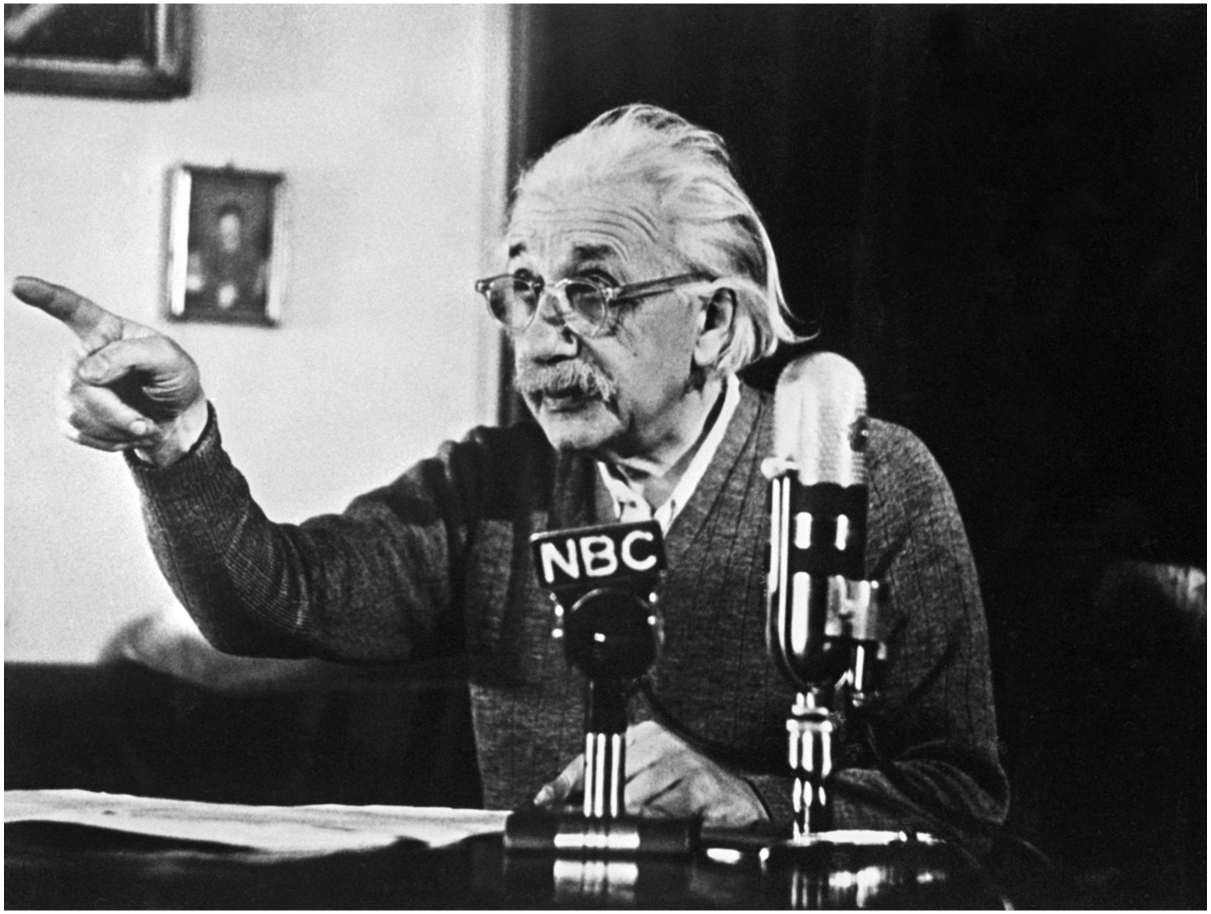
The Special Theory of Relativity

Lecture 16

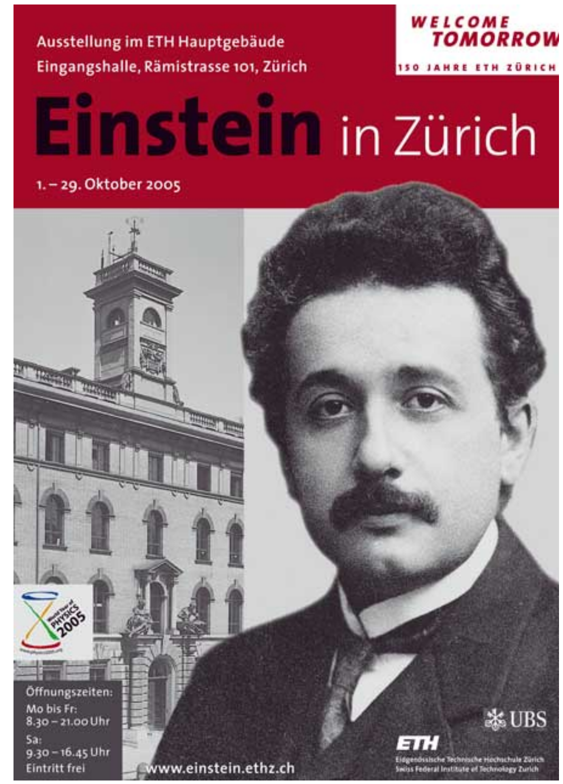
$E = mc^2$



Albert Einstein

Einstein’s Relativity

- Galilean-Newtonian Relativity
- The Ultimate Speed - The Speed of Light
- Postulates of the Special Theory of Relativity
- Simultaneity
- Time Dilation and the Twin Paradox
- Length Contraction
- Train in the Tunnel paradox (or plane in the barn)
- Relativistic Doppler Effect
- Four-Dimensional Space-Time
- Relativistic Momentum and Mass
- $E = mc^2$; Mass and Energy
- Relativistic Addition of Velocities



Recommended Reading: *Conceptual Physics* by Paul Hewitt

A Brief History of Time by Steven Hawking

Galilean-Newtonian Relativity

The Relativity principle:

The basic laws of physics are the same in all inertial reference frames.

(a)
Reference frame = car

(b)
Reference frame = Earth

What's a reference frame? What does "inertial" mean? Etc……..

Think of ways to tell if you are in Motion.
-And hence understand what Einstein meant
By inertial and non inertial reference frames

How does it differ if you' re in a car or plane at different points in the journey

- **Accelerating ?**
- **Slowing down ?**
- **Going around a curve ?**
- **Moving at a constant velocity ?**

Why?

ConcepTest 26.1 Playing Ball on the Train

You and your friend are playing catch in a train moving at 60 mph in an eastward direction. Your friend is at the front of the car and throws you the ball at 3 mph (according to him). What velocity does the ball have when you catch it, according to you?

1) 3 mph eastward
2) 3 mph westward
3) 57 mph eastward
4) 57 mph westward
5) 60 mph eastward

ConcepTest 26.1 Playing Ball on the Train

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4) 57 mph westward
5) 60 mph eastward

In the reference frame of the train car, you and your friend are both at rest. When he throws the ball to you at 3 mph, you will judge the ball to be moving at 3 mph. To you and your friend, it is just the same as if you were playing catch in a stationary room.

Follow-up: What velocity does the ball have, as measured by an observer at rest on the station platform?

ConcepTest 26.3 Inertial Reference Frames

Which of the systems below are not *inertial reference frames*?

1) a person standing still
2) an airplane in mid-flight
3) a merry-go-round rotating at a constant rate
4) all of the above are IRFs
5) none of the above are IRFs

ConcepTest 26.3 Inertial Reference Frames

Which of the systems below are **not** *inertial reference frames*?

