? Will the pole fit into the barn or won't it?

d.) What is important to realize here is that that's the wrong question to ask! Each is correct within the context of the frame from which the measurements are taken. That is:

i.) If you happen to be standing next to the barn, you will actually see the pole fit into the barn before the front of the pole crashes out through the barn's rear window.

ii.) If you are moving along with

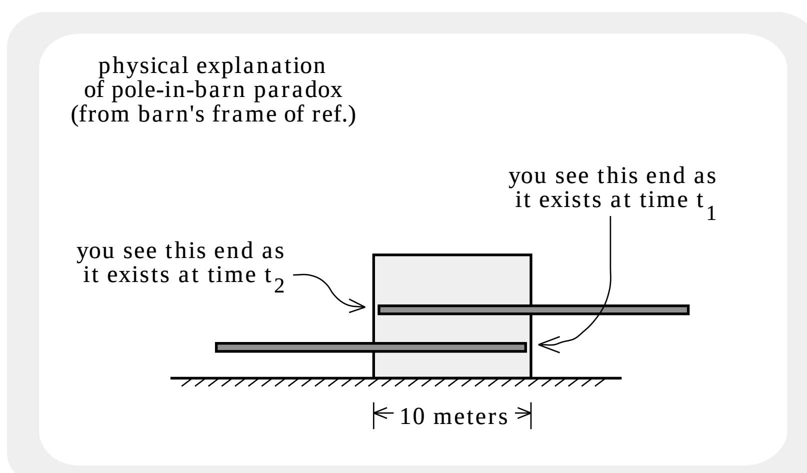

FIGURE 22.12c

the pole, you will actually see the front of the pole crash through the barn's rear window before the end of the pole enters the front door.

e.) But how can this be? It is a consequence of the nature of four-space. When the pole is moving at high velocity relative to you and the barn, you are not seeing the front of the pole and the back of the pole as they exist at the same point in time. What you are seeing is the front of the pole as it exists at one point in time and the back of the pole as it exists at another point in time (see Figure 22.12c). Because you are looking into a fast moving (relative to you) frame of reference, the two events are not simultaneous in time.

12.) Simultaneity Example #2: Two individuals observe two lightening flashes that occur some distance apart. One of the individuals, a man, stands in a field. The other individual, a woman, is in a train. There is relative motion between the two.

It is known that when the lightening flash A occurs, the man is opposite the woman and the physical location of the flashes are equidistant from both (that is, the distance between flash A and the man, and flash B and the man, are the same; likewise for the woman). See Figure 22.13a. Fur-thermore, the man sees the flashes at the same time (i.e., the light from both reaches him at the same instant) and the woman sees the flashes at different times (flash B arrives later than flash A). Did the flashes occur simultaneously? (This example comes from Relativity for the Millions, by Martin Gardner).

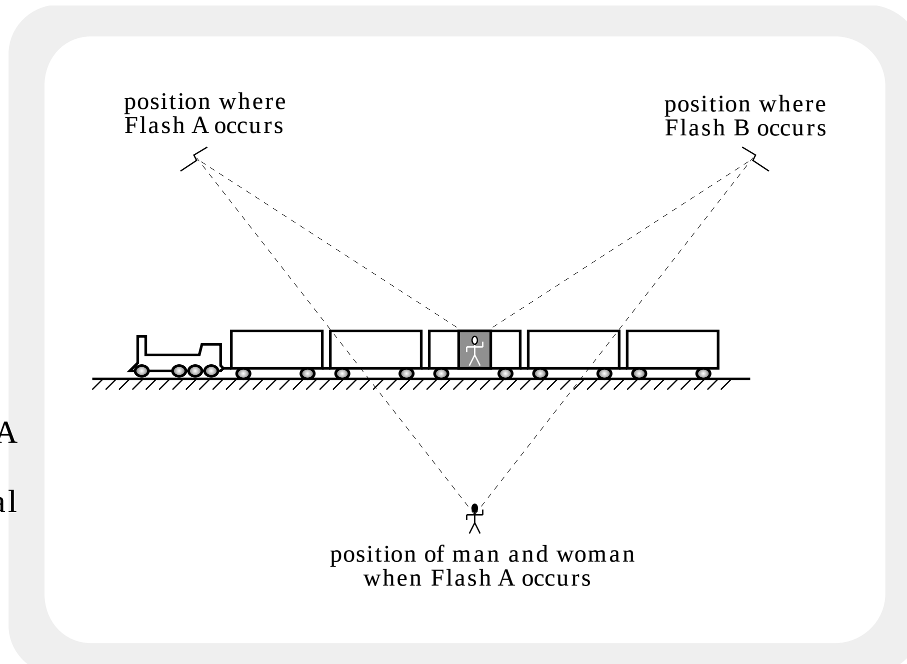

FIGURE 22.13a

SOLUTION: The answer depends upon whether the events are viewed from the man's frame of reference or the woman's frame of reference.

