Chapter 39

Relativity

A Brief Overview of Modern Physics

- 20^{th} Century revolution
  - 1900 Max Planck
    - Basic ideas leading to Quantum theory
  - 1905 Einstein
    - Special Theory of Relativity
- 21^{st} Century
  - Story is still incomplete

Basic Problems

- Newtonian mechanics fails to describe properly the motion of objects whose speeds approach that of light
- Newtonian mechanics is a limited theory
  - It places no upper limit on speed
  - It is contrary to modern experimental results
  - Newtonian mechanics becomes a specialized case of Einstein’s special theory of relativity
    - When speeds are much less than the speed of light

Galilean Relativity

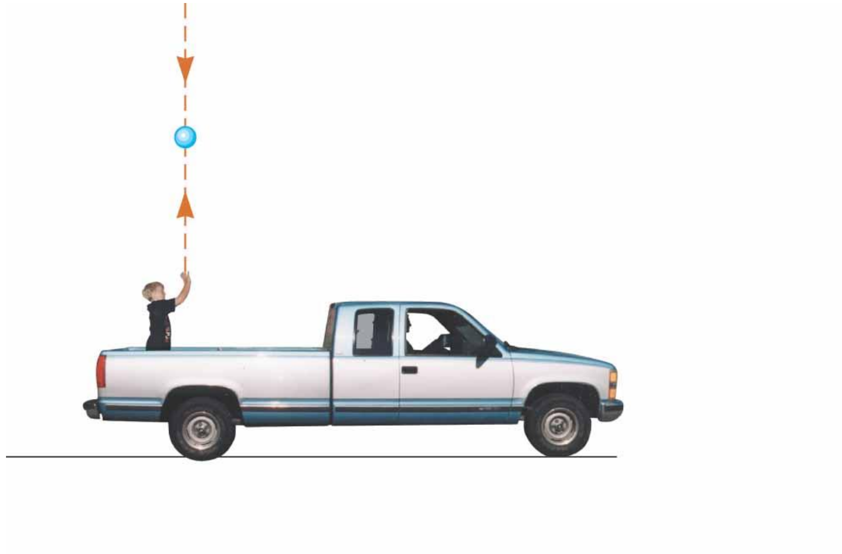
- To describe a physical event, a frame of reference must be established
- There is no absolute inertial frame of reference
  - This means that the results of an experiment performed in a vehicle moving with uniform velocity will be identical to the results of the same experiment performed in a stationary vehicle

Galilean Relativity, cont.

- Reminders about inertial frames
  - Objects subjected to no forces will experience no acceleration
  - Any system moving at constant velocity with respect to an inertial frame must also be in an inertial frame
- According to the **principle of Galilean relativity**, the laws of mechanics must be the same in all inertial frames of reference

Galilean Relativity – Example

- The observer in the truck throws a ball straight up
  - It appears to move in a vertical path
  - The law of gravity and equations of motion under uniform acceleration are obeyed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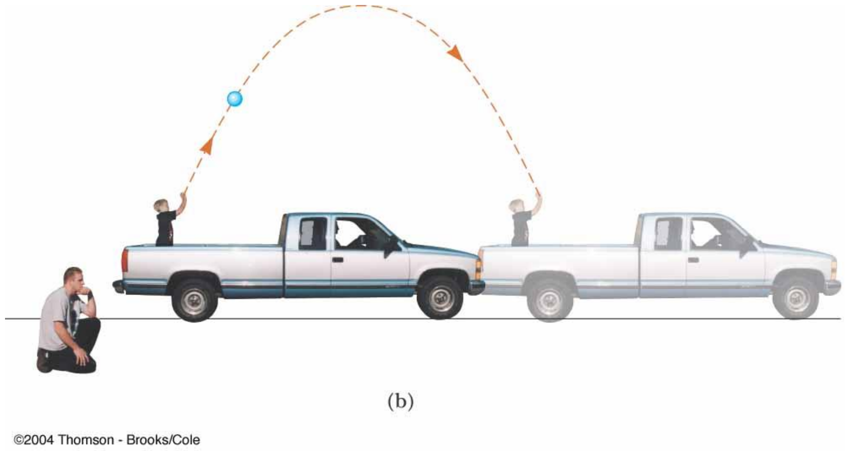
Galilean Relativity – Example, cont.



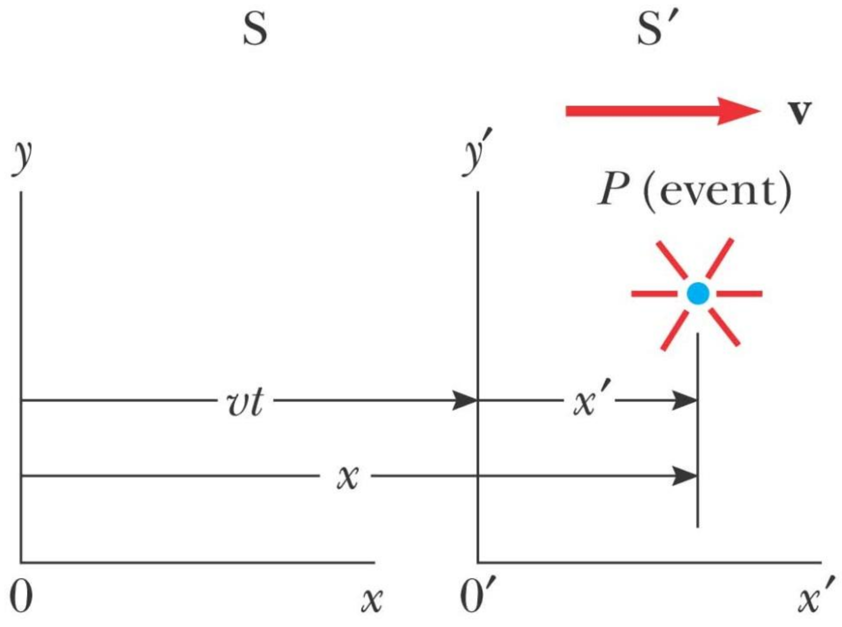
- There is a stationary observer on the ground
  - Views the path of the ball thrown to be a parabola
  - The ball has a velocity to the right equal to the velocity of the truck

Galilean Relativity – Example, conclusion

- The two observers disagree on the shape of the ball’s path
- Both agree that the motion obeys the law of gravity and Newton’s laws of motion
- Both agree on how long the ball was in the air
- Conclusion: There is no preferred frame of reference for describing the laws of mechanics

Views of an Event

- An *event* is some physical phenomenon
- Assume the event occurs and is observed by an observer at rest in an inertial reference frame
- The event's location and time can be specified by the coordinates (x, y, z, t)



Views of an Event, cont.

- Consider two inertial frames, S and S'
- S' moves with constant velocity, $\vec{\mathbf{v}}$, along the common *x* and *x*' axes
- The velocity is measured relative to S
- Assume the origins of S and S' coincide at *t* = 0

Galilean Space-Time Transformation Equations

- An observer in S describes the event with space-time coordinates (x, y, z, t)
- An observer in S' describes the same event with space-time coordinates (x', y', z', t')
- The relationship among the coordinates are
  - $x' = x - vt$
  - $y' = y$
  - $z' = z$
  - $t' = t$

Notes About Galilean Transformation Equations

- The time is the same in both inertial frames
  - Within the framework of classical mechanics, all clocks run at the same rate
  - The time at which an event occurs for an observer in S is the same as the time for the same event in S’
  - This turns out to be incorrect when v is comparable to the speed of light

Galilean Velocity Transformation Equation

- Suppose that a particle moves through a displacement *dx* along the *x* axis in a time *dt*
- The corresponding displacement *dx'* is

$$\frac{dx'}{dt'} = \frac{dx}{dt} - v$$

or $u'_x = u_x - v$

- $\vec{\mathbf{u}}$ is used for the particle velocity and $\vec{\mathbf{v}}$ is used for the relative velocity between the two frames