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4) all of the above are IRFs
5) none of the above are IRFs

An **inertial reference frame** is the same as a **non-accelerating reference frame**. Due to the circular motion of the merry-go-round, there is a **centripetal acceleration**, which means that the system is accelerating. Therefore it is **not** an inertial reference frame.

26.1 Galilean-Newtonian Relativity

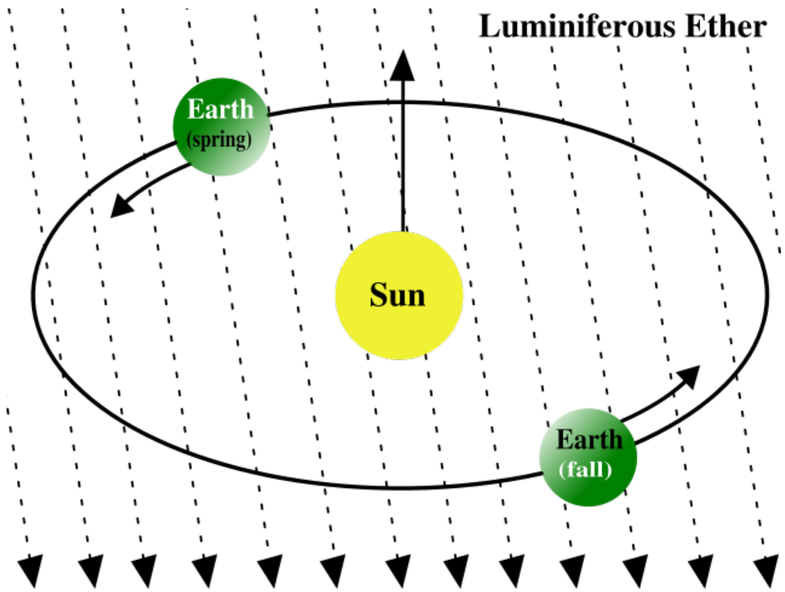
Definition of an inertial reference frame:

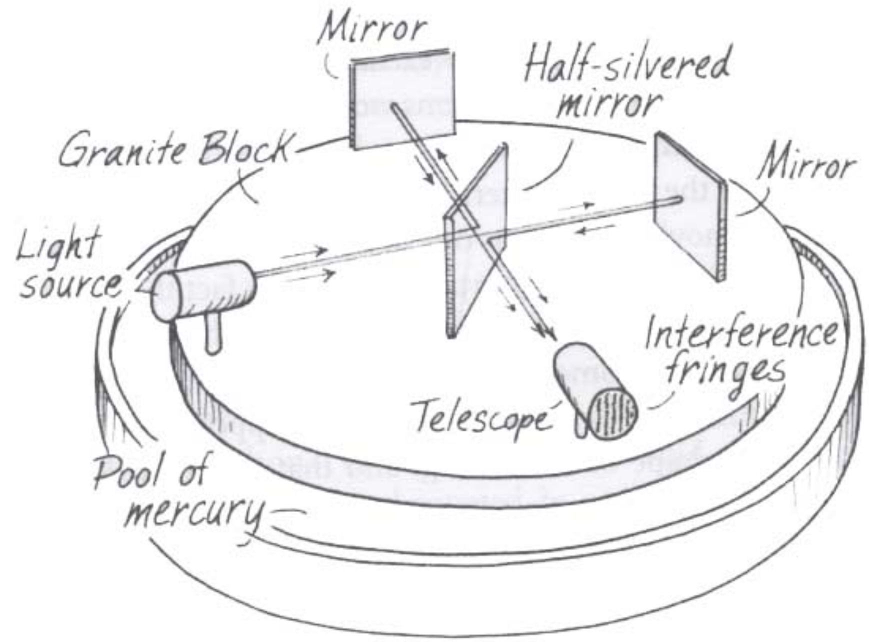
- **Any place where Newton's first law holds (The Law of Inertia) holds.**
- **Earth is rotating and therefore not an inertial reference frame, but can treat it as one for many purposes**
- **A frame moving with a constant velocity with respect to an inertial reference frame is itself inertial**
- **An accelerated frame is said to be Non-Inertial.**

No Still Point in the Moving Universe

- Maxwell's equations predict a precise velocity of light: 3.0 x 10^8 m/s.
- But in what reference frame in which light travels at that speed?
- Or, relative to what is this special speed defined?
- It was widely believed that a universal substance: "Luminiferous Ether" permeated the universe, and was the "ocean" in which the waves of light travel.
- Scientists searched for the Ether, by looking for variations in the speed of light depending on the direction of the ray, but found none.
- The Michelson - Morley Experiment
- Meanwhile, Einstein wondered about Maxwell's Electromagnetic Waves. Just how would the wave appear if one were traveling alongside it?
- Apparently the general idea of running alongside a light beam had puzzled Albert since age 6, and no one could give a good explanation as to what you would "see".
- Realized that a "frozen light wave" was impossible

Michelson, Morley, and the most Successful "Failed Experiment" of all Time.





Michelson (who invented the interferometer) set out to measure the Earth's velocity through the Ether.

Light sent along 2 paths would interfere to create an interference pattern, if the light took longer to travel one path then the other.

Earth circles the sun at 30 km/s, so light should be fighting a substantial "current" - like a swimmer crossing a river.

No change could be detected, no matter what!

Conclusion: Speed of light is the same for all observers -Very Weird

26.2 Postulates of the Special Theory of Relativity

1. The laws of physics have the same form in all inertial reference frames.

2. Light propagates through empty space with speed c independent of the speed of source or observer.

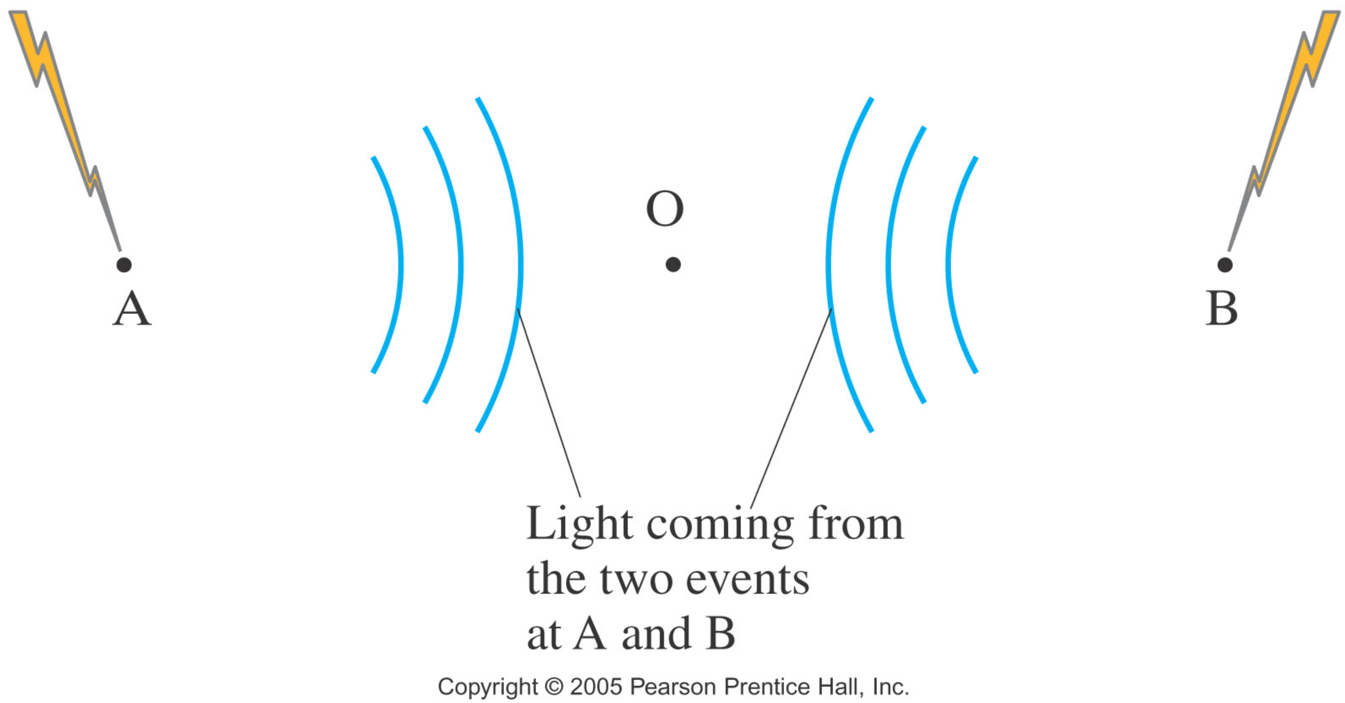
Hence: the speed of light, which is a consequence of the laws of physics (Maxwell) is the same in all inertial reference frames.

