Motion through space is related to motion in time.

15 Special Relativity—Space and Time
Conceptual Physics

Motion through space is related to motion in time.

The first person to understand the relationship between space and time was Albert Einstein.

Einstein stated in 1905 that in moving through space we also change our rate of proceeding into the future—time itself is altered.

His theories changed the way scientists view the workings of the universe.

15 Special Relativity—Space and Time
Conceptual Physics

15.1 Space-Time

From the viewpoint of special relativity, you travel through a combination of space and time. You travel through space-time.

15 Special Relativity—Space and Time
Conceptual Physics

15.1 Space-Time

Newton and other investigators before Einstein thought of space as an infinite expanse in which all things exist.

Einstein theorized both space and time exist only within the universe. There is no time or space “outside.”

Einstein reasoned that space and time are two parts of one whole called **space-time.**

15 Special Relativity—Space and Time
Conceptual Physics

15.1 Space-Time

Einstein’s **special theory of relativity** describes how time is affected by motion in space at constant velocity, and how mass and energy are related.

15 Special Relativity—Space and Time
Conceptual Physics

15.1 Space-Time

The universe does not exist in a certain part of infinite space, nor does it exist during a certain era in time. Space and time exist within the universe.

15.1 Space-Time

You are moving through time at the rate of 24 hours per day. This is only half the story. To get the other half, convert your thinking from “moving through time” to “moving through space-time.”

- When you stand still, all your traveling is through time.
- When you move a bit, then some of your travel is through space and most of it is still through time.

15.1 Space-Time

- If you were able to travel at the speed of light, all your traveling would be through space, with no travel through time!
- Light travels through space only and is timeless.
- From the frame of reference of a photon traveling from one part of the universe to another, the journey takes no time at all!

15.1 Space-Time

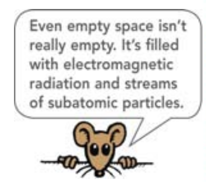
When you stand still, you are traveling at the maximum rate in time: 24 hours per day. If you traveled at the maximum rate through space (the speed of light), time would stand still.

15.1 Space-Time

Whenever we move through space, we, to some degree, alter our rate of moving into the future.

This is known as *time dilation*, or the stretching of time.

The special theory of relativity that Einstein developed rests on two fundamental assumptions, or **postulates.**



15.1 Space-Time

CONCEPT CHECK **How can you describe a person’s travel from the viewpoint of special relativity?**

15.2 The First Postulate of Special Relativity

The first postulate of special relativity states that all the laws of nature are the same in all uniformly moving frames of reference.

15.2 The First Postulate of Special Relativity

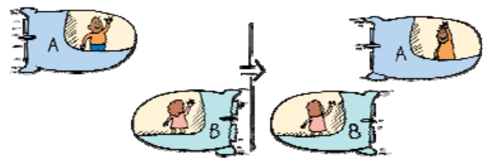
Einstein reasoned all motion is relative and all frames of reference are arbitrary.

A spaceship, for example, cannot measure its speed relative to empty space, but only relative to other objects.

15.2 The First Postulate of Special Relativity

Spaceman A considers himself at rest and sees spacewoman B pass by, while spacewoman B considers herself at rest and sees spaceman A pass by.

Spaceman A and spacewoman B will both observe only the relative motion.



15.2 The First Postulate of Special Relativity

If you look out the window and see the car in the next lane begin moving backward, you may be surprised to find that the car you're observing is really at rest—your car is moving forward.

If you could not see out the windows, there would be no way to determine whether your car was moving with constant velocity or was at rest.

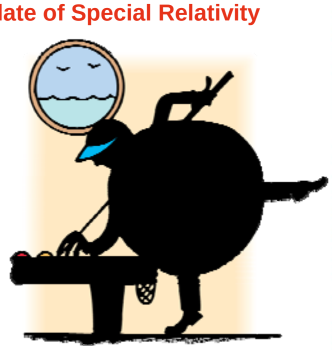
15.2 The First Postulate of Special Relativity

There is no physical experiment we can perform to determine our state of uniform motion.