a.) From the man's frame of reference (see Figure 22.13b):

i.) As far as the man is concerned, his frame of reference is stationary.

ii.) The distance between him and both flashes is the same.

iii.) As he sees both flashes arrive at the same time, he concludes that the flashes must have occurred simultaneously.

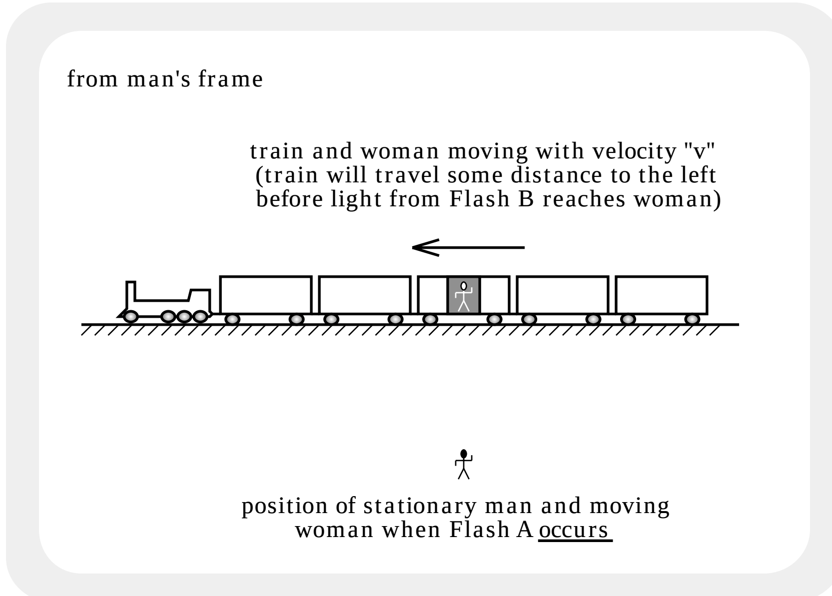

FIGURE 22.13b

b.) If the woman takes the man's frame of reference as stationary, her analysis agrees with his. That is:

i.) She knows she is equidistant from the flash origins when she is opposite the man.

ii.) She knows that flash A <u>occurs</u> when she is across from the man.

iii.) She knows the speed of the train. She can calculate how far the train travels by the time the light from flash A reaches her. With that information, she can calculate how long thereafter the light from flash B should arrive if, in fact, flashes A and B occurred at the same time.

iv.) She makes her calculations and finds that the calculated and observed time differences are the same. Her conclusion is that the flashes must have occurred simultaneously.

c.) <u>From the woman's frame of reference</u> (i.e., from the frame of reference of the train--see Figure 22.13c):

i.) As far as the woman is concerned, her frame of reference (and that of the train) is stationary.

ii.) She knows the distance between herself and both flashes is the same when both flashes occur whether they occurred simultaneously or not.

How so? The flash origins are the same distance apart when she is opposite the man, and she is not moving! Conclusion: the distance between the flash origins and the woman will ALWAYS be the same in this frame of reference.