Galilean Transformation Equations – Final Notes

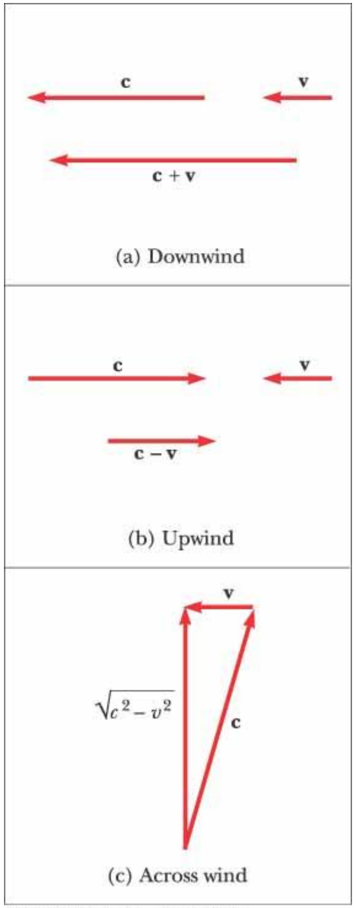
- The x and x' axes coincide, but their origins are different
- The y and y' axes are parallel, but do not coincide
  - This is due to the displacement of the origin of S' with respect to that of S
  - The same holds for z and z' axes
- Time = 0 when the origins of the two coordinate system coincide
- If the S' frame is moving in the positive x direction relative to S, the *v* is positive
  - Otherwise, it is negative

Speed of Light

- Galilean relativity does not apply to electricity, magnetism, or optics
- Maxwell showed the speed of light in free space is $c = 3.00 \times 10^8$ m/s
- Physicists in the late 1800s thought light moved through a medium called the *ether*
  - The speed of light would be *c* only in a special, absolute frame at rest with respect to the ether

Effect of Ether Wind on Light

- Assume *v* is the velocity of the ether wind relative to the earth
- *c* is the speed of light relative to the ether
- Various resultant velocities are shown



Ether Wind, cont.

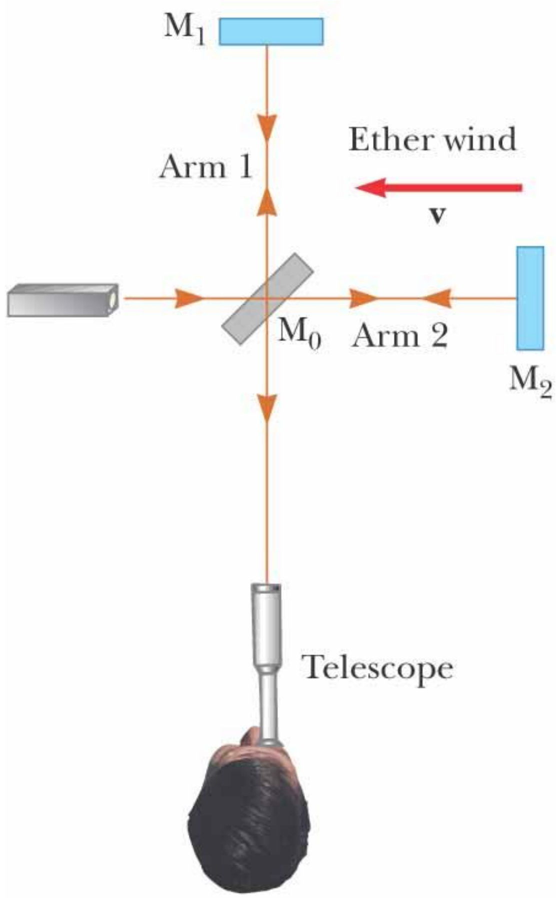
- The velocity of the ether wind is assumed to be the orbital velocity of the Earth
- All attempts to detect and establish the existence of the ether wind proved futile
- But Maxwell's equations seem to imply that the speed of light always has a fixed value in all inertial frames
  - This is a contradiction to what is expected based on the Galilean velocity transformation equation

Michelson-Morley Experiment

- First performed in 1881 by Michelson
- Repeated under various conditions by Michelson and Morley
- Designed to detect small changes in the speed of light
  - By determining the velocity of the Earth relative to the ether

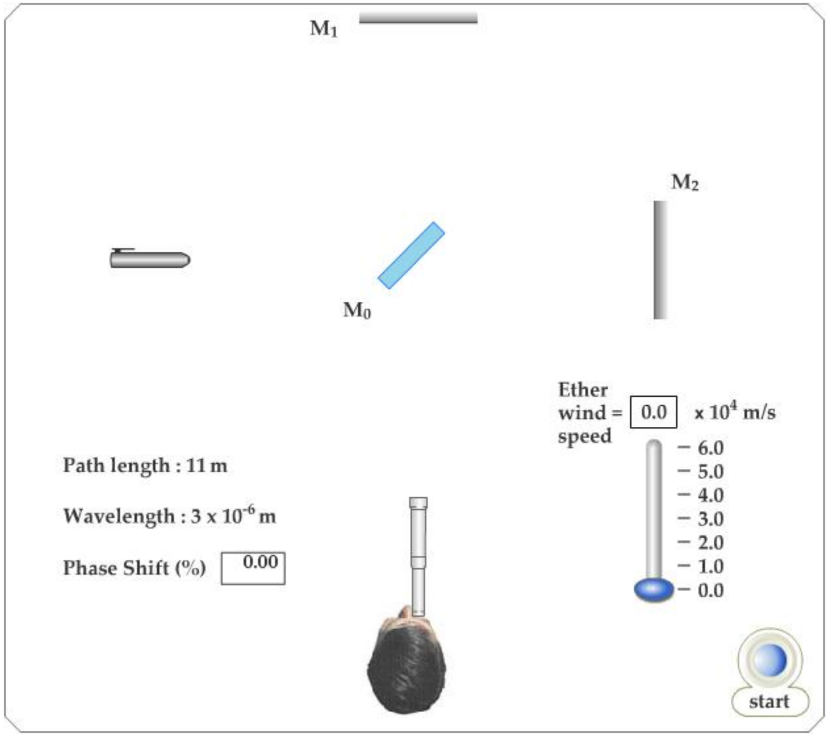
Michelson-Morley Equipment

- Used the Michelson interferometer
- Arm 2 is aligned along the direction of the Earth's motion through space
- The interference pattern was observed while the interferometer was rotated through 90°
- The effect should have been to show small, but measurable shifts in the fringe pattern



Active Figure 39.4

- Use the active figure to adjust the speed of the ether wind
- Observe the effect on the light beams if there were an ether



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ACTIVE FIGURE

Michelson-Morley Expected Results

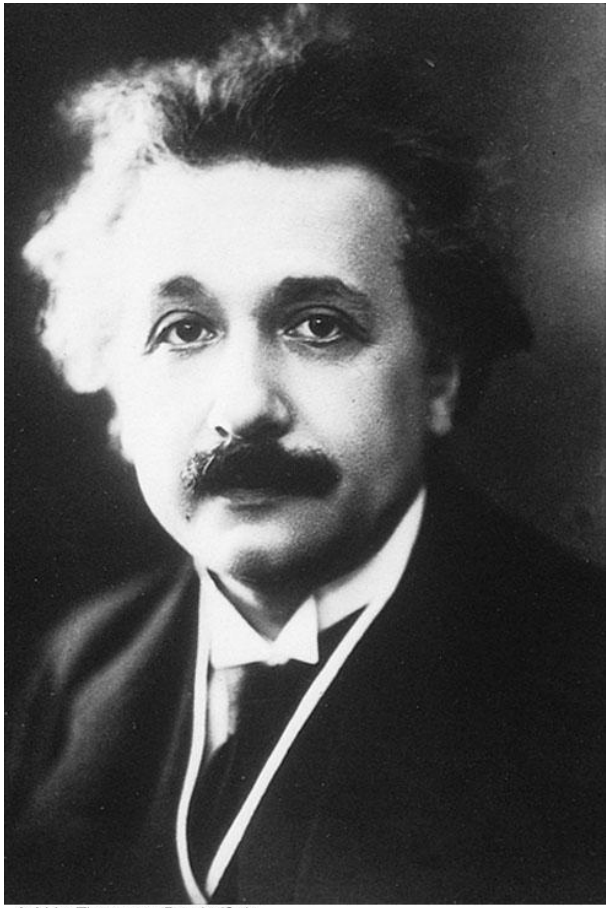
- The speed of light measured in the Earth frame should be $c - v$ as the light approaches mirror M_2
- The speed of light measured in the Earth frame should be $c + v$ as the light is reflected from mirror M_2
- The experiment was repeated at different times of the year when the ether wind was expected to change direction and magnitude