- In a jetliner, we flip a coin and catch it just as we would if the plane were at rest.
- A pendulum will move no differently when the plane is moving uniformly (constant velocity) than when not moving at all.
- No experiment confined within the cabin itself can determine whether or not there is uniform motion.

15.2 The First Postulate of Special Relativity

A person playing pool on a smooth and fast-moving ship does not have to compensate for the ship's speed. The laws of physics are the same whether the ship is moving uniformly or at rest.



15.2 The First Postulate of Special Relativity

Einstein's **first postulate of special relativity** assumes our inability to detect a state of uniform motion.

Many experiments can detect *accelerated* motion, but none can, according to Einstein, detect the state of uniform motion.

15.2 The First Postulate of Special Relativity

CONCEPT CHECK

What does the first postulate of special relativity state?

15.3 The Second Postulate of Special Relativity

The second postulate of special relativity states that the speed of light in empty space will always have the same value regardless of the motion of the source or the motion of the observer.

15.3 The Second Postulate of Special Relativity

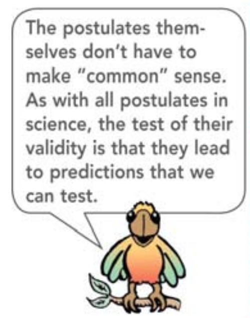
Einstein asked: "What would a light beam look like *if* you traveled along beside it?"

In classical physics, the beam would be at rest to such an observer. Einstein became convinced that this was impossible.

15.3 The Second Postulate of Special Relativity

Einstein concluded that *if* an observer could travel *close* to the speed of light, he would measure the light as moving away at 300,000 km/s.

Einstein's **second postulate of special relativity** assumes that the speed of light is constant.



15.3 The Second Postulate of Special Relativity

The speed of light is constant regardless of the speed of the flashlight or observer.

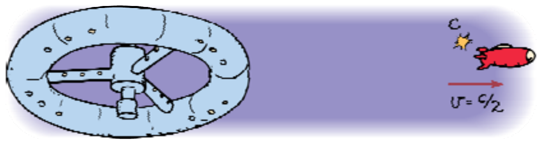
15.3 The Second Postulate of Special Relativity

The speed of light in all reference frames is always the same.

- Consider, for example, a spaceship departing from the space station.
- A flash of light is emitted from the station at 300,000 km/s—a speed we'll call *c*.

15.3 The Second Postulate of Special Relativity

The speed of a light flash emitted by either the spaceship or the space station is measured as *c* by observers on the ship or the space station. Everyone who measures the speed of light will get the same value, *c*.



15.3 The Second Postulate of Special Relativity

No matter what the speed of the spaceship relative to the space station is, an observer on the spaceship will measure the speed of the flash of light passing her as *c.*

If she sends a flash to the space station, observers on the station will measure the speed of these flashes as *c.*

All observers who measure the speed of light will find it has the same value, *c*.

15.3 The Second Postulate of Special Relativity

The constancy of the speed of light is what unifies space and time.

- For any observation of motion through space, there is a corresponding passage of time.
- The ratio of space to time for light is the same for all who measure it.
- The speed of light is a constant.

$$\frac{\text{SPACE}}{\text{TIME}} = \frac{\text{SPACE}}{\text{TIME}} = c$$

15.3 The Second Postulate of Special Relativity

CONCEPT CHECK

What does the second postulate of special relativity state?

15.4 Time Dilation

Time dilation occurs ever so slightly for everyday speeds, but significantly for speeds approaching the speed of light.

15.4 Time Dilation

Einstein proposed that time can be stretched depending on the motion between the observer and the events being observed.

The stretching of time is **time dilation.**

15.4 Time Dilation

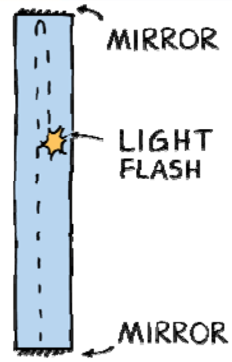
A Moving Light Clock

Consider a “light clock,” a rather impractical device, but one that will help to describe time dilation.