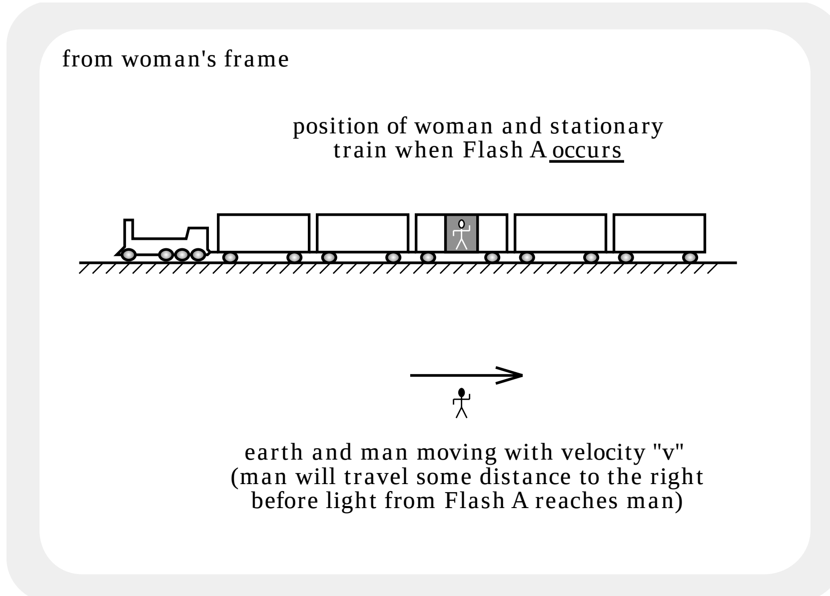

FIGURE 22.13c

iii.) The only way the flashes can travel equidistant paths and arrive at different times is if they flash at different times. In short, the two flash events must not have occurred simultaneously.

d.) If the man takes the woman's frame of reference as stationary (i.e., if he accepts the notion that the earth is moving underneath the stationary train and, hence, that he is moving to the right), his analysis will agree with hers. Specifically:

i.) He knows he is equidistant from the flash origins when he is opposite the woman.

ii.) He knows that flash A occurs when he is opposite the woman.

iii.) He knows that by the time the light from flash A reaches him, he will have moved to the right of the stationary woman. That means the light from flash A moves further to reach him than does the light from Flash B.

iv.) But the light from the two flashes arrive at the same time, so flash A must have occurred before flash B and the two events must not be simultaneous.

e.) Bottom line: Simultaneity depends upon the frame of reference you choose. If you find it evident in one frame, it may not be evident in another even though both frames are perfectly legitimate.

f.) Again, the question "Which one is correct?" is the wrong question to ask. The results from each frame are correct within the context of that frame.

i.) This seems contradictory, but it's not. Humans are not equipped to think four-dimensionally, so it shouldn't be surprising to find that the four-dimensional world appears strange when viewed from different frames of reference.

Part of the appeal of Relativity is that within its mathematical structure are the transformations required to translate from one frame of reference to another. That means that as long as you are consistent in solving a problem within the context of one frame only, you can then use the transformations to determine how things will look from any other frame.

In short, there is linkage within the system even if individual parts don't, on the surface, appear to agree.

C.) Einstein's General Relativity:

1.) The Special Theory of Relativity deals with phenomena associated with constant-velocity situations. The General Theory of Relativity deals with situations in which acceleration is present (this includes the study of gravitational effects).

2.) We have already established that spatial and temporal measurements are related to one another; that time is literally a part of the fabric of space. As such, the rate at which the moment passes is related to where the moment passes. A perfectly legitimate question is, "What makes time move more slowly in some places and faster in other places?"

The answer: "The presence of matter." Specifically:

a.) Out in the void between the stars where there is no appreciable matter, space-time is homogeneous--the same here as there. Time runs at some constant rate, the same everywhere. Regions like this are called "flat space" (flat in the sense that there is no variation in the space-time structure).

b.) But sidle up to a planet, star, or other massive object and, assuming you have the equipment required to make the measurements, you will find that the geometry of space-time differs from place to place. In an attempt to verbally depict this inhomogeneity, physicists call regions like this either warped space or curved space.

i.) To put in physics terms, the closer one gets to a massive object, the more space-time in the vicinity warps.

c.) One observable consequence of warped space is related to time. The rate at which the moment passes depends upon the curvature of the warped space in which the measurement is taken. The more warped space-time is, the more deeply curved the region and the more time slows down (actually, curvature is related in a complicated way to the second derivative of the rate at which time passes).

Note: This is not like the apparent slowing of time in the chimp's fast-moving space ship. That was a situation in which high relative velocities rotated the perceived three-dimensional projection of four-dimensional objects. The phenomenon we are examining now is the consequence of space-time being altered quite literally by the proximity of a massive object.

i.) As bizarre as this may seem, this slowing of time as one gets closer to the surface of the earth (or any massive body) has been experimentally observed. The Pound-Rebka experiment at Harvard University used a gamma ray source, a Mossbauer detector and the Doppler effect to indirectly show that time on one floor of a Harvard building ran more slowly than time on an upper floor of that same building. In 1969, another experiment determined that time measured at the Bureau of Standards at Boulder, Colorado (altitude 5400 feet above sea level) gains 5 microseconds per year relative to a similar clock at the Royal Greenwich Observatory in England (altitude only 80 feet above sea level). Nowadays, all clocks used to track international time (i.e., in Paris, in Tokyo, etc.) must be adjusted to correct for the fact that time runs more slowly at sea level than it does in the mountains.