Michelson-Morley Results

- Measurements failed to show any change in the fringe pattern
  - No fringe shift of the magnitude required was ever observed
  - The negative results contradicted the ether hypothesis
  - They also showed that it was impossible to measure the absolute velocity of the Earth with respect to the ether frame
- Light is now understood to be an electromagnetic wave, which requires no medium for its propagation
  - The idea of an ether was discarded

Albert Einstein

- 1879 – 1955
- 1905
  - Special theory of relativity
- 1916
  - General relativity
  - 1919 – confirmation
- 1920's
  - Didn't accept quantum theory
- 1940's or so
  - Search for unified theory - unsuccessful



Einstein's Principle of Relativity

- Resolves the contradiction between Galilean relativity and the fact that the speed of light is the same for all observers
- Postulates
  - **The principle of relativity**: The laws of physics must be the same in all inertial reference frames
  - **The constancy of the speed of light**: the speed of light in a vacuum has the same value, $c = 3.00 \times 10^8$ m/s, in all inertial frames, regardless of the velocity of the observer or the velocity of the source emitting the light

The Principle of Relativity

- This is a generalization of the principle of Galilean relativity, which refers only to the laws of mechanics
- The results of any kind of experiment performed in a laboratory at rest must be the same as when performed in a laboratory moving at a constant speed past the first one
- No preferred inertial reference frame exists
- It is impossible to detect absolute motion

The Constancy of the Speed of Light

- This is required by the first postulate
- Confirmed experimentally in many ways
- Explains the null result of the Michelson-Morley experiment
- Relative motion is unimportant when measuring the speed of light
  - We must alter our common-sense notions of space and time

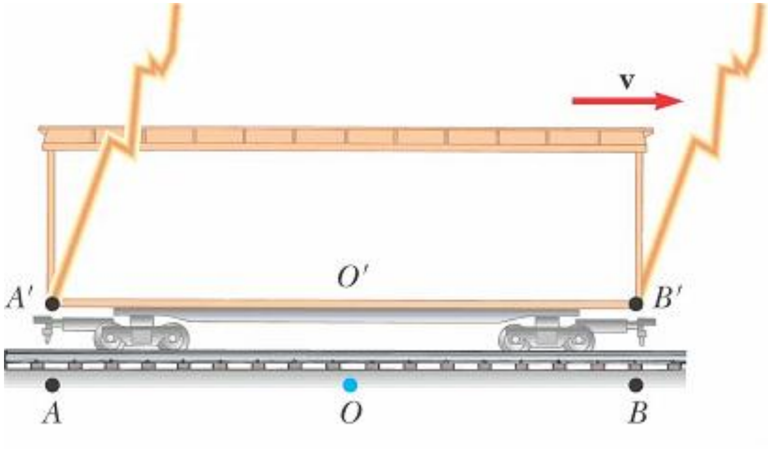
Consequences of Special Relativity

- Restricting the discussion to concepts of simultaneity, time intervals, and length
  - These are quite different in relativistic mechanics from what they are in Newtonian mechanics
- In relativistic mechanics
  - There is no such thing as absolute length
  - There is no such thing as absolute time
  - Events at different locations that are observed to occur simultaneously in one frame are not observed to be simultaneous in another frame moving uniformly past the first

Simultaneity

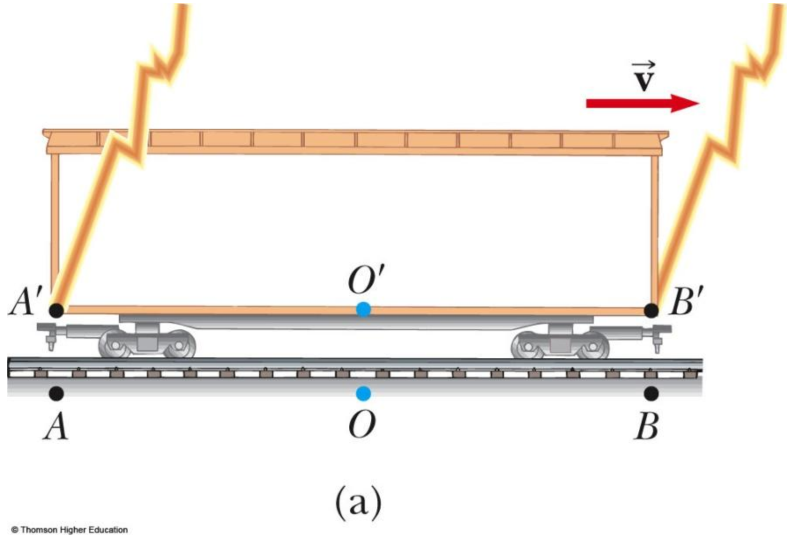
- In special relativity, Einstein abandoned the assumption of simultaneity
- Thought experiment to show this
  - A boxcar moves with uniform velocity
  - Two lightning bolts strike the ends
  - The lightning bolts leave marks (A' and B') on the car and (A and B) on the ground
  - Two observers are present: O' in the boxcar and O on the ground

Simultaneity – Thought Experiment Set-up



- Observer O is midway between the points of lightning strikes on the ground, A and B
- Observer O’ is midway between the points of lightning strikes on the boxcar, A’ and B’

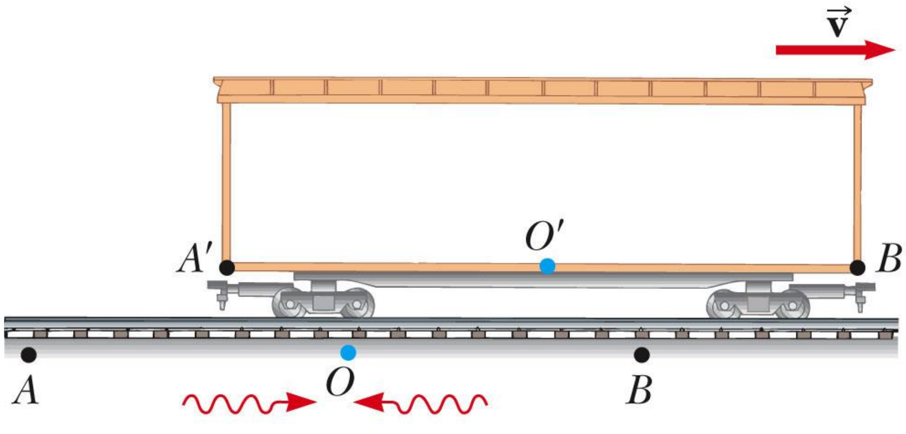
Simultaneity – Thought Experiment Results



- The light reaches observer O at the same time
  - He concludes the light has traveled at the same speed over equal distances
  - Observer O concludes the lightning bolts occurred simultaneously

Simultaneity – Thought Experiment Results, cont.

- By the time the light has reached observer *O*, observer *O*' has moved
- The signal from *B*' has already swept past *O*', but the signal from *A*' has not yet reached him
  - The two observers must find that light travels at the same speed
  - Observer *O*' concludes the lightning struck the front of the boxcar before it struck the back (they were not simultaneous events)



(b)

Simultaneity – Thought Experiment, Summary

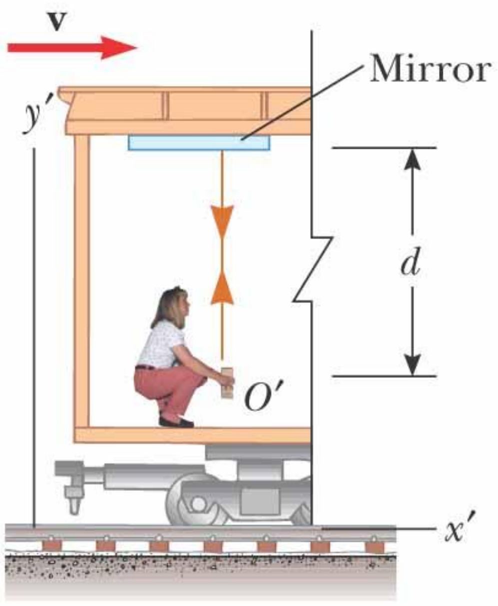
- Two events that are simultaneous in one reference frame are in general not simultaneous in a second reference frame moving relative to the first
- That is, simultaneity is not an absolute concept, but rather one that depends on the state of motion of the observer
  - In the thought experiment, both observers are correct, because there is no preferred inertial reference frame

Simultaneity, Transit Time

- In this thought experiment, the disagreement depended upon the transit time of light to the observers and doesn't demonstrate the deeper meaning of relativity
- In high-speed situations, the simultaneity is relative even when transit time is subtracted out
  - We will ignore transit time in all further discussions