- Imagine an empty tube with a mirror at each end.
- A flash of light bounces back and forth between the parallel mirrors.
- The mirrors are perfect reflectors, so the flash bounces indefinitely.

15.4 Time Dilation

A stationary light clock is shown here. Light bounces between parallel mirrors and “ticks off” equal intervals of time.



15.4 Time Dilation

Suppose we view the light clock as it whizzes past us in a high-speed spaceship.

We see the light flash bouncing up and down along a longer diagonal path.

15.4 Time Dilation

The moving ship contains a light clock.

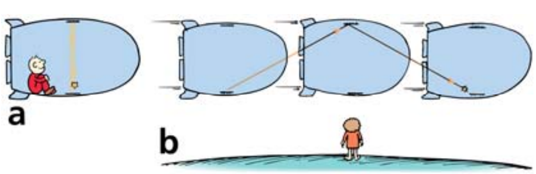
a. An observer moving with the spaceship observes the light flash moving vertically.

15.4 Time Dilation

The moving ship contains a light clock.

a. An observer moving with the spaceship observes the light flash moving vertically.

b. An observer who is passed by the moving ship observes the flash moving along a diagonal path.



15.4 Time Dilation

Remember the second postulate of relativity: The speed will be measured by *any* observer as *c*.

- Since the speed of light will not increase, we must measure more time between bounces!
- From the outside, one tick of the light clock takes longer than it takes for occupants of the spaceship.
- The spaceship’s clock has slowed down.
- However, for occupants of the spaceship, it has not slowed.

15.4 Time Dilation

Einstein showed the relation between the time t_0 in the observer's own frame of reference and the relative time t measured in another frame of reference is:

$$t = \frac{t_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

where v represents the relative velocity between the observer and the observed and c is the speed of light.

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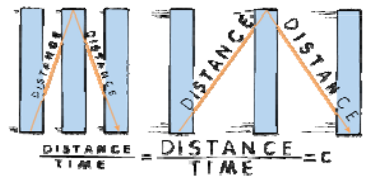
15.4 Time Dilation

The longer distance taken by the light flash in following the diagonal path must be divided by a correspondingly longer time interval to yield an unvarying value for the speed of light.



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15.4 Time Dilation

The slowing of time is not peculiar to the light clock. It is time itself in the moving frame of reference, as viewed from our frame of reference that slows.

- The heartbeats of the spaceship occupants will have a slower rhythm.
- All events on the moving ship will be observed by us as slower.
- We say that time is stretched—it is dilated.

Cosmonaut Sergei Avdeyev spent more than two years aboard the orbiting *Mir* space station, and due to time dilation is today two-hundredths of a second younger than he would be if he'd never been in space!

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15.4 Time Dilation

How do the occupants on the spaceship view their own time?

Time for them is the same as when they do not appear to us to be moving at all.

There is no way the spaceship occupants can tell uniform motion from rest. They have no clues that events on board are seen to be dilated when viewed from other frames of reference.

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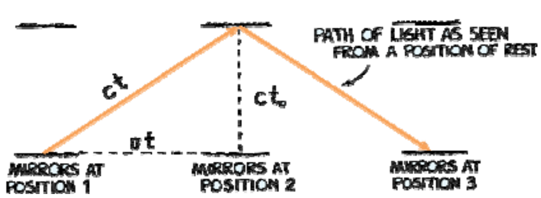
15.4 Time Dilation

A light clock moves to the right at a constant speed, v.



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15.4 Time Dilation

How do occupants on the spaceship view *our* time?

From *their* frame of reference it appears that *we* are the ones who are moving.

They see our time running slowly, just as we see their time running slowly.

15.4 Time Dilation

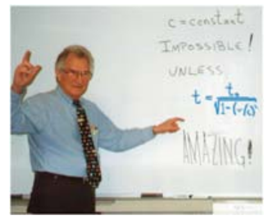
It is physically impossible for observers in different frames of reference to refer to one and the same realm of space-time.