3.) Acceleration fields--Newton's theory:

a.) Newton dealt with the acceleration field we associate with gravity using what is called an action at a distance model. He theorized as follows:

i.) Massive bodies are attracted to one another due to a force, a gravitational force. The magnitude of that force is Gmm_1/r^2, where m_1 is taken here to be the mass feeling the force, m is the field-producing mass (m and m_1 are actually interchangeable), r is the distance between the center of mass of m and the center of mass of m_1, and G is a constant.

b.) When m_1 is in a gravitational force field, it will accelerate (assuming there are not other forces present to prevent it from doing so). Using the gravitational force equation quote above with Newton's

Second Law, we can write $\frac{Gmm_1}{r^2} = m_1 a$. Dividing out the m_1 terms leaves us with the acceleration expression $a = \frac{Gm}{r^2}$.

c.) Observation 1: According to our derived acceleration equation, the acceleration of m_1 is completely independent of the size of the mass of m_1. Evidently, it doesn't matter whether a body's mass is one kilogram or two kilograms or three kilograms (neither does it matter what the body is made of), the body will always accelerate at the same rate at a given place (on Earth at sea level, this rate is the ever favorite 9.8 m/s^2).

d.) Observation 2: As an object's acceleration has nothing to do with its mass, even massless photons of light will fall when in an acceleration field like the one produced by the earth (that's right, light passing by the earth at sea level falls at 9.8m/s^2 toward the earth's center--this assertion was first verified using satellites in the early 1990's).

e.) Reiterating: Newton's theory is based on an action at a distance model--one body affecting a distant body through what Newton called a gravitational force.

4.) Acceleration fields--Einstein's theory:

a.) Put simply, Einstein did not view gravitational effects (apples falling out of trees, etc.) from an action at a distance perspective. Einstein suggested that such effects were the consequence of a body's interaction with the local geometry in which it resides. He maintained that bodies accelerate at 9.8 m/s^2 at the earth's surface because that is what the curved space-time geometry at the earth's surface motivates bodies to do.

b.) An example:

i.) According to Newton, the moon follows its orbital path around the earth because the earth applies a gravitational force (action at a distance) that pulls the moon centripetally into a nearly circular trajectory.

ii.) According to Relativity, the massive earth warps the <u>geometry</u> of the space-time in which the moon moves.

iii.) In relativity, there are no outside action at a distance gravitational forces acting on the moon, so it moves as all force free objects do--it moves in a straight line. But because the geometry of space in which the moon travels has been warped (curved!), the moon follows this straight line path in a curved geometry. As such, it moves on what is to us a curved path around the earth.

iv.) This following a straight line path in a curved geometry is not as bizarre as you might think--even you can experience it. All you have to do is begin walking toward the east; sooner or later you will come up over the horizon from the west. You will have followed a straight line path, but you will have done it in a curved (spherical) geometry (see Figure 22.14).

This is similar to what Einstein believed the moon was doing, except in the case of the moon the curvature is due to warped space-time.

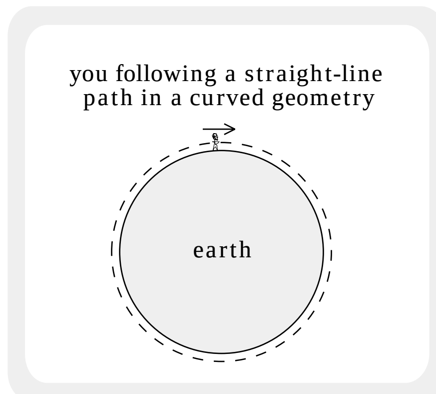

FIGURE 22.14

c.) A commonly used analogy between curved space-time geometry and everyday life is as follows: Visualize a bowling ball placed on a thin, tightly stretched piece of rubber. The rubber's geometry will deform as shown in Figure 22.15. Shoot a marble past the ball and it will change directions. Why? Not because there is a gravitational/action at a distance-type force between the ball and the marble (this would be analogous to Newton's theory of gravity). The marble changes directions because it is affected by the geometry of the space through which it passes.