26.3 Simultaneity

- One of the implications of relativity theory is that time is not absolute.
- Distant observers do not necessarily agree on time intervals between events, or on whether they are simultaneous or not.
- Observers in Relative Motion do not agree on the simultaneity of events.
- For example clock "ticks" will no longer be synchronized.
- If simultaneity is breached then so must be TIME itself!

26.3 Simultaneity

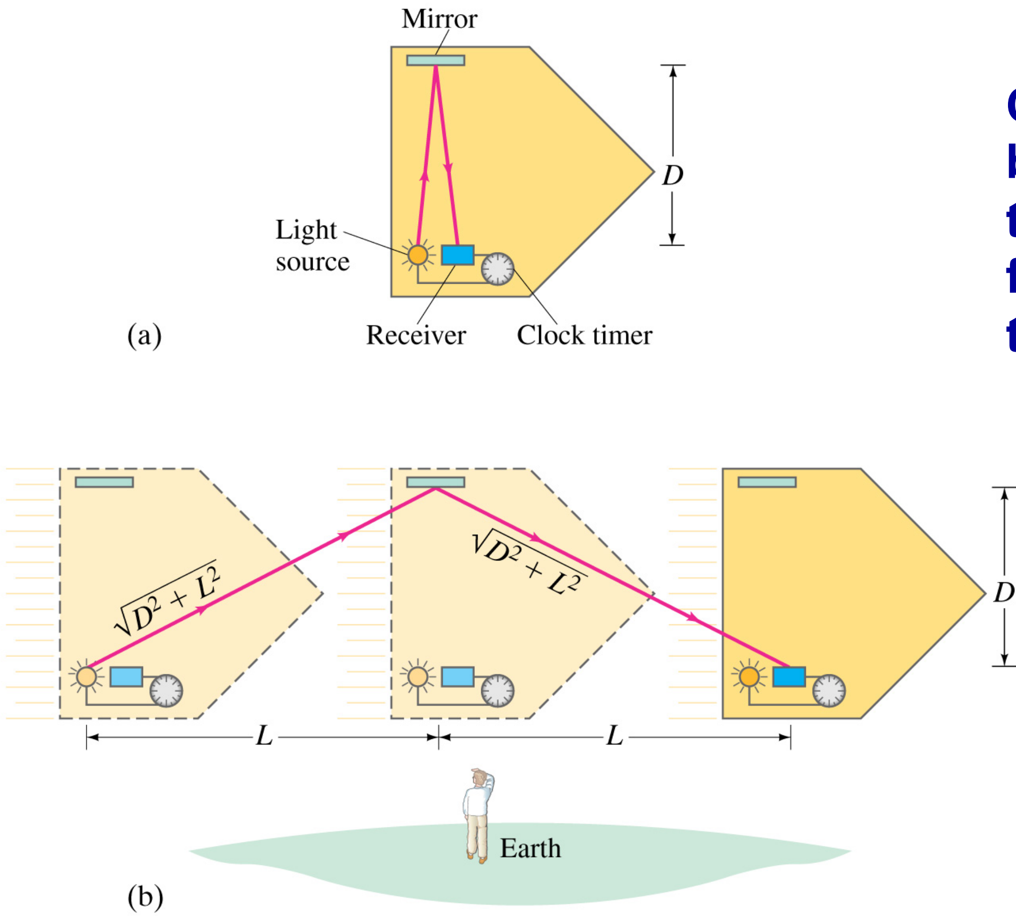
Thought experiment: Lightning strikes at two separate places. One observer believes the events are simultaneous – the light has taken the same time to reach her – but another, moving with respect to the first, does not.



Someone running (very fast!) past O (say toward B) will move a certain distance in the time it takes light to arrive from A & B. They will say that B was struck first.

26.4 Time Dilation

A Thought experiment, using a clock consisting of a light beam and mirrors, shows that moving observers must disagree on the passage of time.



Calculating the difference between clock "ticks," we find that the interval in the moving frame is related to the interval in the clock's rest frame:

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - v^2/c^2}}$$

This exact situation occurs every day for satellites and their operators

26.5 Length Contraction

If time intervals are different in different reference frames, lengths must be different as well. Length contraction is given by:

$$L = L_0 \sqrt{1 - v^2/c^2} \qquad \textbf{(26-3a)}$$

or

Length contraction occurs only along the direction of motion.

Relativistic "Gamma"

This factor multiplying occurs so often in relativity that it is given its own symbol, *γ*.

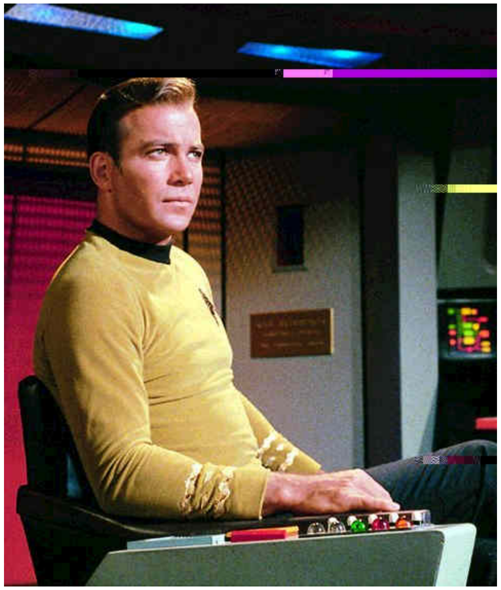
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \tag{26-2}$$

We can then write:

(26-1b) $\Delta t = \gamma \, \Delta t_0$ **and** $L = \dfrac{L_0}{\gamma}$ (26-3b)

- **The effects of Relativity are noticeable when gamma gets larger than 1.**
- **I.e. when speeds are a significant fraction of c**

If the Starship enterprise were to travel at 90% of the speed of light, how many Earth seconds would elapse for every second on Captain Kirk's watch?



A. 1 earth second.

B. 2.29 earth seconds

C. 0.9 earth seconds

D. 0.43 earth seconds

Gamma and Velocity - When do I need to consider Relativity?