The measurements in one frame of reference need not agree with the measurements made in another reference frame.

There is only one measurement they will always agree on: the speed of light.

15.4 Time Dilation

Physicist Ken Ford emphasizes the meaning of the time dilation equation.



15.4 Time Dilation

The Twin Trip

A dramatic illustration of time dilation is afforded by identical twins, one an astronaut who takes a high-speed round-trip journey while the other stays home on Earth.

When the traveling twin returns, he is younger than the stay-at-home twin. How much younger depends on the relative speeds involved.

15.4 Time Dilation

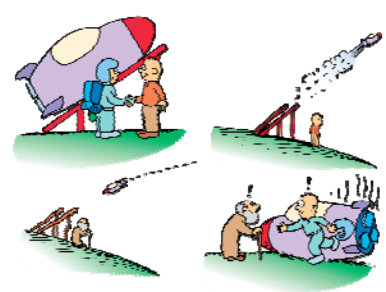
If the traveling twin maintains a speed of 50% the speed of light for one year (according to clocks aboard the spaceship), 1.15 years will have elapsed on Earth.

If the traveling twin maintains a speed of 87% the speed of light for a year, then 2 years will have elapsed on Earth.

15.4 Time Dilation

At 99.5% the speed of light, 10 Earth years would pass in one spaceship year. At this speed, the traveling twin would age a single year while the stay-at-home twin ages 10 years.

15.4 Time Dilation



15.4 Time Dilation

The question arises, since motion is relative, why isn't it just as well the other way around—why wouldn't the traveling twin return to find his stay-at-home twin younger than himself?

There's a fundamental difference here. The space-traveling twin experiences two frames of reference in his round trip—one receding from Earth, and the other approaching Earth. He has been in two realms of space-time, separated by the event of turning around.

15.4 Time Dilation

Clockwatching on a Trolley-Car Ride

Suppose a trolley car is moving in a direction away from a huge clock displayed in a village square.

The clock reads 12 noon. An observer in space who later receives the light says, "Oh, it's 12 noon on Earth now." You and the distant observer will see 12 noon at different times.

15.4 Time Dilation

If the trolley car traveled as fast as the light, then it would keep up with the information that says "12 noon."

Traveling at the speed of light, then, tells the time is always 12 noon at the village square. Time at the village square is frozen!

15.4 Time Dilation

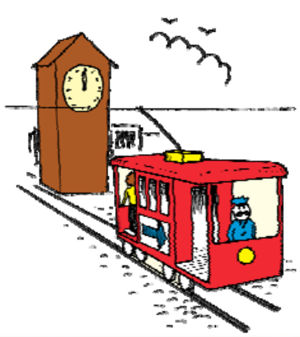
If the trolley car is not moving, you see the village-square clock move into the future at the rate of 60 seconds per minute.

If you move at the speed of light, you see seconds on the clock taking infinite time.

These are the two extremes. What's in between? What happens for speeds less than the speed of light?

15.4 Time Dilation

Light that carries the information "12 noon" is reflected by the clock and travels toward the trolley.



15.4 Time Dilation

You will receive the message "one o'clock" anywhere from 60 minutes to an infinity of time after you receive the message "12 noon."

It depends on your speed between the extremes of zero and the speed of light.

15.4 Time Dilation

From a high-speed (but less than *c*) moving frame of reference, you see all events taking place in the reference frame of the clock on Earth as happening in slow motion.

One second on a stationary clock is stretched out, as measured on a moving clock.

At high speed back toward the clock, you'll see all events occurring in the clock's frame of reference as being speeded up.

15.4 Time Dilation

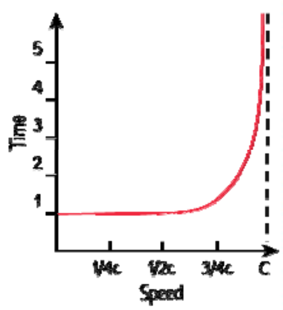
When you return and are once again sitting in the square, will the effects of going and coming compensate each other?