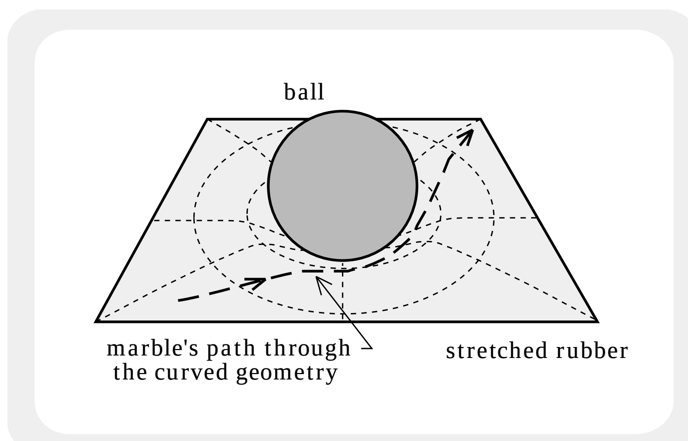

FIGURE 22.15

d.) In a nutshell, Einstein attributed gravitational effects to the curvature of space-time. An interesting astronomical experiment in 1919 was done to test this hypothesis:

i.) Under normal circumstances, sun light blots out all other star light during the day. Only during a total solar eclipse can light from other stars be seen.

ii.) In 1919, there was a total eclipse. Before the eclipse, astronomers realized that one, known, particularly bright star would just peek out from the behind the sun's disk during the eclipse. In other words, with the sun blanked out by the moon, that star's appearance from behind the sun would be visible.

iii.) Newton's theory of gravity predicts that a photon of light passing close to the sun should be deflected by the sun's acceleration field (remember $a = \frac{Gm}{r^2}$). A little Calculus shows that the angle of deflection from its otherwise straight-line path in such cases is $\frac{2Gm}{rc^2}$, where m is the mass of the field-producing body (the sun in this case), c is the speed of light, and r is the closest distance between the body and light's path (this is called the impact parameter).

Assuming Newton was correct, scientists calculated the exact time the bright star in the 1919 eclipse would show itself from behind the sun.

iv.) Einstein's theory, based on the idea that a body's acceleration is related to the curvature of the geometry of space through which it passes, produced a theoretical light deflection angle of $\frac{4Gm}{rc^2}$--twice as large as that determined using Newton's theory. As a consequence, assuming that Einstein's theory about warped space was correct, the light from the star should show itself from behind the sun prematurely (prematurely, that is, in comparison to Newton's suggested time of arrival).

v.) The experiment was done and the star's light presented itself exactly as Einstein's theory predicted. Light had, evidently, followed a straight-line path through the curved geometry in close to the sun, and had become visible to the earth before the star was geometrically beyond the edge of the sun's disk.

Einstein's theory was corroborated.

5.) The TWINS PARADOX and Special Relativity:

a.) Assume you and your twin sister are both twenty years old. You get into your space ship, accelerate to a high velocity over a long period of time, then after ten of your years (i.e., years as measured by your space-ship clock), you return. Biologically, you are thirty years old. Why? Because ten of your years have passed. But when you open the space-craft's door and greet your sister, you find she is forty years old.

This is a statement of what is called the Twins paradox. Before we get to the paradox itself, let's examine the basis of the situation. How can the twins be different ages?

b.) Although acceleration problems generally fall within the domain of General Relativity, we can cleverly make this acceleration problem into a series of constant velocity problems, then analyze it using Special Relativity. The idea is to break the ship's motion into tiny segments. In each segment, the ship has an average relative velocity (relative to the earth). This means that the amount of time dilation (relative to the earth) associated with each segment can be calculated. As the acceleration takes the ship to higher and higher relative velocities, the ship's clock ticks more and more slowly (relative to the earth's clocks). To get the net time difference between the two frames of reference, all we have to do is count the number of ticks that occur on Earth while the ship is away, do the same for the number of ticks that occur in the ship during that same interval (i.e., sum the ticks in each segment), and we end up with twins of unequal ages.

i.) An interesting and truly bizarre corollary to this: If your mother were to step into a space ship when she was forty and you were twenty, she could accelerate to high velocities out in space, then turn around and arrive back on Earth with a biological age of fifty-five when your biological age was sixty.

