Phys 100: The Physical World

Chapters 35 & 36

Aaron Wirthwein

Department of Physics and Astronomy
University of Southern California

The Role of Postulates

- A postulate is a foundational assumption, a statement we take to be true without proof.
  - Newton's laws, gravitational and electromagnetic fields
- We assess the validity of a postulate by examining its consequences. A good set of postulates leads to predictions that can be tested.
  - We **do not** assess the validity of a postulate by asking ourselves if it "makes sense" because it is supposed to be a statement by which we make sense of the world, so that would be absurd.
- If those predictions agree with observations and experiments, the postulates are supported but not proven.
- If the predictions fail, we may have to revise the postulates themselves, but not before refining the models, making many observations, and performing many experiments.

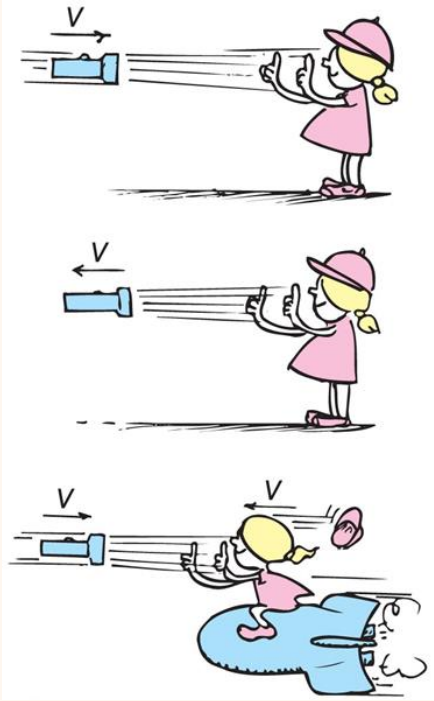
Postulates of Newtonian Physics

- In addition to Newton's three laws, there are other postulates of Newtonian physics related to the nature of space and time.
  - Space and time are absolute and exist independently of any observer. In other words, time flows uniformly for all observers, and distances and durations are the same in all inertial frames.
  - A meter stick is always one meter no matter what speed it's moving, and a clock will tick at a uniform rate no matter what speed it's moving at.
- In Newtonian physics, simultaneity is absolute: if two events happen at the same time in one frame, they happen at the same time in all frames. Everyone agrees on what "simultaneous" means, no matter what speed they're moving.
- These postulates work incredibly well when two observers are not moving very fast relative to one another, but they lead to contradictions that were not fully understood until the 20th century.