Amazingly, no! Time will be stretched.

The wristwatch you were wearing the whole time and the village clock will disagree. This is time dilation.

15.4 Time Dilation

The graph shows how 1 second on a stationary clock is stretched out, as measured on a moving clock.



15.4 Time Dilation

think!

Does time dilation mean that time really passes more slowly in moving systems or that it only seems to pass more slowly? Explain.

15.4 Time Dilation

think!

Does time dilation mean that time really passes more slowly in moving systems or that it only seems to pass more slowly? Explain.

Answer:

The slowing of time in moving systems is not merely an illusion resulting from motion. Time really does pass more slowly in a moving system compared with one at relative rest.

15.4 Time Dilation

think!

If you were moving in a spaceship at a high speed relative to Earth, would you notice a difference in your pulse rate? In the pulse rate of the people back on Earth? Explain.

15.4 Time Dilation

think!

If you were moving in a spaceship at a high speed relative to Earth, would you notice a difference in your pulse rate? In the pulse rate of the people back on Earth? Explain.

Answer:

There would be no relative speed between you and your own pulse, so no relativistic effects. There is a relativistic effect between you and Earth. You would find their pulse rate slower than normal (and they would find your pulse rate slower than normal). Relativity effects are always attributed to "the other guy."

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15.4 Time Dilation

think!

Will observers A and B agree on measurements of time if A moves at half the speed of light relative to B? If both A and B move together at 0.5*c* relative to Earth? Explain.

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15.4 Time Dilation

think!

Will observers A and B agree on measurements of time if A moves at half the speed of light relative to B? If both A and B move together at 0.5*c* relative to Earth? Explain.

Answer:

When A and B have different motions relative to each other, each will observe a slowing of time in the frame of reference of the other. So they will not agree on measurements of time. When they are moving in unison, they share the same frame of reference and will agree on measurements of time.

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15.4 Time Dilation

CONCEPT CHECK

How does time dilation at everyday speeds compare with time dilation at light speed?

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15.5 Space and Time Travel

The amounts of energy required to propel spaceships to relativistic speeds are billions of times the energy used to put the space shuttles into orbit.

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15.5 Space and Time Travel

Before the theory of special relativity was introduced, it was argued that humans would never be able to venture to the stars.

- Our life span is too short to cover such great distances.
- Alpha Centauri is the nearest star to Earth, after the sun, and it is 4 light-years away.
- A round trip even at the speed of light would require 8 years.

15.5 Space and Time Travel

The center of our galaxy is some 30,000 light-years away, so it was reasoned that a person traveling even at the speed of light would have to survive for 30,000 years to make such a voyage!

These arguments fail to take into account time dilation.

Time for a person on Earth and time for a person in a high-speed spaceship are not the same.

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15.5 Space and Time Travel

A person's heart beats to the rhythm of the realm of time it is in.

- Astronauts traveling at 99% the speed of light could go to the star Procyon (11.4 light-years distant) and back in 23.0 years in Earth time.
- Because of time dilation, it would seem that only 3 years had gone by for the astronauts.
- It would be the space officials greeting them on their return who would be 23 years older.

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15.5 Space and Time Travel

At higher speeds, the results are even more impressive. At a speed of 99.99% the speed of light, travelers could travel slightly more than 70 light-years in a single year of their own time.

At 99.999% the speed of light, this distance would be pushed appreciably farther than 200 years.

A 5-year trip for them would take them farther than light travels in 1000 Earth-time years.

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15.5 Space and Time Travel

From Earth's frame of reference, light takes 30,000 years to travel from the center of the Milky Way galaxy to our solar system.

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15.5 Space and Time Travel

Such journeys seem impossible to us today.

The practicalities of such space journeys are prohibitive, so far.

For the present, interstellar space travel must be relegated to science fiction because of the impracticality of space travel.

15 Special Relativity—Space and Time
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15.5 Space and Time Travel

Traveling close to the speed of light in order to take advantage of time dilation is completely consistent with the laws of physics.