6.) The TWINS PARADOX and General Relativity:

a.) Although the Twins Paradox is usually analyzed using Special Relativity, it is instructive to look at it for what it is--an acceleration problem. In a theoretical sense, this is not mathematically easy. One has to use elegant conformal geometry and what is called Rindler space to do the problem (this is the kind of thing Stephen Hawking does). Nevertheless, a qualitative explanation is interesting.

b.) BACKGROUND: One of the things Einstein noticed is that there is no difference between a frame of reference that is under the influence of what Newton would have called gravity (i.e., one that resides in curved space) and a frame of reference that is accelerated (Einstein called this observation the Principle of Equivalence).

How so? Consider:

i.) You are standing in a small room. You feel the floor pushing up against you as expected. Can you tell whether the room is sitting stationary on the earth's surface, or whether the room is in an enclosed rocket ship that is accelerating at 9.8 m/s^2 out in space?

Answer: You have no way of telling.

ii.) What Einstein said was that if you cannot experimentally tell the difference between two situations, they must be treated comparably. As such, the effects that one observes as a consequence of curved space (the slowing of time, etc.) should also be observed in an accelerating frame of reference.

c.) In relativity, time is expected to slow down close to the earth's surface (the earth warps the space around itself). Time is also expected to slow in an accelerating space ship due to the Principle of Equivalence. What is peculiar is that if a ship's acceleration is 9.8 m/s^2, time will not slow in the ship in the same way that it slows on Earth where the gravitational acceleration is 9.8 m/s^2. Why? Because the relationship between curved space and the slowing of time is not a linear one--the relationship is quite complex. In short, if the ship accelerates to high velocities at a rate of 9.8 m/s^2, time will slow more in the ship than on earth and our twins will age at different rates.

d.) To be complete, the paradox part of the Twins Paradox is as follows: If, from the earth's frame of reference, the traveling twin ages less than the earth-bound twin, what happens if we look at the problem from the space ship's perspective? In that case, the earth accelerates to high velocity away from the ship and, seemingly, should act like a platform on which time slows down. In other words, it looks from that frame as though the twin on Earth should age less than the twin in the space ship.

There is a perfectly acceptable solution to this apparent paradox, but it takes time to explain. I'll leave it as my little puzzle for you--something to spur you on to independent study of your own. After all, that's what education is all about--piqueing curiosity and tweaking the student to want to learn more.

Consider yourself tweaked.

7.) Black holes and warped space-time--BACKGROUND:

a.) The following is more for fun than anything else. Treat it so:

b.) When a moderately large star dies, it does so by exploding in what is called a supernova. How does this occur?

i.) Although there are currently competing theories as to the exact mechanisms involved, it is generally accepted that stars form when enormous amounts of galactic gas and dust gravitationally attract (notice we are using Newtonian terminology here) and coalesce into a huge ball. As the attraction proceeds, the ball's density gets greater and greater. When the core's pressure reaches a billion atmospheres (one atmosphere equals 14.7 pounds per square inch) and its temperature reaches 10,000,000^o Celsius, hydrogen fusion begins, energy is given off, and a star is born.

ii.) Hydrogen fusion is the process whereby two hydrogen atoms are forced together to make a helium atom. An enormous amount of energy is released with this process. Specifically, .7% of the fused mass is converted into pure energy via $E = mc^2$.

Example 1: In fusing one gram of hydrogen into helium, .007 grams of mass is turned into pure energy. Using $E = mc^2$, that is enough energy to send 200 four-thousand pound Cadillacs 100 miles up into the atmosphere.

Example 2: The sun fuses 657,000,000 tons of hydrogen into 653,000,000 tons of helium every second. The 4,000,000 missing tons are turned into pure energy (that is why the sun, which is 93,000,000 miles away, can so easily heat the earth).

iii.) After a long period of time (anywhere from millions to billions of years, depending upon the size of the star), the hydrogen used to fuel the fusion reaction has been replaced by helium and the core runs out of fuel. When this happens, the core begins to collapse. As it does, the core temperature rises (objects that contract heat up). If the core temperature reaches 100,000,000^o Celsius, helium will begin to fuse to make still larger atoms.

iv.) In very large stars, this process repeats itself over and over again with smaller atoms fusing to make larger, then the large atoms fusing to make larger atoms yet. The process can continue until the core is mainly iron. Fusion of elements heavier than iron does not give off energy in the process but rather absorbs energy.