Postulates of Special Relativity

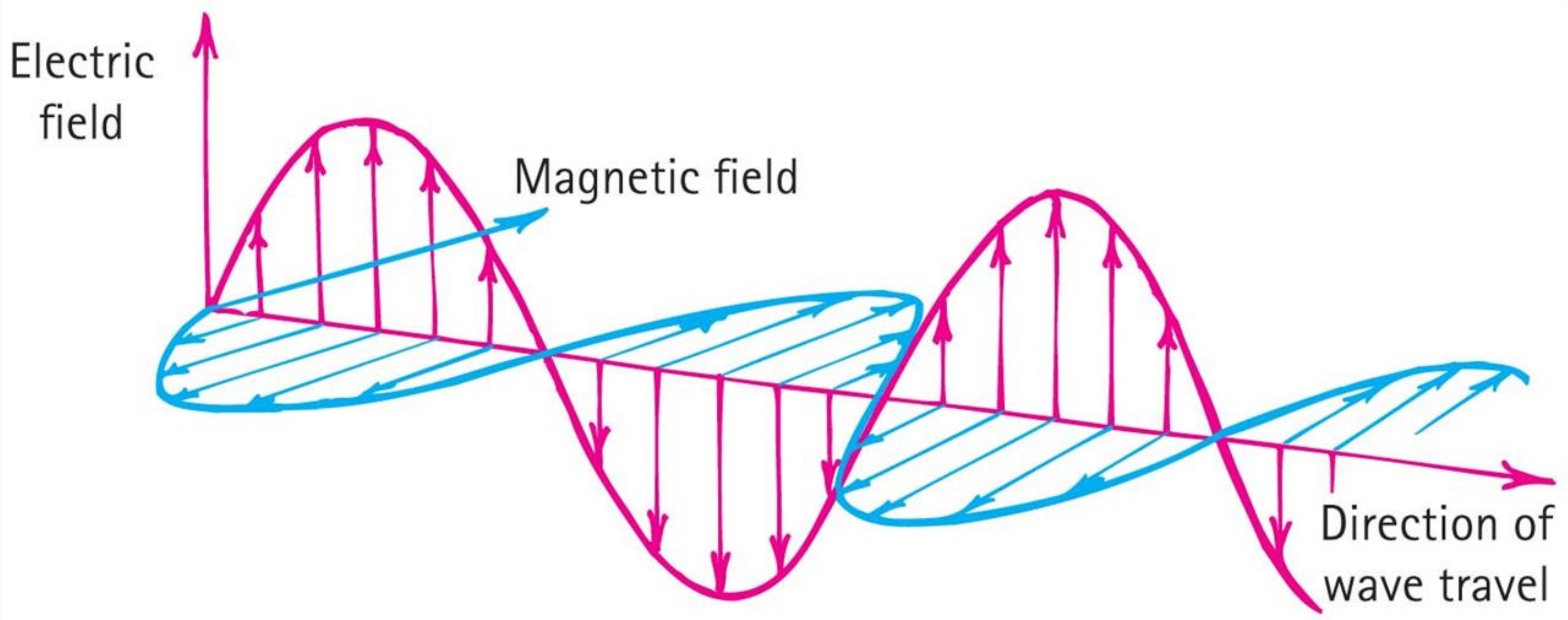
Relativity explores how measurements of time, space, motion, and energy depend on the observer's frame of reference, and crucially, **what remains invariant**.

1. Principle of relativity: all laws of nature are the same in all uniformly moving frames of reference (inertial frames).
2. Constancy of the speed of light: light in vacuum propagates at a constant speed in all directions, in all inertial frames, independent of the motion of the source or observer.

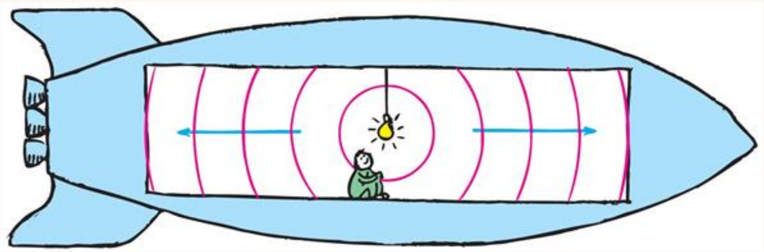


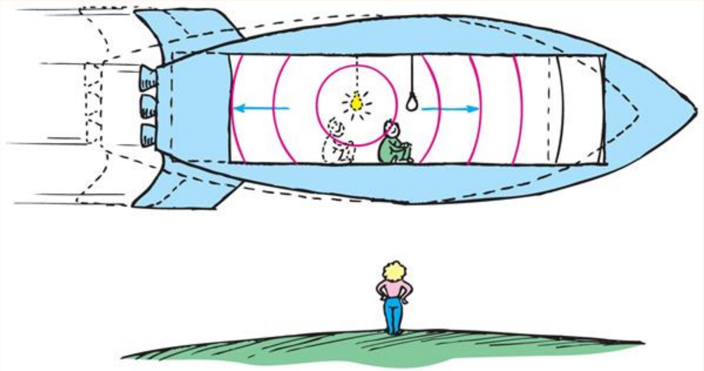
Postulate #2 was Einstein's original insight, but today we say that *there exists a maximum speed at which causal influences can propagate*, and light happens to travel at that speed, denoted c.

Can you surf an EM wave?



Relativity of Simultaneity





- From the point of view of the observer who travels with the compartment, light from the source travels equal distances to both ends of the compartment and therefore strikes both ends simultaneously.
- The events of light striking the front and back of the compartment are not simultaneous from the point of view of an observer in a different frame of reference. Because of the ship's motion, light that strikes the back of the compartment doesn't have as far to go and strikes sooner than light that strikes the front of the compartment.

Relativity of Simultaneity

Different scenario than the last slide—same principle

Conceptual Question 1

Is the nonsimultaneity of hearing thunder after seeing lightning similar to relativistic nonsimultaneity?