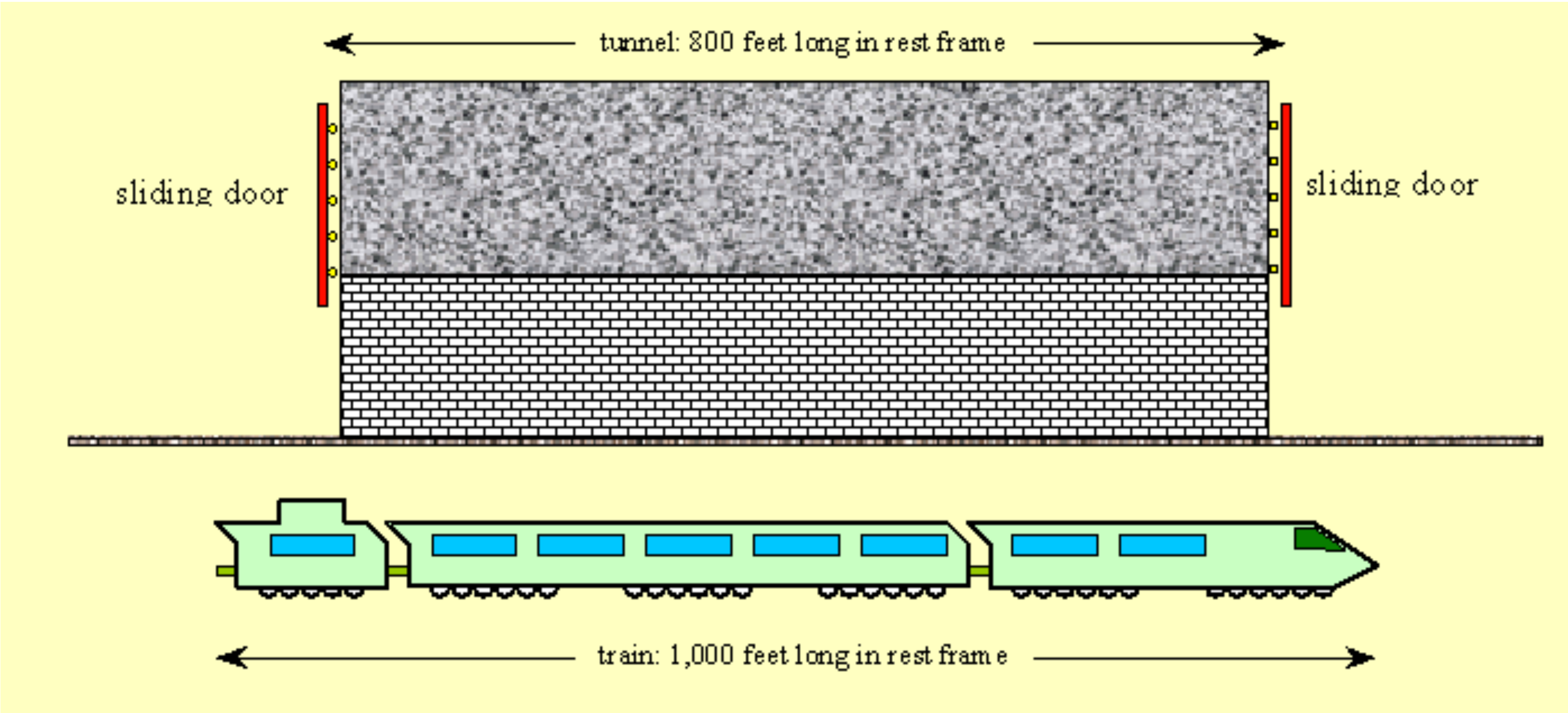
- Relativity is always present!
- This table provides a guide to when you would notice it.
- At 10% of the speed of light the effect is only 0.5%.
- At and above 90% of *c*,

relativity dominates the picture.