Time Dilation

- A mirror is fixed to the ceiling of a vehicle
- The vehicle is moving to the right with speed ***v***
- An observer, *O*', at rest in the frame attached to the vehicle holds a flashlight a distance *d* below the mirror
- The flashlight emits a pulse of light directed at the mirror (event 1) and the pulse arrives back after being reflected (event 2)

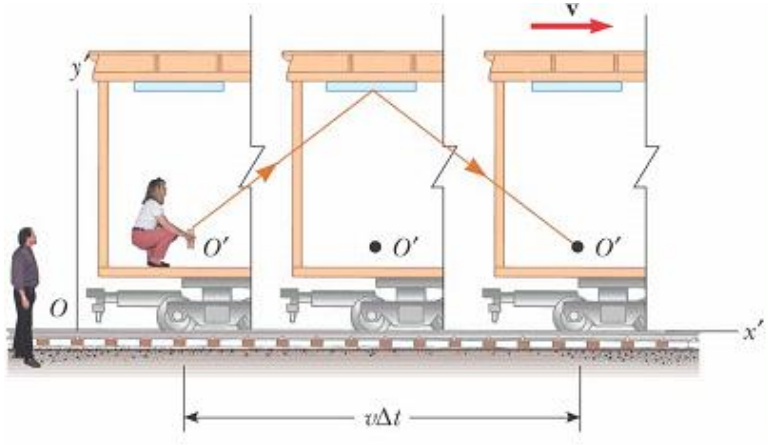


(a)

Time Dilation, Moving Observer

- Observer *O*’ carries a clock
- She uses it to measure the time between the events (Δt_p)
  - She observes the events to occur at the same place
  - Δt_p = distance/speed = $(2d)/c$

Time Dilation, Stationary Observer



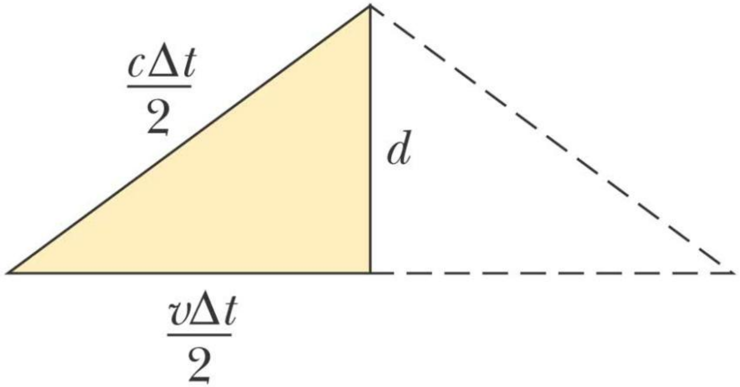
- Observer O is a stationary observer on the Earth
- He observes the mirror and O’ to move with speed *v*
- By the time the light from the flashlight reaches the mirror, the mirror has moved to the right
- The light must travel farther with respect to O than with respect to O’

Time Dilation, Observations

- Both observers must measure the speed of the light to be *c*
- The light travels farther for O
- The time interval, Δt, for O is longer than the time interval for O', Δt_p

Time Dilation, Time Comparisons

$$\Delta t = \frac{\Delta t_p}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma \Delta t_p$$



(c)

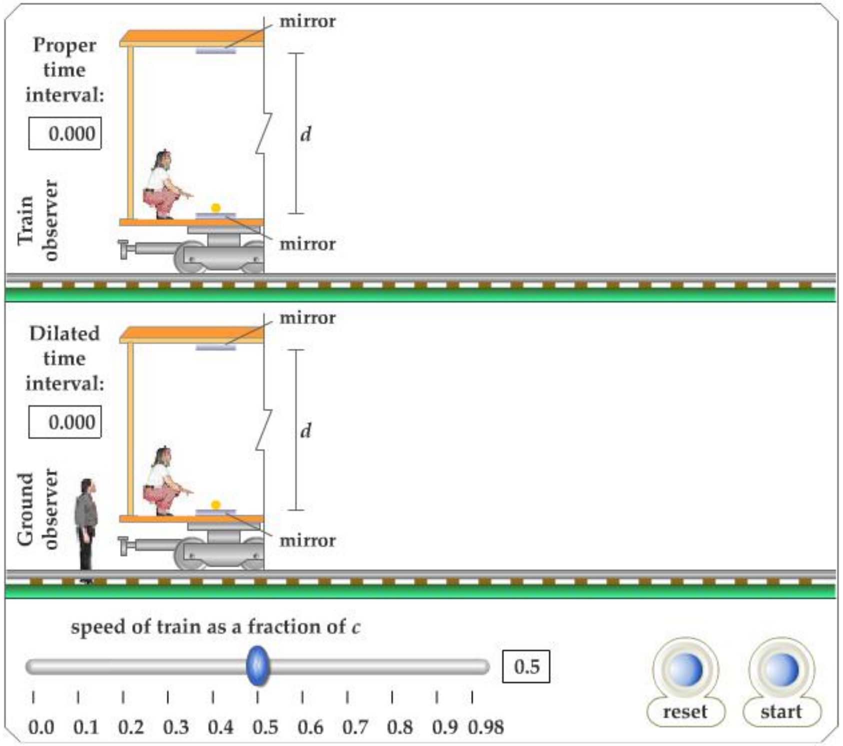
$$\text{where } \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Time Dilation, Summary

- The time interval Δt between two events measured by an observer moving with respect to a clock is longer than the time interval Δt_p between the same two events measured by an observer at rest with respect to the clock
  - This effect is known as time dilation

Active Figure 39.6

- Use the active figure to set various speeds for the train
- Observe the light pulse



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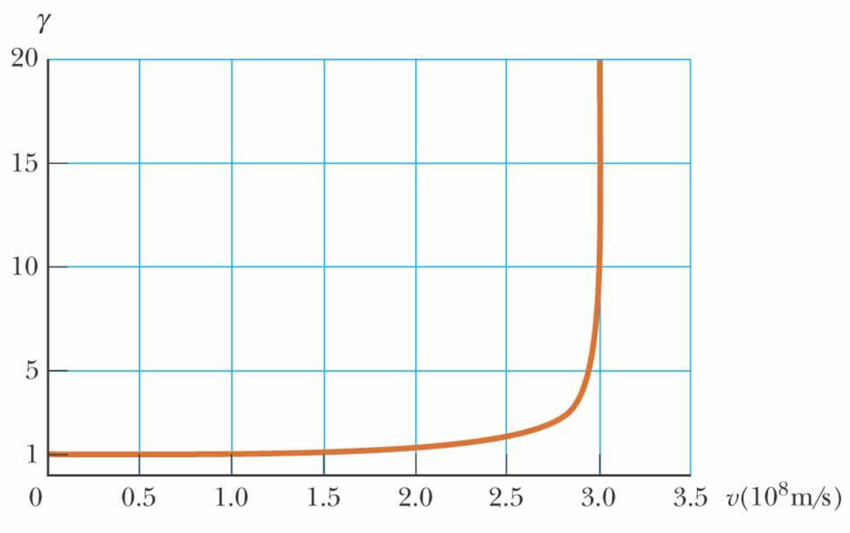
γ Factor

- Time dilation is not observed in our everyday lives
- For slow speeds, the factor of γ is so small that no time dilation occurs
- As the speed approaches the speed of light, γ increases rapidly



γ Factor Table

TABLE 39.1

Approximate Values for γ at Various Speeds

v/c	γ
0.001 0	1.000 000 5
0.010	1.000 05
0.10	1.005
0.20	1.021
0.30	1.048
0.40	1.091
0.50	1.155
0.60	1.250
0.70	1.400
0.80	1.667
0.90	2.294
0.92	2.552
0.94	2.931
0.96	3.571
0.98	5.025
0.99	7.089
0.995	10.01
0.999	22.37

Identifying Proper Time

- The time interval Δt_p is called the proper time interval
  - The proper time interval is the time interval between events as measured by an observer who sees the events occur at the same point in space
    - You must be able to correctly identify the observer who measures the proper time interval

Time Dilation – Generalization

- If a clock is moving with respect to you, the time interval between ticks of the moving clock is observed to be longer that the time interval between ticks of an identical clock in your reference frame
- All physical processes are measured to slow down when these processes occur in a frame moving with respect to the observer
  - These processes can be chemical and biological as well as physical