A. Yes, it is exactly the same phenomenon.

B. No, it is a completely different phenomenon.

C. It depends upon how loud the thunder is.

D. It depends upon how far the thunder is.

Conceptual Question 2

Suppose that an observer standing on a planet sees a pair of lightning bolts simultaneously strike the front and rear ends of the compartment in a high-speed rocket ship. Will the lightning strikes be simultaneous to an observer in the middle of the compartment in the rocket ship?

A. Yes, they will be simultaneous.

B. No, they will be nonsimultaneous.

C. It depends upon how fast the ship is moving.

D. It depends upon how long the ship is.

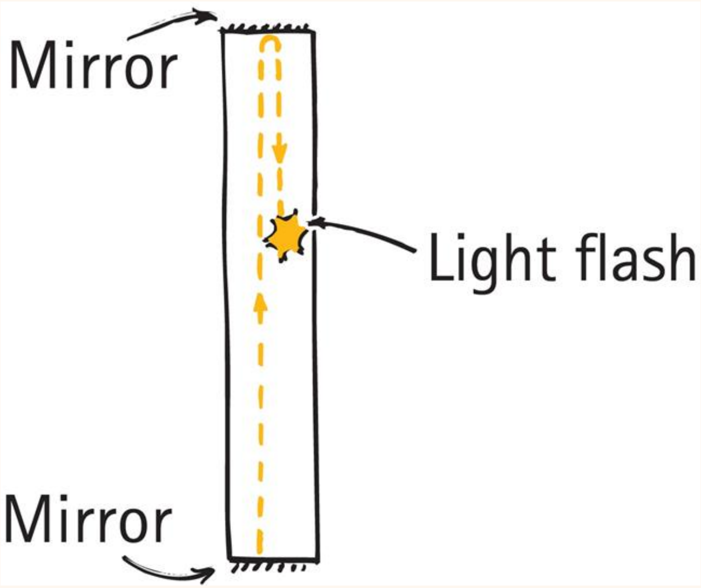
Spacetime

- Space and time are distinct concepts but they are intimately linked together. Things exist in *spacetime*.
  - Each object, each person, each planet, each star, each galaxy exists in what physicists call “the spacetime continuum.”
- One observer’s measurements of distance and time differs from similar measurements by another observer in a different reference frame. However, both measure the same ratio of the distance to the time separating events linked by a light beam: a greater measured distance in space coordinates with a greater measured time interval.

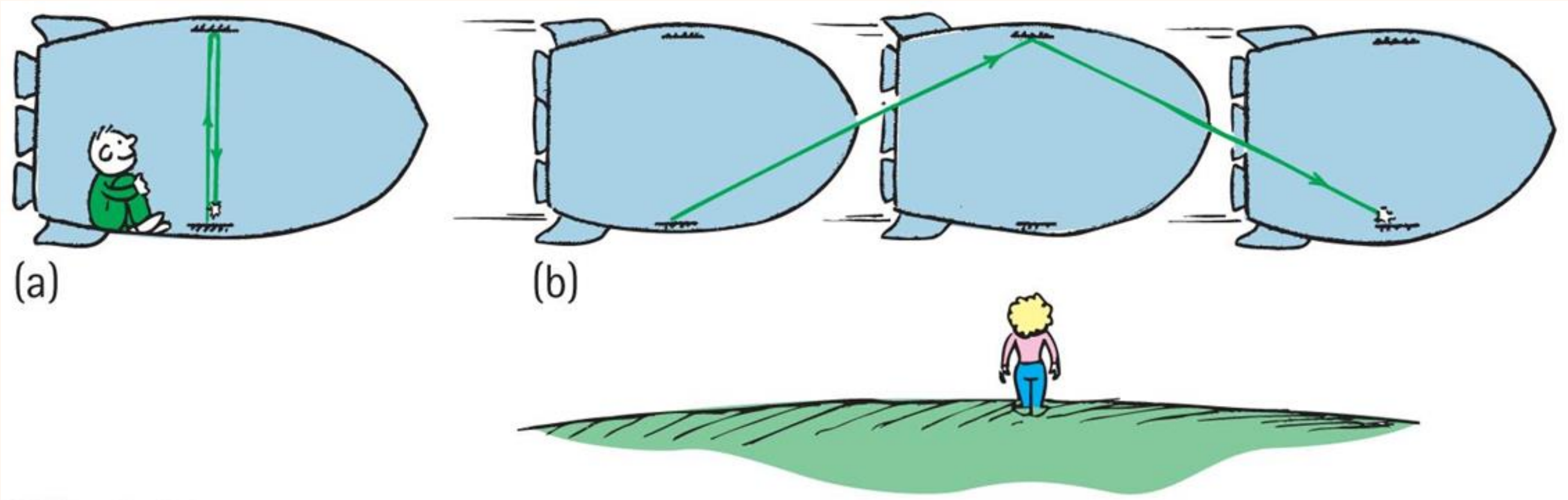
Constant for two observers $\longrightarrow$ $c = \dfrac{\text{distance}}{\text{time}}$ Varies for two observers