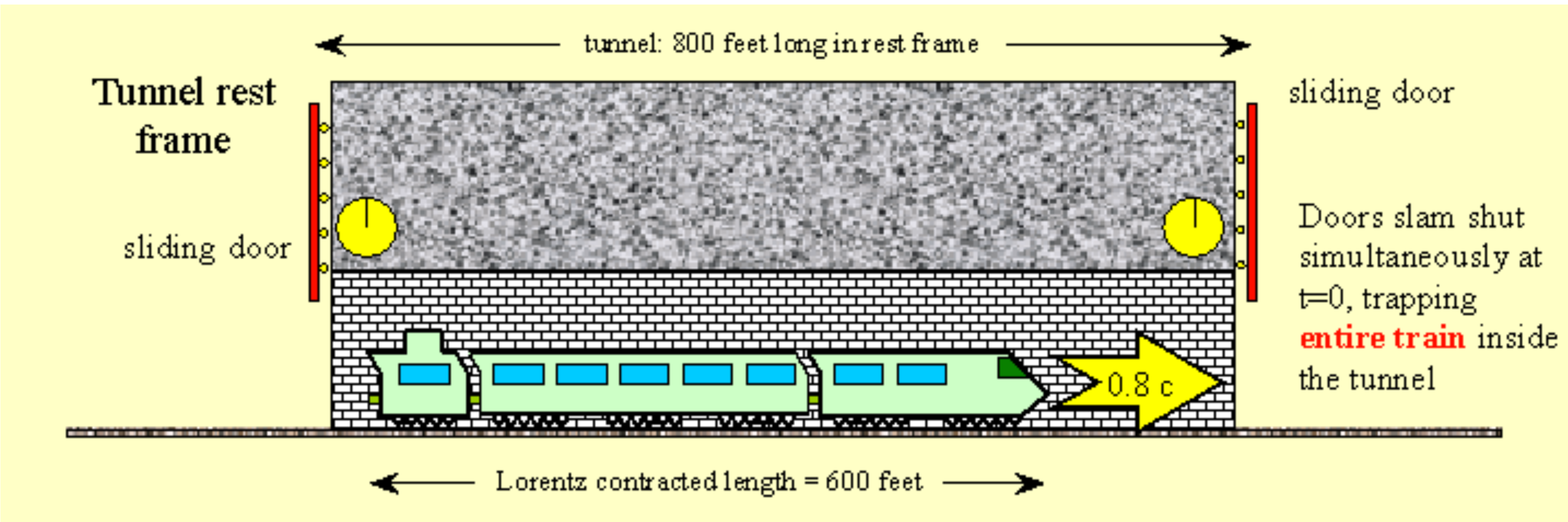
TABLE 26–1 Values of γ

v	γ
0	1.000
0.01c	1.000
0.10c	1.005
0.50c	1.15
0.90c	2.3
0.99c	7.1

The Train and the Tunnel Paradox .1



The Train and the Tunnel Paradox .1



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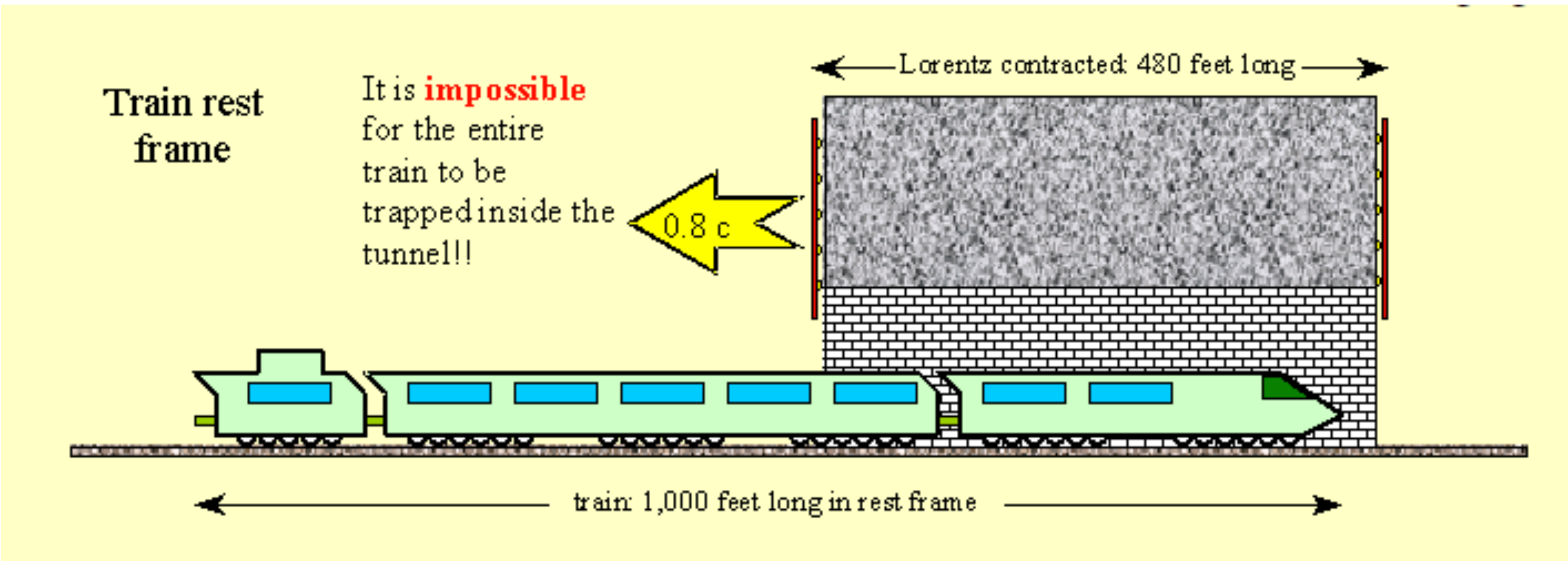


Can an 80m long train ever fit inside a 70m long tunnel ?

A. No, never.
B. Yes, if going fast enough
C. No it would just appear that way

26.4 Time Dilation and the Twin Paradox

It has been proposed that space travel could take advantage of time dilation – if an astronaut's speed is close enough to the speed of light, a trip of 100 light-years could appear to the astronaut as having been much shorter.

The astronaut would return to Earth after being away for a few years, and would find that hundreds of years had passed on Earth.

26.4 Time Dilation and the Twin Paradox

This brings up the twin paradox – if any inertial frame is just as good as any other, why can't the argument be played in reverse, to end up with the astronaut aging faster as than the Earth appears to travel away from her?

The solution to the paradox is that the astronaut's reference frame has not been continuously inertial – she turns around at some point and comes back.

The twin on Earth remains in a single inertial frame throughout.

In General Relativity (GR: Einstein's theory of Gravity and space-time) acceleration and gravity are found to be equivalent. So when the astronaut accelerates/decelerates/turns around she experiences much higher effective gravity than her Twin on Earth. In GR, time passes more slowly in places where gravity is stronger, so the twin paradox is fully solved by General Relativity.

Beyond the Twin Paradox: The Relativistic Doppler Effect

• If the astronaut twin sends out regular signals (say one per day, at the same time each day) the earthbound twin will receive them "delayed" because the distance that the signal must travel, which increases in the interval between transmissions.

• Same argument applies to the peaks of the electromagnetic (e.g. light or radio) waves used for the transmission.

• Wavelength will be stretched/compressed (Lorentz contraction), or equivalently the frequency will fall/rise due to time dilation.

• During outbound trip, the wavelength increases.

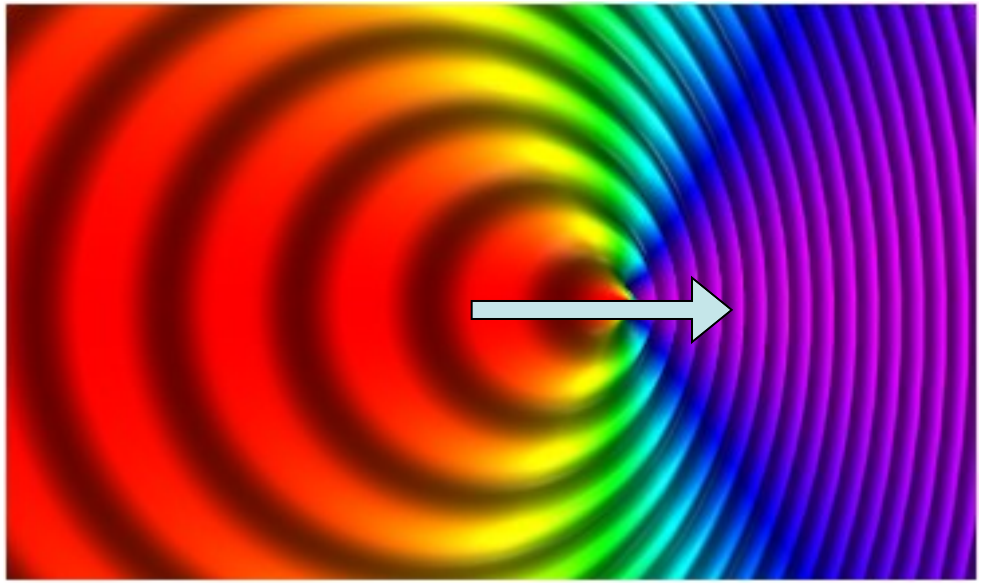
• On homeward trip, wavelength gets smaller.