Time Dilation – Verification

- Time dilation is a very real phenomenon that has been verified by various experiments
- These experiments include:
  - Airplane flights
  - Muon decay
  - Twin Paradox

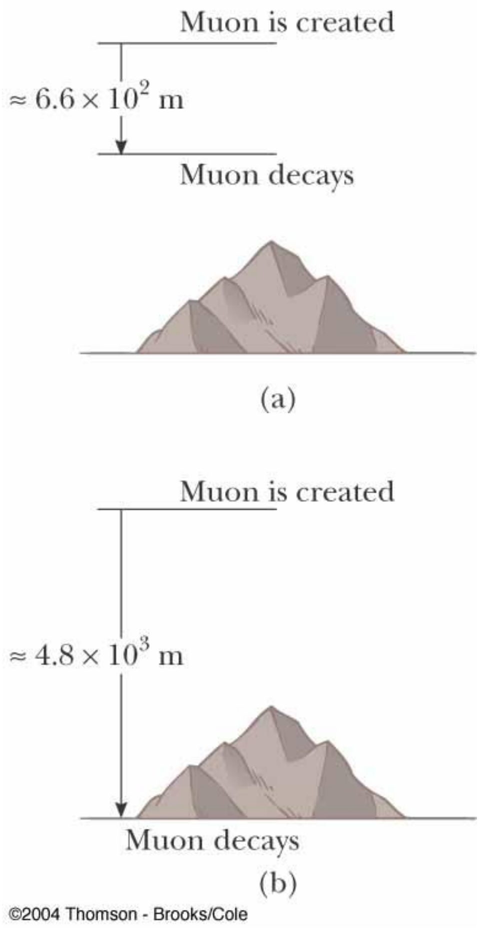
Airplanes and Time Dilation

- In 1972 an experiment was reported that provided direct evidence of time dilation
- Time intervals measured with four cesium clocks in jet flight were compared to time intervals measured by Earth-based reference clocks
- The results were in good agreement with the predictions of the special theory of relativity

Time Dilation Verification – Muon Decays

- Muons are unstable particles that have the same charge as an electron, but a mass 207 times more than an electron
- Muons have a half-life of Δt_p = 2.2 μs when measured in a reference frame at rest with respect to them (a)
- Relative to an observer on the Earth, muons should have a lifetime of

  $\gamma \, \Delta t_p$ (b)
- A CERN experiment measured lifetimes in agreement with the predictions of relativity



The Twin Paradox – The Situation

- A thought experiment involving a set of twins, Speedo and Goslo
- Speedo travels to Planet X, 20 light years from the Earth
  - His ship travels at 0.95c
  - After reaching Planet X, he immediately returns to the Earth at the same speed
- When Speedo returns, he has aged 13 years, but Goslo has aged 42 years

The Twins' Perspectives

- Goslo's perspective is that he was at rest while Speedo went on the journey
- Speedo thinks he was at rest and Goslo and the Earth raced away from him and then headed back toward him
- The paradox – which twin has developed signs of excess aging?

The Twin Paradox – The Resolution

- Relativity applies to reference frames moving at uniform speeds
- The trip in this thought experiment is not symmetrical since Speedo must experience a series of accelerations during the journey
- Therefore, Goslo can apply the time dilation formula with a proper time of 42 years
  - This gives a time for Speedo of 13 years and this agrees with the earlier result
- There is no true paradox since Speedo is not in an inertial frame

Length Contraction

- The measured distance between two points depends on the frame of reference of the observer
- The proper length, L_p, of an object is the length of the object measured by someone at rest relative to the object
- The length of an object measured in a reference frame that is moving with respect to the object is always less than the proper length
  - This effect is known as length contraction

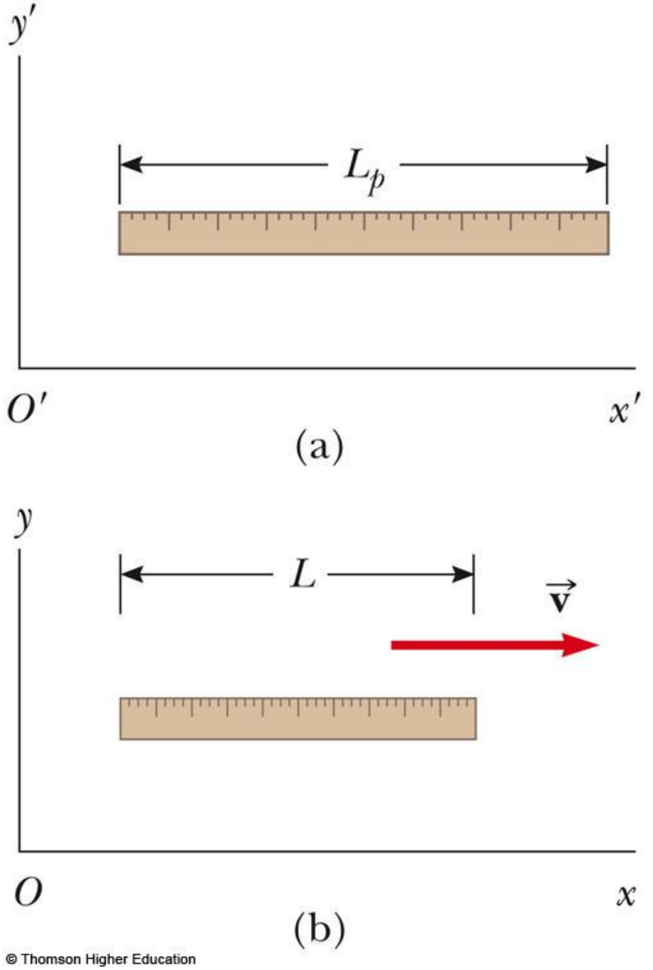
More About Proper Length

- Very important to correctly identify the observer who measures proper length
- The proper length is always the length measured by the observe at rest with respect to the points
- Often the proper time interval and the proper length are *not* measured by the same observer

Length Contraction – Equation

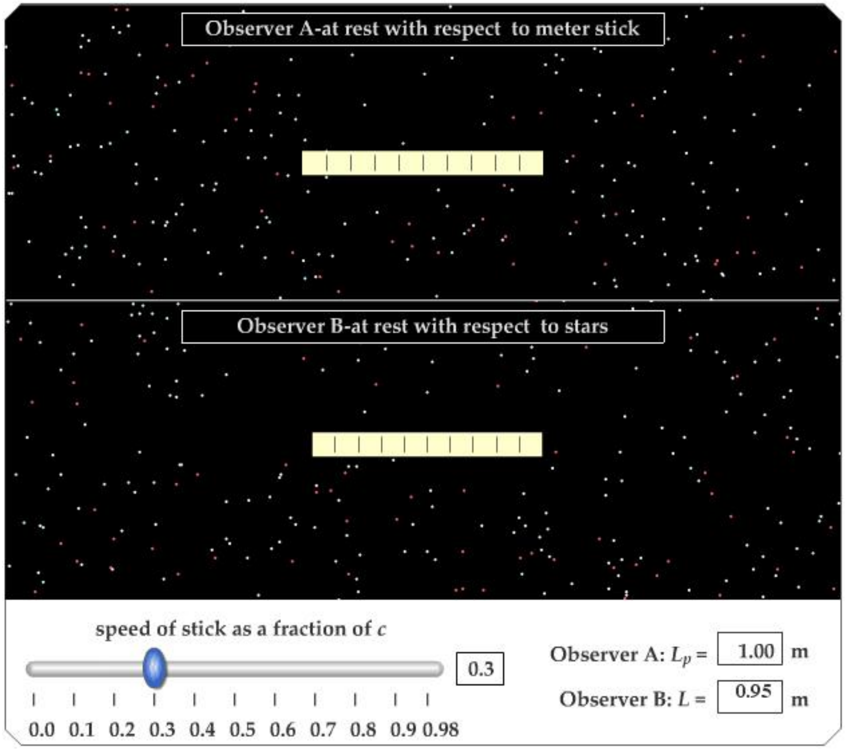
$$L = \frac{L_P}{\gamma} = L_P\sqrt{1 - \frac{v^2}{c^2}}$$

- Length contraction takes place only along the direction of motion



Active Figure 39.10

- Use the active figure to view the meterstick from the points of view of the two observers
- Compare the lengths