Light Clock

Imagine that we are somehow able to observe a flash of light bouncing up and down between a pair of parallel mirrors. If the distance between the mirrors is fixed, then the arrangement constitutes a **light clock**, because the back-and-forth trips of the flash take equal time intervals.



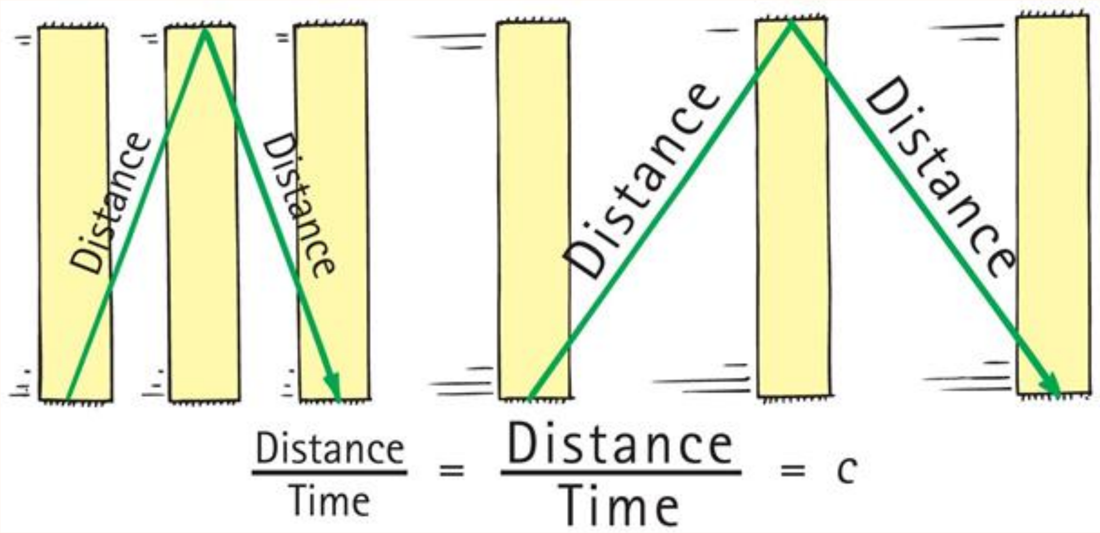
Gedankenexperiment



(a) An observer moving with the spaceship observes the light flash moving vertically between the mirrors of the light clock.
(b) An observer who sees the moving ship pass by observes the flash moving along a diagonal path.

Time Dilation

The two observers agree that light traveled at speed c between the two ticks of the clock, but they disagree about how far the light went, so they must disagree about how much time passed. In fact, the observer who sees the clock moving will conclude that more time passed between two consecutive ticks of the clock.