• One can show that $\Delta\lambda/\lambda = \sqrt{[(1+v/c)/(1-v/c)]}$

• For speeds $v \ll c$ this reduces to $\Delta\lambda/\lambda \approx v/c$

The Relativistic Doppler Effect

Light is redshifted for observer here



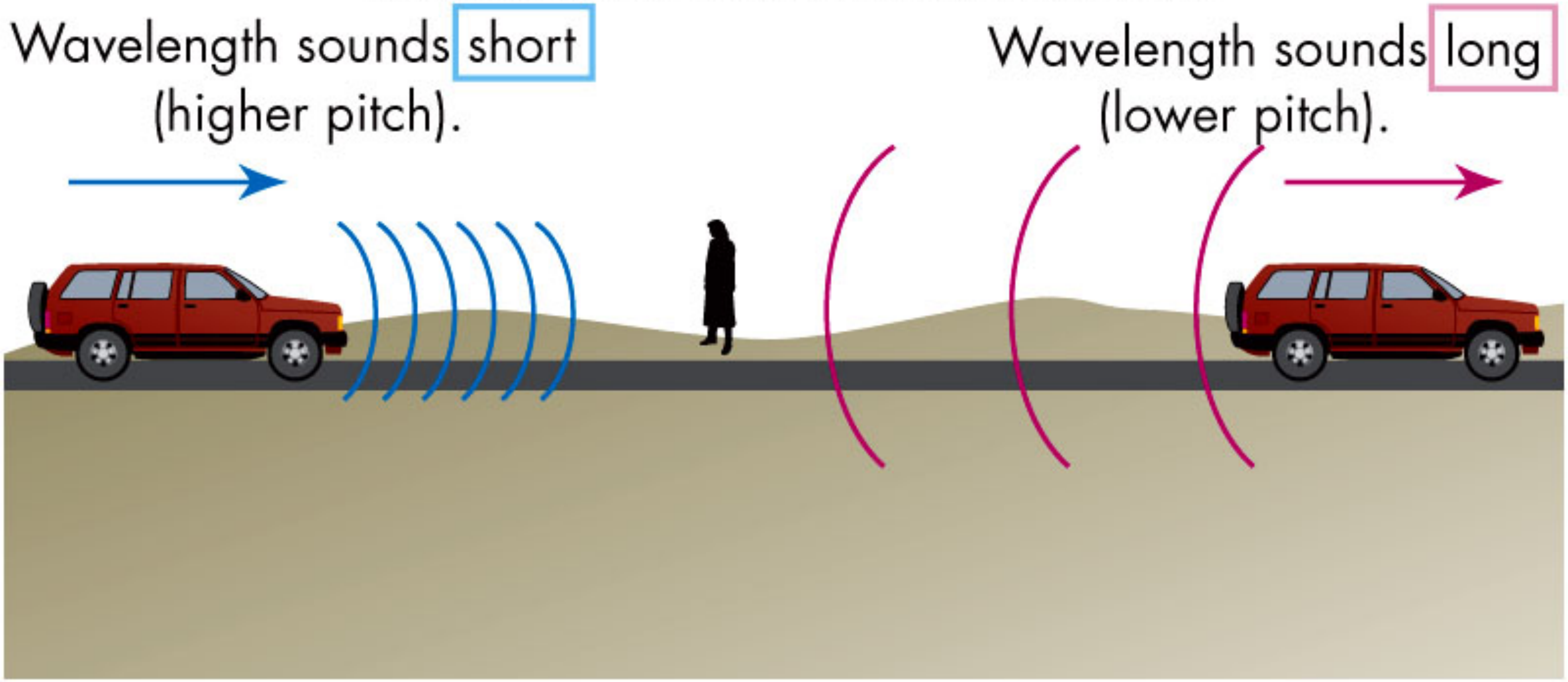
Light is blueshifted for observer here

• Light emitted by a moving source will have its wavelength compressed or stretched-out, as seen by a stationary observer.

• Is of huge practical importance, as it enables us to measure speeds in astronomy, in laboratories, in meteorology, and on the highway.

•The doppler effect is a central piece of the theory of relativity, because reconciles the fixed speed of light with the conservation of energy

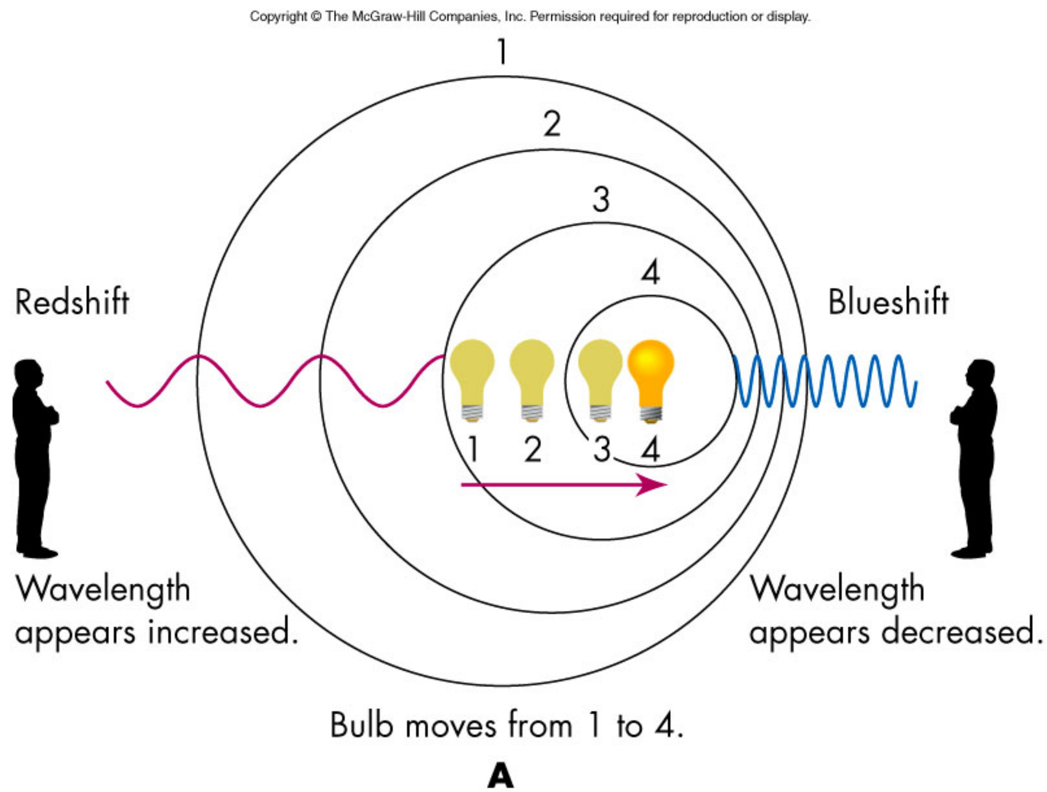
Doppler Shift in Sound



B

- If the source of sound is moving, the pitch changes!

Doppler Shift in Light



– If a source of light is set in motion relative to an observer, its spectral lines shift to new wavelengths in a similar way

– The shift in wavelength is given as

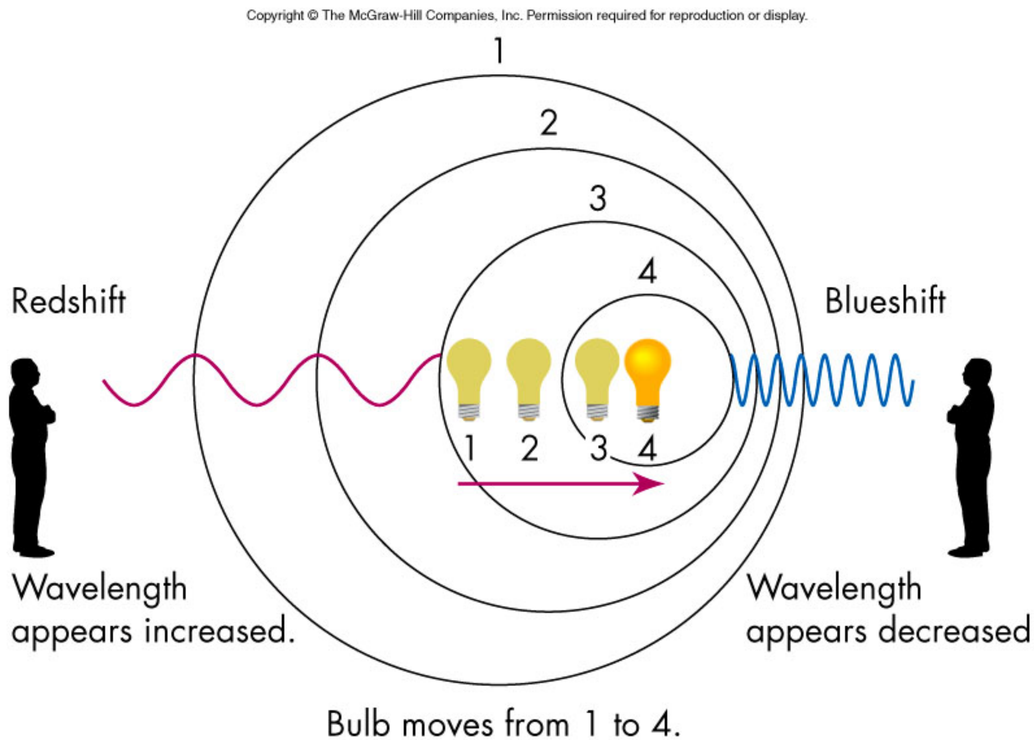
$$\Delta\lambda = \lambda - \lambda_o$$

$$\Delta\lambda/\lambda_o = v/c$$

where λ is the observed (shifted) wavelength, λ_o is the emitted wavelength, v is the source non-relativistic <u>radial velocity</u>, and c is the speed of light

Redshift and Blueshift

- An observed increase in wavelength is called a redshift, and a decrease in observed wavelength is called a blueshift (regardless of whether or not the waves are visible)
- Doppler shift is used to determine an object's velocity



A

26.7 Relativistic Momentum and Mass

Expressions for momentum and mass also change at relativistic speeds.