If space travel becomes routine, people might have the option of taking a trip and returning in future centuries of their choosing.

15.5 Space and Time Travel

One might depart from Earth in a high-speed ship in the year 2150, travel for 5 years or so, and return in the year 2500.

One might live among Earthlings of that period for a while and depart again to try out the year 3000 for style.

People could keep jumping into the future with some expense of their own time, but they could not travel into the past.

15.5 Space and Time Travel

Time, as we know it, travels only one way—forward.

We constantly move into the future at the steady rate of 24 hours per day.

An astronaut on a deep-space voyage must live with the fact that more time will have elapsed on Earth than she has experienced on her voyage.

Star travelers will not bid "so long, see you later" to those they leave behind but, rather, a permanent "good-bye."

15.5 Space and Time Travel

15.5 Space and Time Travel

CONCEPT CHECK **Why does space travel at relativistic speeds seem impossible?**

15.6 Length Contraction

When an object moves at a very high speed relative to an observer, its measured length in the direction of motion is contracted.

15.6 Length Contraction

For moving objects, space as well as time undergoes changes.

The observable shortening of objects moving at speeds approaching the speed of light is **length contraction.**

The amount of contraction is related to the amount of time dilation. For everyday speeds, the amount of contraction is much too small to be measured.

15.6 Length Contraction

For relativistic speeds, the contraction would be noticeable.

At 87% of *c*, it would appear to you to be 0.5 meter long.

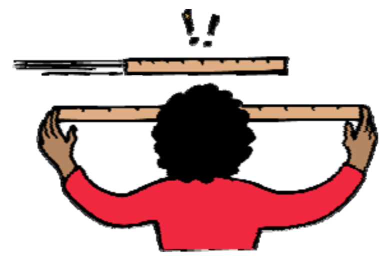
At 99.5% of *c*, it would appear to you to be 0.1 meter long.

As relative speed gets closer and closer to the speed of light, the measured lengths of objects contract closer and closer to zero.

The width of a stick, perpendicular to the direction of travel, doesn't change.

15.6 Length Contraction

A meter stick traveling at 87% the speed of light relative to an observer would be measured as only half as long.



15.6 Length Contraction

Do people aboard the spaceship also see their meter sticks—and everything else in their environment—contracted?

No, people in the spaceship see nothing at all unusual about the lengths of things in their own reference frame.

If they did, it would violate the first postulate of relativity.

15.6 Length Contraction

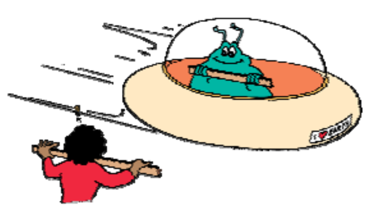
Recall that all the laws of physics are the same in all uniformly moving reference frames.

There is no relative speed between the people on the spaceship and the things they observe in their own reference frame.

There is a relative speed between themselves and *our* frame of reference, so they will see *our* meter sticks contracted—and us as well.

15.6 Length Contraction

In the frame of reference of the meter stick on the spaceship, its length is 1 meter. Observers from this frame see our meter sticks contracted. The effects of relativity are always attributed to "the other guy."



15.6 Length Contraction

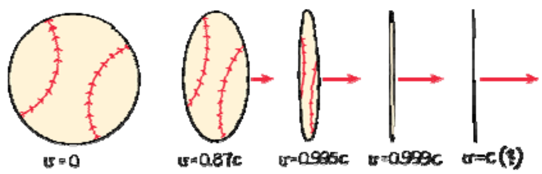
The contraction of speeding objects is the contraction of space itself.

Space contracts in only one direction, the direction of motion.

Lengths along the direction perpendicular to this motion are the same in the two frames of reference.

15.6 Length Contraction

As relative speed increases, contraction in the direction of motion increases. Lengths in the perpendicular direction do not change.