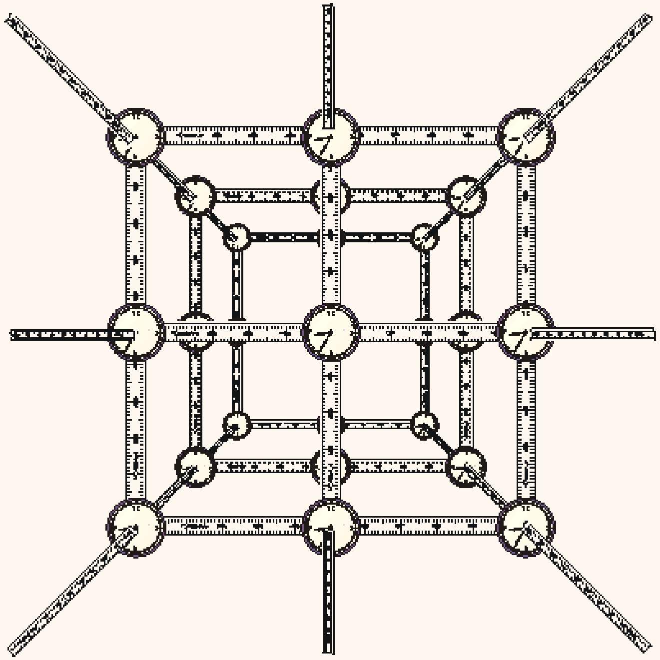


Proper Time vs. Coordinate Time

Proper time is the time between two events that occur at the same location, as measured by a clock that is present at both events. It's like the time between when you wake up and go to sleep as measured by the watch you carry.

Coordinate time is the time measured between two events according to a system of stationary *synchronized clocks*.

- A proper time interval is always a coordinate time interval, but not all coordinate time intervals are proper time intervals.
- Events may occur at different locations or the same location.



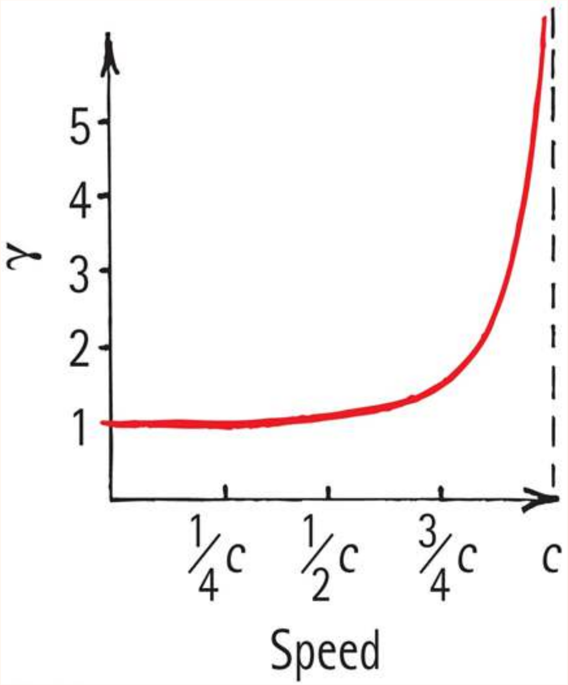
Time Dilation Equation

- The coordinate time is always greater than or equal to the proper time.

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

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

"Lorentz factor"



Accelerating Spaceship

- As the speed of a spaceship increases, the Lorentz factor increases.
- According to an observer on Earth, clocks on the spaceship will tick slower and slower as the spaceship approaches the speed of light.
- When we see the rocket traveling at close to the speed of light, we see its time practically standing still.

Conceptual Question 3

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

A. Yes, you would notice a difference in both pulse rates.

B. You would notice a difference in your pulse rate, but not the pulse rate of people on Earth.

C. You would notice a difference in the pulse rate of people on Earth, but not in your own pulse rate.

D. You would not notice a difference in either pulse rate.

Conceptual Question 4

Will observers A and B agree on measurements of time if A moves at half the speed of light relative to B?

A. Yes, they would agree completely.

B. No, they would disagree completely.

C. They would agree half of the time and disagree the other half of the time.

D. None of the above is correct.

Conceptual Question 5

Will observers A and B agree on measurements of time if both A and B move together at half the speed of light relative to Earth?

A. Yes, they would agree completely.

B. No, they would disagree completely.

C. They would agree half of the time and disagree the other half of the time.

D. None of the above is correct.

Conceptual Question 6

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

A. Time really passes more slowly in moving systems.

B. Time only **seems** to pass more slowly in moving systems.

C. It depends upon how fast the system is moving.

D. It depends upon the direction in which the system is moving.

The Twin Paradox

- Identical twins, one an astronaut who takes a high-speed round-trip journey in the galaxy 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 speed.
- Since motion is relative, why doesn’t the effect work equally well the other way around? Why wouldn’t the traveling twin return to find his stay-at-home twin younger than himself?