Momentum:

$$p = \frac{m_0 v}{\sqrt{1 - v^2/c^2}} = \gamma m_0 v \qquad \textbf{(26-4)}$$

Gamma and the rest mass are sometimes combined to form the relativistic mass:

$$m_{\text{rel}} = \frac{m_0}{\sqrt{1 - v^2/c^2}} = \gamma m_0 \qquad \textbf{(26-5)}$$

26.9 $E = mc^2$; Mass and Energy

At relativistic speeds, not only is the formula for momentum modified; that for energy is as well.

The total energy can be written:

$$E = \gamma m_0 c^2 = \frac{m_0 c^2}{\sqrt{1 - v^2/c^2}} \qquad \text{(26-7b)}$$

Where the particle is at rest,

$$E_0 = m_0 c^2 \qquad \text{(26-8)}$$

Correspondance Principle

All the formulas presented here become the usual Newtonian kinematic formulas when the speeds are much smaller than the speed of light. (The correspondence principle)

There is no rule for when the speed is high enough that relativistic formulas must be used – it depends on the desired accuracy of the calculation.

Use Gamma as a guide (table on a previous slide)

Another basic result of special relativity is that nothing can equal or exceed the speed of light. This would require infinite momentum – not possible for anything with mass.

Mass and Energy $E=mc^2$

Einstein's 1905 paper pointed out that under
Certain conditions mass and energy
interchange.

Practical applications of this principle include
the mass of the reactants and product of

- Nuclear reactions
- Chemical reactions

at the time nuclear reactions were not understood
But by the 1940's a mechanism had been identified
For converting mass to energy……

Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work,which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

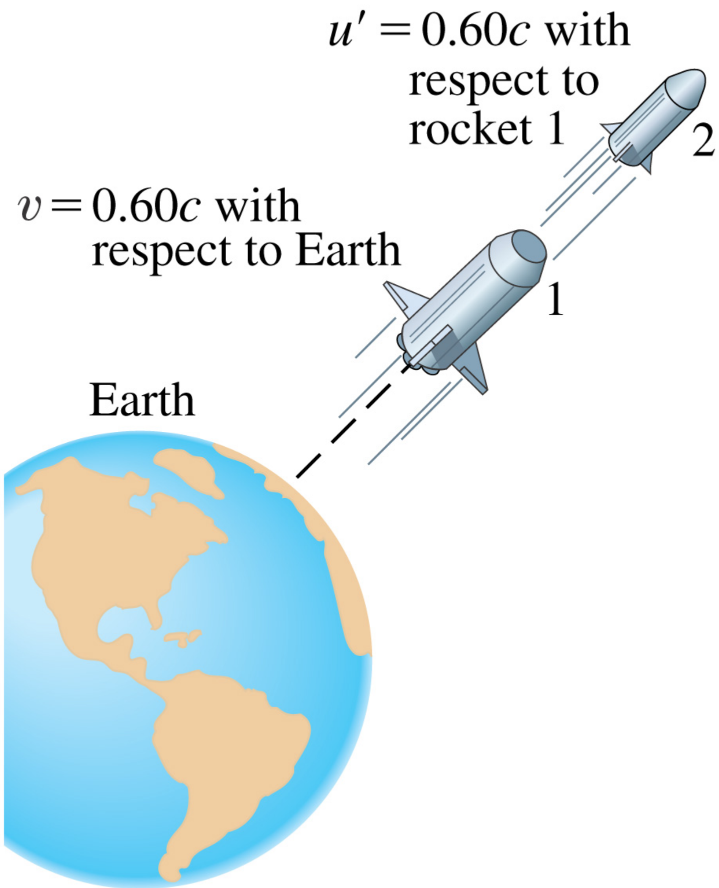
Yours very truly,
A. Einstein
(Albert Einstein)

“Trinity” atom bomb test. New Mexico, July 16th,1945

At 05:29:45 AM “The Gadget” exploded with an energy equivalent to around 20 kilotons of TNT It left a crater of radioactive glass in the desert 10 feet deep and 1,100 feet wide. The surrounding mountains were illuminated "brighter than daytime" for one to two seconds, and the heat was reported as "being as hot as an oven" at the base camp. The observed colors of the illumination ranged from purple to green and eventually to white. The roar of the shock wave took 40 seconds to reach the observers. The shock wave was felt over 100 miles away, and the mushroom cloud reached 7.5 miles (12 km) in height. After the initial euphoria of witnessing the explosion had passed, test director Kenneth Bainbridge commented to Los Alamos director J. Robert Oppenheimer, "Now we are all sons of bitches.” Oppenheimer later stated that, while watching the test, he was reminded of a line from the Bhagavad Gita, a Hindu scripture:Now I am become Death, the destroyer of worlds., General Farrell wrote, "The lighting effects beggared description. The whole country was lighted by a searing light with the intensity many times that of the midday sun. It was golden, purple, violet, gray, and blue. It lighted every peak, crevasse and ridge of the nearby mountain range with a clarity and beauty that cannot be described but must be seen to be imagined..."

26.10 Relativistic Addition of Velocities

Relativistic velocities cannot simply add; the speed of light is an absolute limit. The relativistic formula is:



$$u = \frac{v + u'}{1 + vu'/c^2} \qquad \textbf{(26-11)}$$

ConcepTest 26.5 Windowless Spaceship

You are in a spaceship with no windows, radios or other means to check outside. How would you determine if the spaceship is at rest or moving at constant velocity?

1) by determining the apparent velocity of light in the spaceship
2) by checking your precision watch. If it's running slow, then the ship is moving.
3) by measuring the lengths of objects in the spaceship. If they are shorter, then the ship is moving.
4) You should give up because you've taken on a impossible task.

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4) You should give up because you've taken on a impossible task.

According to you (in the spaceship), your clock runs exactly the same as it did when you were at rest on Earth, all objects in your ship appear the same to you as they did before, and the speed of light is still *c*. There is nothing you can do to find out if you are actually moving.

ConcepTest 26.7a Speed of Light I

It is said that Einstein, in his teenage years, asked the question: "What would I see in a mirror if I carried it in my hands and ran with the speed of light?" How would you answer this question?

1) The mirror would be totally black
2) You would see the same thing as if you were at rest
3) The image would be distorted
4) None of the above

ConcepTest 26.7a Speed of Light I

It is said that Einstein, in his teenage years, asked the question: "What would I see in a mirror if I carried it in my hands and ran with the speed of light?" How would you answer this question?