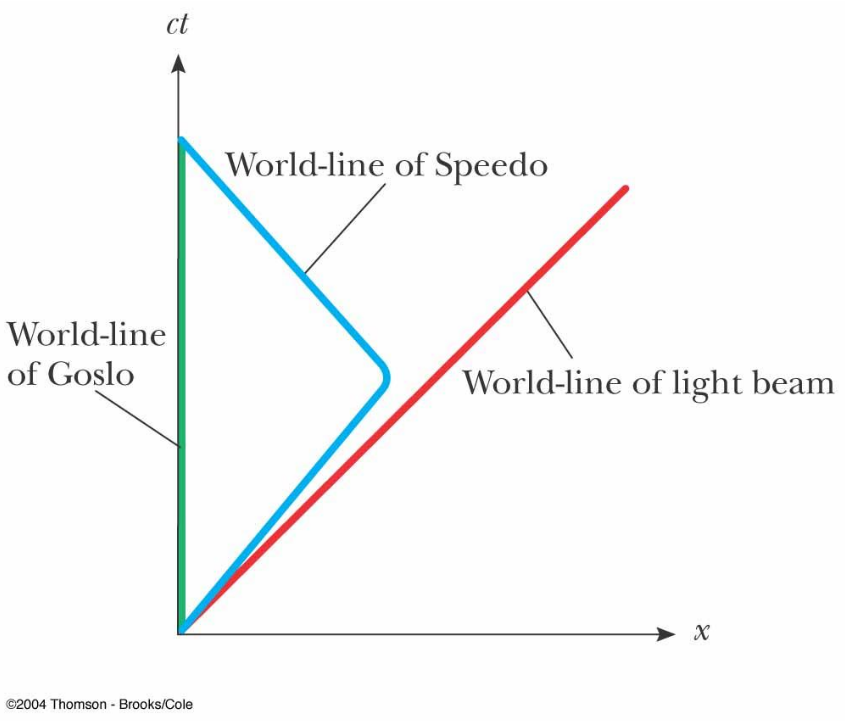
PLAY ACTIVE FIGURE

Proper Length vs. Proper Time

- The proper length and proper time interval are defined differently
- The proper length is measured by an observer for whom the end points of the length remained fixed in space
- The proper time interval is measured by someone for whom the two events take place at the same position in space

Space-Time Graphs

- In a *space-time graph,* *ct* is the ordinate and position *x* is the abscissa
- The example is the graph of the twin paradox
- A path through space-time is called a **world-line**
- World-lines for light are diagonal lines



Relativistic Doppler Effect

- Another consequence of time dilation is the shift in frequency found for light emitted by atoms in motion as opposed to light emitted by atoms at rest
- If a light source and an observer approach each other with a relative speed, *v*, the frequency measured by the observer is

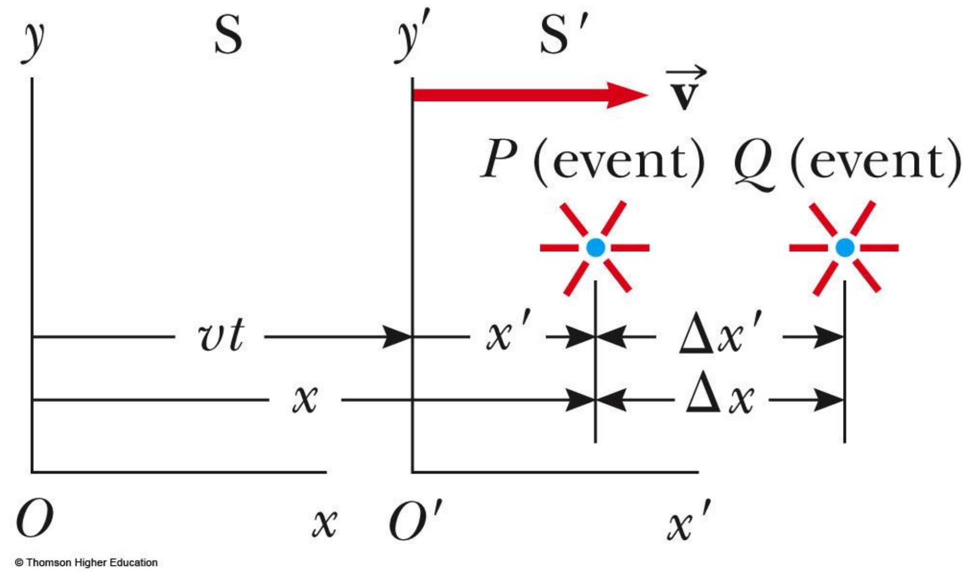
$$f_{\text{obs}} = \frac{\sqrt{1 + v/c}}{\sqrt{1 - v/c}} f_{\text{source}}$$

Relativistic Doppler Effect, cont.

- The frequency of the source is measured in its rest frame
- The shift depends only on the relative velocity, v, of the source and observer
- $f_{obs} > f_{source}$ when the source and the observer approach each other
- An example is the red shift of galaxies, showing most galaxies are moving away from us

Lorentz Transformation Equations, Set-Up

- Assume the events at points *P* and *Q* are reported by two observers
- One observer is at rest in frame S
- The other observer is in frame S' moving to the right with speed *v*



Lorentz Transformation Equations, Set-Up, cont.

- The observer in frame S reports the event with space-time coordinates of (x, y, z, t)
- The observer in frame S' reports the same event with space-time coordinates of (x', y', z', t')
- The Galilean transformation would predict that $\Delta x = \Delta x'$
  - The distance between the two points in space at which the events occur does not depend on the motion of the observer

Lorentz Transformations Compared to Galilean

- The Galilean transformation is not valid when *v* approaches *c*
  - $\Delta x = \Delta x'$ is contradictory to length contraction
- The equations that are valid at all speeds are the Lorentz transformation equations
  - Valid for speeds $0 < v < c$

Lorentz Transformations, Equations

- To transform coordinates from S to S' use

$$\frac{dx'}{dt'} = \frac{dx}{dt} - v$$

or $u'_x = u_x - v$

- These show that in relativity, space and time are not separate concepts but rather closely interwoven with each other
- To transform coordinates from S' to S use

$$x = \gamma(x' + vt') \quad y' = y \quad z' = z \quad t = \gamma\left(t' + \frac{v}{c^2}x'\right)$$

Lorentz Transformations, Pairs of Events

- The Lorentz transformations can be written in a form suitable for describing pairs of events
- For S to S'

For S' to S

$$\Delta x' = \gamma(\Delta x - v\Delta t)$$

$$\Delta t' = \gamma\left(\Delta t - \frac{v}{c^2}\Delta x\right)$$

$$\Delta x = \gamma(\Delta x' + v\Delta t')$$

$$\Delta t = \gamma\left(\Delta t' + \frac{v}{c^2}\Delta x'\right)$$

Lorentz Transformations, Pairs of Events, cont.

- In the preceding equations, observer O' measures $\Delta x' = x'_2 - x'_1$ and $\Delta t' = t'_2 - t'_1$
- Also, observer O measures $\Delta x = x_2 - x_1$ and $\Delta t = t_2 - t_1$
- The y and z coordinates are unaffected by the motion along the x direction

Lorentz Velocity Transformation

- The "event" is the motion of the object
- S' is the frame moving at v relative to S
- In the S' frame

$$u_x' = \frac{dx'}{dt'} = \frac{u_x - v}{1 - \frac{u_x v}{c^2}}$$

$$u_y' = \frac{u_y}{\gamma\left(1 - \frac{u_x v}{c^2}\right)} \quad \text{and} \quad u_z' = \frac{u_z}{\gamma\left(1 - \frac{u_x v}{c^2}\right)}$$

Lorentz Velocity Transformation, cont.