15.6 Length Contraction

Relativistic length contraction is stated mathematically:

$$L = L_0\sqrt{1-\left(\frac{v^2}{c^2}\right)}$$

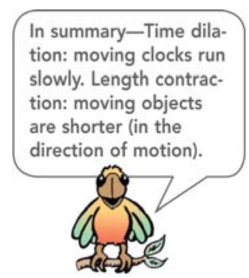
v is the speed of the object relative to the observer
c is the speed of light
L is the length of the moving object as measured by the observer
L_0 is the measured length of the object at rest

15.6 Length Contraction

Suppose that an object is at rest, so that $v = 0$. When 0 is substituted for *v* in the equation, we find $L = L_0$.
When 0.87*c* is substituted for *v* in the equation, we find $L = 0.5L_0$.
Or when 0.995*c* is substituted for *v*, we find $L = 0.1L_0$.

15.6 Length Contraction

If the object could reach the speed *c,* its length would contract to zero. This is one of the reasons that the speed of light is the upper limit for the speed of any object.



15.6 Length Contraction

think!

A spacewoman travels by a spherical planet so fast that it appears to her to be an ellipsoid (egg shaped). If she sees the short diameter as half the long diameter, what is her speed relative to the planet?

15.6 Length Contraction

think!

A spacewoman travels by a spherical planet so fast that it appears to her to be an ellipsoid (egg shaped). If she sees the short diameter as half the long diameter, what is her speed relative to the planet?

Answer:

The spacewoman passes the spherical planet at 87% the speed of light.

15.6 Length Contraction

CONCEPT CHECK

How does the length of an object change when it is moving at a very high speed relative to an observer?

Assessment Questions

1. What Einstein discovered about space and time is that they
   a. are separate entities.
   b. are parts of one whole.
   c. follow an inverse-square law.
   d. are special to space travelers.

Assessment Questions

1. What Einstein discovered about space and time is that they
   a. are separate entities.
   b. are parts of one whole.
   c. follow an inverse-square law.
   d. are special to space travelers.

Answer: B

Assessment Questions

2. Einstein stated that the laws of physics are
   a. different depending on the situation.
   b. common sense applied to microscopic and macroscopic things.
   c. the same in all frames of reference.
   d. the same in all uniformly moving frames of reference.

Assessment Questions

2. Einstein stated that the laws of physics are
   a. different depending on the situation.
   b. common sense applied to microscopic and macroscopic things.
   c. the same in all frames of reference.
   d. the same in all uniformly moving frames of reference.

Answer: D

Assessment Questions

3. Einstein's second postulate tells us that the speed of light
   a. depends on one's frame of reference.
   b. is a constant in all frames of reference.
   c. changes depending on the time of day.
   d. slows in a transparent medium.

Assessment Questions

3. Einstein's second postulate tells us that the speed of light
   a. depends on one's frame of reference.
   b. is a constant in all frames of reference.
   c. changes depending on the time of day.
   d. slows in a transparent medium.

Answer: B

Assessment Questions

4. When we speak of time dilation, we mean that time
   a. compresses with speed.
   b. stretches with speed.
   c. is a constant at all speeds.
   d. is related to space.

Assessment Questions

4. When we speak of time dilation, we mean that time
   a. compresses with speed.
   b. stretches with speed.
   c. is a constant at all speeds.
   d. is related to space.

Answer: B

Assessment Questions

5. If you travel at speeds close to the speed of light, then, compared with your friends who "stay at home," you are
   a. older.
   b. younger.
   c. no younger nor no older.
   d. longer.

Assessment Questions

5. If you travel at speeds close to the speed of light, then, compared with your friends who "stay at home," you are
   a. older.
   b. younger.
   c. no younger nor no older.
   d. longer.

Answer: B

Assessment Questions

6. To an observer at rest, an object traveling at very high speeds appears to be
   a. shorter in the direction of travel.
   b. shrunken uniformly.
   c. shorter in the direction perpendicular to travel.
   d. longer in all directions.

Assessment Questions

6. To an observer at rest, an object traveling at very high speeds appears to be
   a. shorter in the direction of travel.
   b. shrunken uniformly.
   c. shorter in the direction perpendicular to travel.
   d. longer in all directions.

Answer: A