1) The mirror would be totally black
2) You would see the same thing as if you were at rest
3) The image would be distorted
4) None of the above

The speed of light is the **same** in all reference frames, independent of the speed of the source or the observer. Therefore, the light **still travels at the speed *c***, and what you see in the mirror will be exactly the same as what you would see if you were at rest.

ConcepTest 26.8 Foghorns

All of the boats on the bay have foghorns of equal intensity. One night on the shore, you hear two horns at **exactly the same time** -- one is loud and the other is softer. What do you conclude from this?

1) softer one sounded first
2) louder one sounded first
3) both sounded at the same time
4) unable to conclude anything

ConcepTest 26.8 Foghorns

All of the boats on the bay have foghorns of equal intensity. One night on the shore, you hear two horns at exactly the same time -- one is loud and the other is softer. What do you conclude from this?

1) softer one sounded first
2) louder one sounded first
3) both sounded at the same time
4) unable to conclude anything

Since all boats sound their foghorns at the same intensity but you hear them at different intensities, the softer one must have traveled a greater distance. That means the softer one sounded first.

ConcepTest 26.13a Time Dilation I

An astronaut moves away from earth at close to the speed of light. How would an observer on Earth measure the astronaut's pulse rate?

1) It would be faster
2) It would be slower
3) It wouldn't change
4) No pulse - the astronaut died a long time ago

ConcepTest 26.13a Time Dilation I

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1) It would be faster
2) It would be slower
3) It wouldn't change
4) No pulse - the astronaut died a long time ago

The astronaut's pulse would function like a clock. Since time moves slower in a moving reference frame, the observer on Earth would measure a slower pulse.

ConcepTest 26.14 Length Contraction

A spaceship moves faster and faster, approaching the speed of light. How would an observer on Earth see the spaceship?

1) It becomes shorter and shorter

2) It becomes longer and longer

3) There is no change

ConcepTest 26.14 Length Contraction

A spaceship moves faster and faster, approaching the speed of light. How would an observer on Earth see the spaceship?

1) It becomes shorter and shorter
2) It becomes longer and longer
3) There is no change

Due to length contraction an observer would see the spaceship become shorter and shorter.

Follow-up: What would the astronaut measure about his spaceship?

ConcepTest 26.16a The Tunnel I

A spacecraft has a length of 100 m, when parked on Earth. It is now moving toward a tunnel with a speed of 0.8 c (γ =1.66). The lady living near the tunnel can control doors that open and shut at each end of the tunnel, which is 65 m long. The doors are open as the spaceship approaches, but in the very moment that she sees the back of the spaceship in the tunnel, she closes both doors and then immediately opens them again.

- ***According to the lady living near the tunnel:***

1) no door hit the spaceship because for her the doors weren't closed simultaneously
2) no door hit the spacecraft because length contraction makes the spaceship only 60 m long
3) no door hits the spaceship because length contraction has made the tunnel 109 m long
4) a door hits the spaceship

ConcepTest 26.16a The Tunnel I

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- ***According to the lady living near the tunnel:***

1) no door hit the spaceship because for her the doors weren't closed simultaneously
2) no door hit the spacecraft because length contraction makes the spaceship only 60 m long
3) no door hits the spaceship because length contraction has made the tunnel 109 m long
4) a door hits the spaceship

The rocket is in the moving reference frame and therefore length contracted by the amount γ.

ConcepTest 26.16b The Tunnel II

A spacecraft has a length of 100 m, when parked on Earth. It is now moving toward a tunnel with a speed of 0.8 c. The lady living near the tunnel can control doors that open and shut at each end of the tunnel, which is 65 m long. The doors are open as the spaceship approaches, but in the very moment that she sees the back of the spaceship in the tunnel, she closes both doors and then immediately opens them again.

- *According to the captain in the spaceship:*

1) no door hit the spaceship because for her the doors weren't closed simultaneously
2) no door hit the spacecraft because length contraction shortens the spaceship to 60 m long
3) no door hits the spaceship because length contraction has made the tunnel 109 m long
4) a door hits the spaceship

ConcepTest 26.16b The Tunnel II

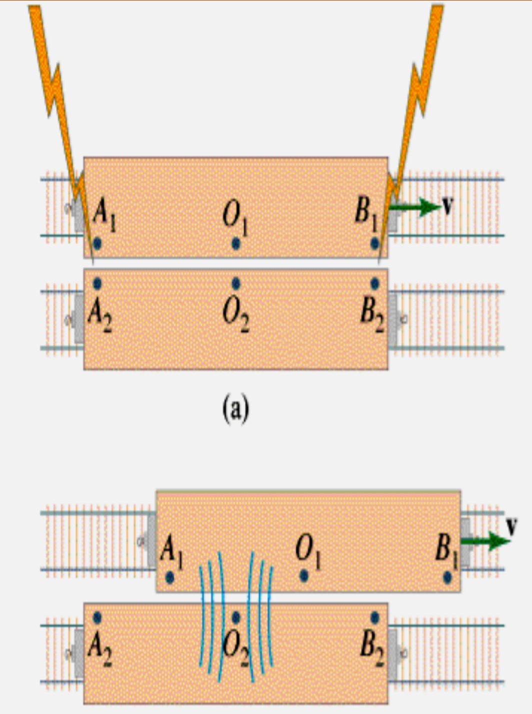
1) no door hit the spaceship because for him the doors weren't closed simultaneously

2) no door hit the spacecraft because length contraction makes the spaceship only 60 m long

3) no door hits the spaceship because length contraction has made the tunnel 109 m long

4) a door hits the spaceship

Remember the flashes hitting the box cars; here the doors of the tunnel work like the flashes; just as the *moving* box car sees the front flash first, before the back flash, the captain sees the *front door close (and open!)* while the back of the space ship is still sticking out the end of the tunnel. Then he sees the back doors close while the front of the spaceship is already out of the tunnel.



ConcepTest 26.18 Muon Decay

The short lifetime of particles called muons (created in Earth's upper atmosphere) would not allow them to reach the surface of Earth unless their lifetime increased by time dilation.

- From the reference system of the muons, they can reach the surface of Earth because:

1) time dilation increases their velocity
2) time dilation increases their energy
3) length contraction decreases the distance to the surface of Earth
4) the creation and decay of the muons is simultaneous
5) the relativistic speed of Earth toward them is added to their speed

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In the muon frame of reference, they see the distance to the surface of Earth "moving toward them" and therefore this length is relativistically contracted. Thus, according to the muons, they are able to traverse this shorter distance in their proper lifetime, which is how long they live in their frame.

Summary of Chapter 26

- **Gamma:** $$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$
- **Time dilation:** $$\Delta t = \gamma\, \Delta t_0$$
- **Length contraction:** $$L = \frac{L_0}{\gamma}$$
- **Relativistic momentum:** $$p = \gamma m_0 v$$
- **Relativistic mass:** $$m_{\text{rel}} = \gamma m_0$$
- **Kinetic energy:** $$= (\gamma - 1) m_0 c^2$$
- **Mass-energy relation:** $$E_0 = m_0 c^2$$
- **Total energy:** $$E = \text{KE} + m_0 c^2$$ $$= \gamma m_0 c^2$$

26.11 The Impact of Special Relativity

The predictions of special relativity have been tested thoroughly, and verified to great accuracy.

The correspondence principle says that a more general theory must agree with a more restricted theory where their realms of validity overlap. This is why the effects of special relativity are not obvious in everyday life.

Big Bang Theory Doppler Effect

http://www.youtube.com/watch?v=Y5KaeCZ_AaY