- The term v does not appear in the u'_y and u'_z equations since the relative motion is in the x direction
- When v is much smaller than c, the Lorentz velocity transformation reduces to the Galilean velocity transformation equation
- If v = c, u'x = c and the speed of light is shown to be independent of the relative motion of the frame

Lorentz Velocity Transformation, final

- To obtain u_x in terms of u'_x, use

$$u_x = \frac{u'_x + v}{1 + \frac{u'_x v}{c^2}}$$

Measurements Observers Do Not Agree On

- Two observers *O* and *O'* do not agree on:
  - The time interval between events that take place in the same position in one reference frame
  - The distance between two points that remain fixed in one of their frames
  - The velocity components of a moving particle
  - Whether two events occurring at different locations in both frames are simultaneous or not

Measurements Observers Do Agree On

- Two observers *O* and *O'* can agree on:
  - Their relative speed of motion *v* with respect to each other
  - The speed c of any ray of light
  - The simultaneity of two events which take place at the same position and time in some frame

Relativistic Linear Momentum

- To account for conservation of momentum in all inertial frames, the definition must be modified to satisfy these conditions
  - The linear momentum of an isolated particle must be conserved in all collisions
  - The relativistic value calculated for the linear momentum p of a particle must approach the classical value m*u* as *u* approaches zero

$$\vec{\mathbf{p}} \equiv \frac{m\vec{\mathbf{u}}}{\sqrt{1-\frac{u^2}{c^2}}} = \gamma m\vec{\mathbf{u}}$$

- $\vec{u}$ is the velocity of the particle, m is its mass

Mass in Relativity

- In older treatments of relativity, conservation of momentum was maintained by using "relativistic mass"
- Today, mass is considered to be *invariant*
  - That means it is independent of speed
- The mass of an object in all frames is considered to be the mass as measured by an observer at rest with respect to the object

Relativistic Form of Newton's Laws

- The relativistic force acting on a particle whose linear momentum is $\vec{\mathbf{p}}$ is defined as

$$\vec{\mathbf{F}} = \frac{d\vec{\mathbf{p}}}{dt}$$

- This preserves classical mechanics in the limit of low velocities
- It is consistent with conservation of linear momentum for an isolated system both relativistically and classically
- Looking at acceleration it is seen to be impossible to accelerate a particle from rest to a speed u $\geq$ c

Speed of Light, Notes

- The speed of light is the speed limit of the universe
- It is the maximum speed possible for energy and information transfer
- Any object with mass must move at a lower speed

Relativistic Energy

- The definition of kinetic energy requires modification in relativistic mechanics
- $E = \gamma mc^2 - mc^2$
  - This matches the classical kinetic energy equation when $u \ll c$
  - The term mc^2 is called the rest energy of the object and is independent of its speed
  - The term γmc^2 is the total energy, E, of the object and depends on its speed and its rest energy

Relativistic Kinetic Energy

- The Work-Kinetic Energy Theorem can be applied to relativistic situations
- This becomes

$$W = K = \frac{mc^2}{\sqrt{1-\frac{u^2}{c^2}}} - mc^2 =$$

$$\gamma mc^2 - mc^2 = (\gamma - 1)mc^2$$

Relativistic Energy – Consequences

- A particle has energy by virtue of its mass alone
  - A stationary particle with zero kinetic energy has an energy proportional to its inertial mass
  - This is shown by $E = K + mc^2 = 0 + mc^2$
- A small mass corresponds to an enormous amount of energy

Energy and Relativistic Momentum

- It is useful to have an expression relating total energy, E, to the relativistic momentum, p
  - $E^2 = p^2c^2 + (mc^2)^2$
    - When the particle is at rest, p = 0 and $E = mc^2$
    - Massless particles (m = 0) have E = pc
  - The mass m of a particle is independent of its motion and so is the same value in all reference frames
    - m is often called the invariant mass

Mass and Energy

- This is also used to express masses in energy units
  - Mass of an electron = 9.11×10^{-31} kg = 0.511 MeV
  - Conversion: 1 u = 929.494 MeV/c^2
- When using Conservation of Energy, rest energy must be included as another form of energy storage
- The conversion from mass to energy is useful in nuclear reactions

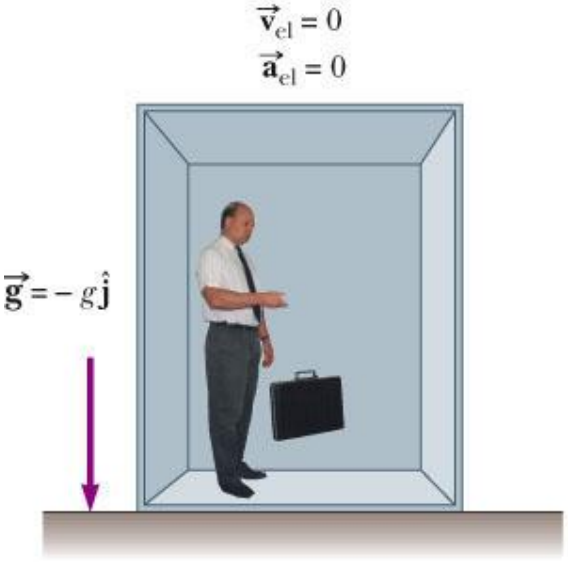
More About Mass

- Mass has two seemingly different properties
  - A *gravitational attraction* for other masses: $F_g = m_g g$
  - An inertial property that represents a resistance to acceleration: $\Sigma F = m_i a$
- That m_g and m_i were directly proportional was evidence for a connection between them
- Einstein's view was that the dual behavior of mass was evidence for a very intimate and basic connection between the two behaviors

Elevator Example, 1

- The observer is at rest in a uniform gravitational field, directed downward
- He is standing in an elevator on the surface of a planet
- He feels pressed into the floor, due to the gravitational force
- If he releases his briefcase, it will move toward the floor with an acceleration of

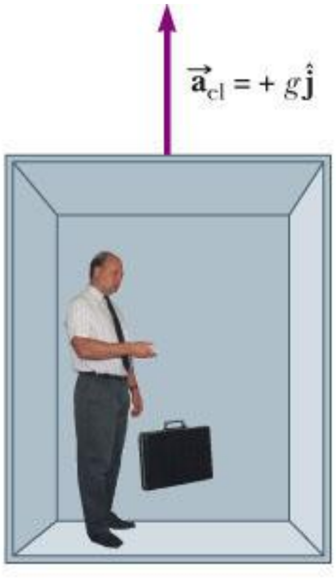
$$\vec{\mathbf{g}} = -g\hat{\mathbf{j}}$$



(a)

Elevator Example, 2

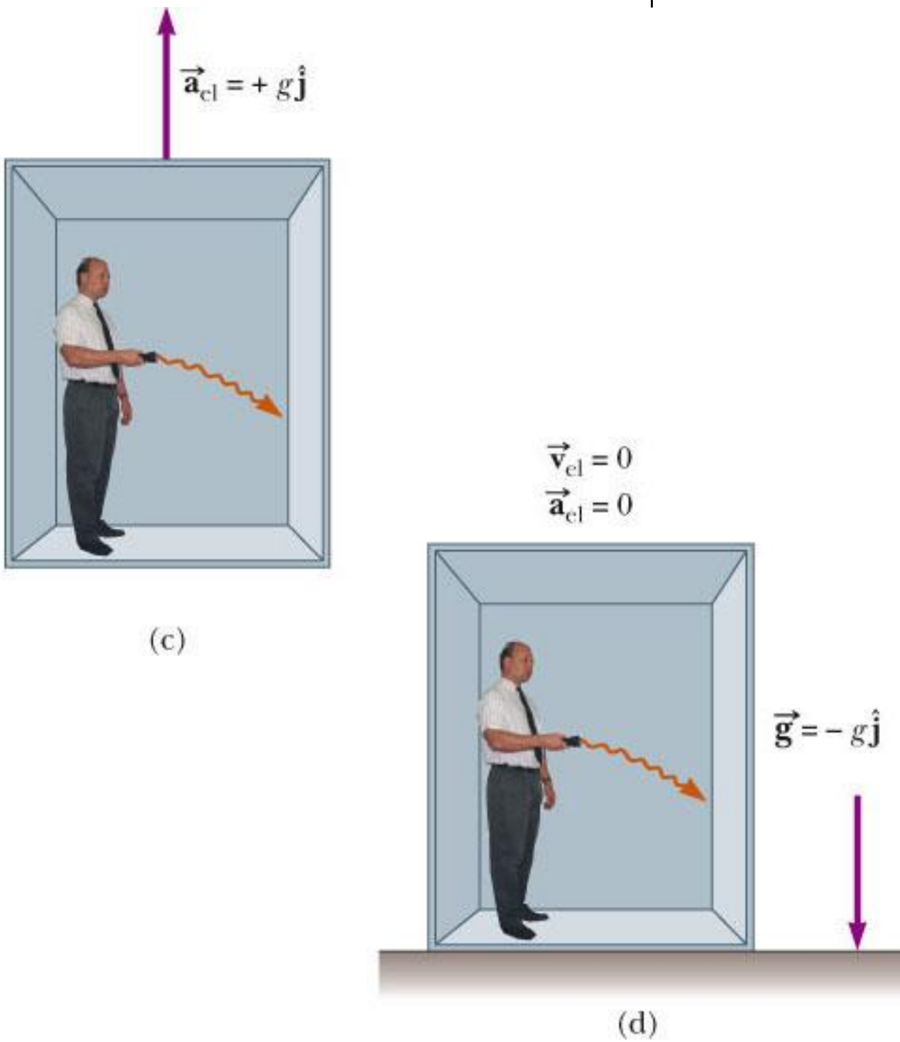
- Here the observer is accelerating upward
- A force is producing an upward acceleration of $a = g$
- The person feels pressed to the floor with the same force as in the gravitational field
- If he releases his drops his briefcase, he observes it moving toward the floor with $a = g$