v.) Assume we are looking at a star that has gone beyond the hydrogen-fusion stage (i.e., a moderately large star). There will come a time when the star's fuel runs out and its core begins to contract due to the fuel depletion. If the contraction does not generate temperatures high enough to begin the next level of fusion (i.e., fusion of still larger atoms), the envelope of the star (the area outside the core) begins to gravitationally collapse in on the core (the core will also continue to contract). As this occurs, electrons in the core's atoms begin to degenerate (that is, they are forced into energy states they would not normally occupy). If the star is massive enough, the degeneracy escalates to the point where the core electrons are literally forced into the nuclei of their respective atoms. Once there, they combine with protons to make neutrons. As the electrons provide the pressure needed to hold the star in form, when they disappear, the star contracts.

vi.) All the electrons in the core execute this collapse at the same time. That means that in only a few seconds, a core whose initial radius had been, say, 1,000 kilometers will implode to a radius of, maybe, 10 kilometers.

Note: This sudden collapse is stopped by nuclear forces. That is, it is neutrons jammed up against one another that stops the implosion.

vii.) A tremendous amount of gravitational potential energy is released when this collapse occurs. That energy explodes out from the core, moving through the envelope like a shock wave. If the energy content of this shock wave is great enough, the envelope will be blown completely off into space (in a ten solar mass star, this would amount to around eight solar masses worth of material) leaving the compressed core behind.

viii.) This is a supernova. It leaves a super-dense core called a neutron star (a neutron star typically has a weight density of somewhere around 7,000,000,000,000 pounds per cubic centimeter) and many solar masses worth of debris moving outward into space (if this material is backlit by stars in the vicinity, and if it is visible on Earth, we call it called a nebula).

Note 1: During a supernova, a star puts out millions of times its normal energy emission. That is why the Chinese-observed supernova (we also have American Indian drawings of the event on cave and pueblo walls) in 1054 was visible during the day for a full two weeks (this nebula is called the Crab Nebula and is visible with a backyard telescope--what you see, should you look, is the cooling, ejected stellar envelope kept illuminated by the spinning neutron star at its center).

Note 2: Under normal conditions, stars haven't the ability to fuse elements larger than iron because iron fusion requires the taking-in of energy, versus the giving-off of energy observed with small-element fusion.

So when are elements larger than iron produced? During supernovas. The gold in your rings and the silver in your fillings, not to mention every other element on Earth that is larger than iron, was created during the death of a star. You and I are, quite literally, made up of the stuff of stars.

c.) If the energy content of the shock wave created by the core implosion is not great enough to blow off the star's envelope, the star's envelope will proceed to gravitationally collapse down on the core. As the implosion progresses, it becomes so fierce that not even nuclear forces can stop it. That means the implosion continues on forever (though the idea of time becomes blurred here for relativistic reasons that will become evident shortly).

When all the mass of the star has been compressed down inside a diameter of around 2 kilometers (remember, this could be, maybe, ten or twenty solar masses worth of material), the structure's density is so great that light leaving from a source inside that radius will be pulled back to the star's surface.

This radius is called the event horizon, and this structure is called a black hole.

d.) In relativistic terms, the super massive nature of a black hole warps the curvature of space around it so radically that not even light emitted inside the event horizon can escape (just outside the event horizon, light traveling directly away from the star can escape; light traveling obliquely will be pulled back down to the star).

8.) Black holes and warped space-time--What would it be like if you went for the ultimate thrill and jumped into a 10^8 solar mass black hole?

a.) If a friend was watching from a distance, he or she (we'll say it's a he) will see something unexpected. Specifically, as you approach the event horizon, you will (from their vantage point) begin to slow down. The closer you get, the slower you will go. In fact, if your friend could watch long enough, you would sooner or later come to an apparent, complete stop just outside the event horizon.

Strange, but true.

b.) From your perspective, on the other hand, things will happen very fast. If you go in feet first, the tidal forces at your feet will be so much greater than at your head that in only a few seconds you will just noodle out into an aggregate of individual atoms.

c.) BUT, if you could look out into the universe during those last fleeting seconds, you would witness amazing things. You would see the evolution of our universe passing before your eyes at incredible speed. You would witness the birth, life, and death of whole galaxies, and it all would happen in the time it takes you to wink.

Why? Because the incredibly massive character of the black hole would so warp the geometry of space-time around you that, as seen from "out there", your time would slow almost to a standstill. You would feel normal because you would be a part of it, but in relation to the rest of the universe, your moment would take aeons.