(b)

Elevator Example, 3

- In c, the elevator is accelerating upward
- From the point of view of an observer in an inertial frame outside of the elevator sees the light pulse travel in a straight line while the elevator accelerates upward
- In d, the observer in the elevator sees the light pulse bend toward the floor
- In either case, the beam of light is bent by a gravitational field



Elevator Example, Conclusions

- Einstein claimed that the two situations were equivalent
- No local experiment can distinguish between the two frames
  - One frame is an inertial frame in a gravitational field
  - The other frame is accelerating in a gravity-free space

Einstein's Conclusions, cont.

- Einstein extended the idea further and proposed that no experiment, mechanical or otherwise, could distinguish between the two cases
- He proposed that a beam of light should be bent downward by a gravitational field
  - The bending would be small
  - A laser would fall less than 1 cm from the horizontal after traveling 6000 km
- Experiments have verified the effect

Postulates of General Relativity

- All the laws of nature have the same form for observers in any frame of reference, whether accelerated or not
- In the vicinity of any point, a gravitational field is equivalent to an accelerated frame of reference in gravity-free space
  - This is the *principle of equivalence*

Implications of General Relativity

- Time is altered by gravity
  - A clock in the presence of gravity runs slower than one where gravity is negligible
- The frequencies of radiation emitted by atoms in a strong gravitational field are shifted to lower frequencies
  - This has been detected in the spectral lines emitted by atoms in massive stars

More Implications of General Relativity

- A gravitational field may be “transformed away” at any point if we choose an appropriate accelerated frame of reference – a freely falling frame
- Einstein specified a certain quantity, the *curvature of time-space*, that describes the gravitational effect at every point

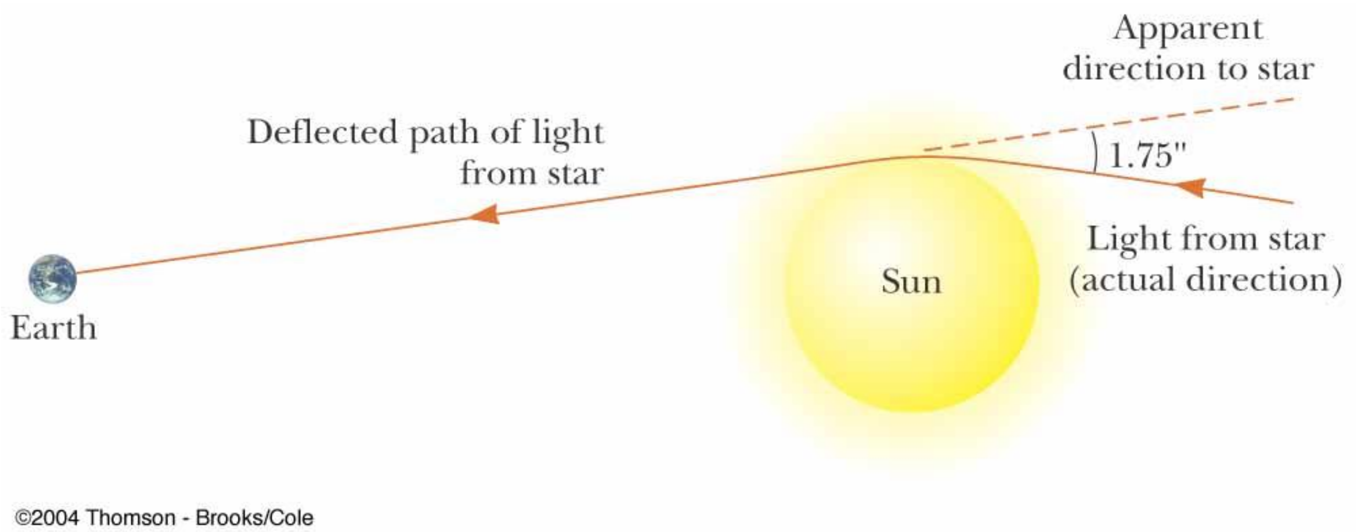
Curvature of Space-Time

- The curvature of space-time completely replaces Newton’s gravitational theory
- There is no such thing as a gravitational force
  - According to Einstein
- Instead, the presence of a mass causes a curvature of time-space in the vicinity of the mass
  - This curvature dictates the path that all freely moving objects must follow

Effect of Curvature of Space-Time

- Imagine two travelers moving on parallel paths a few meters apart on the surface of the Earth, heading exactly northward
- As they approach the North Pole, their paths will be converging
- They will have moved toward each other as if there were an attractive force between them
- It is the geometry of the curved surface that causes them to converge, rather than an attractive force between them

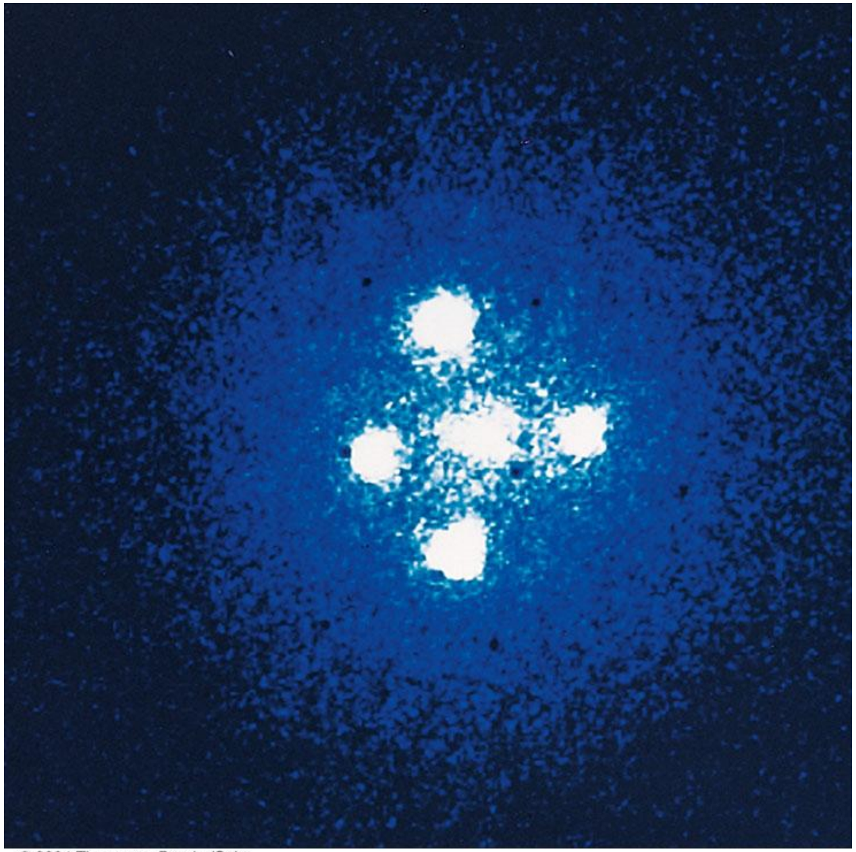
Testing General Relativity



- General relativity predicts that a light ray passing near the Sun should be deflected in the curved space-time created by the Sun's mass
- The prediction was confirmed by astronomers during a total solar eclipse

Einstein's Cross

- The four spots are images of the same galaxy
- They have been bent around a massive object located between the galaxy and the Earth
- The massive object acts like a lens



Black Holes

- If the concentration of mass becomes very great, a black hole may form
- In a black hole, the curvature of space-time is so great that, within a certain distance from its center, all light and matter become trapped