The Twin Paradox

Conceptual Question 7

The ship sends equally spaced flashes every 6 minutes while approaching the receiver at constant speed. How will these flashes be spaced when they encounter the receiver?

A. They will be equally spaced 6 minutes apart.

B. They will be equally spaced less than 6 minutes apart.

C. They will be equally spaced more than 6 minutes apart.

D. They will not be equally spaced.

Conceptual Question 8

Since motion is relative, can’t we say as well that the spaceship is at rest and the Earth moves, in which case the twin on the spaceship ages more?

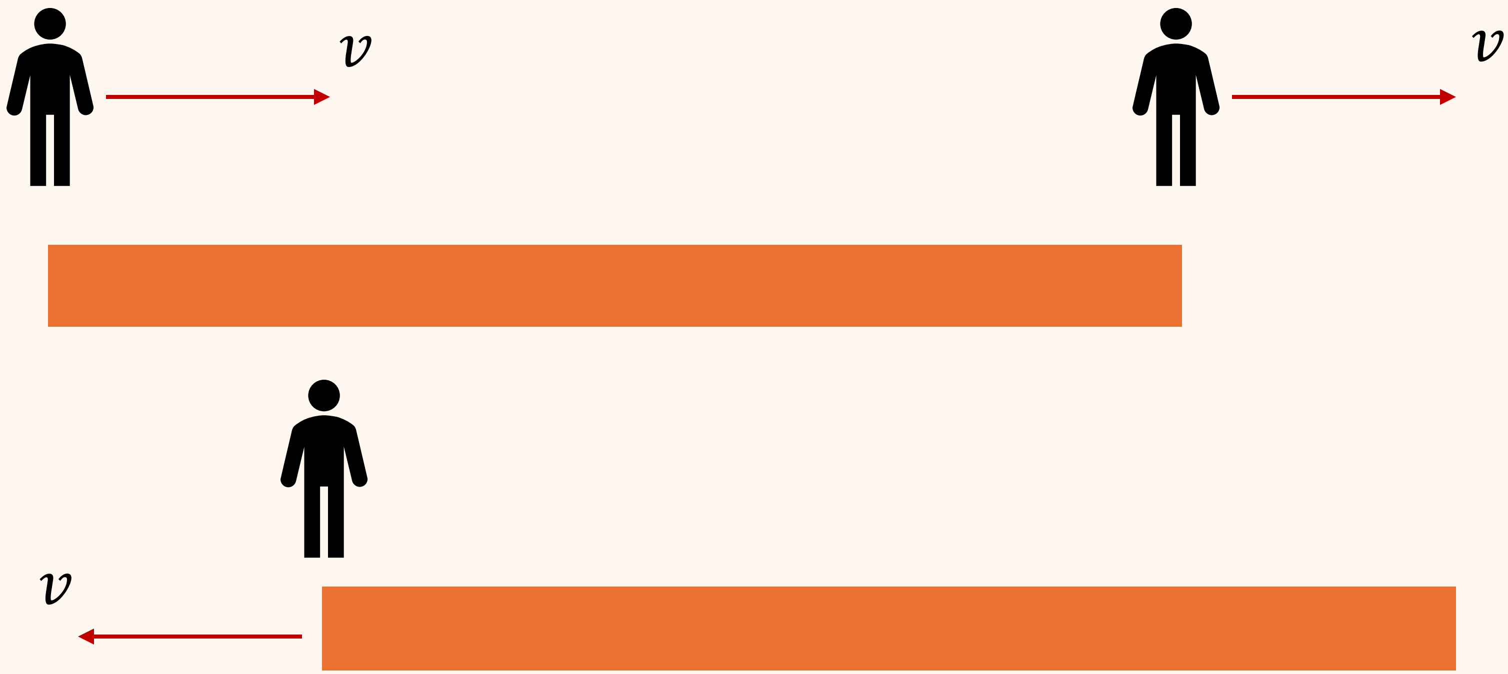
A. Yes.

B. No.

C. It depends on how fast the ship is moving.

D. It depends upon the direction in which the ship is moving.

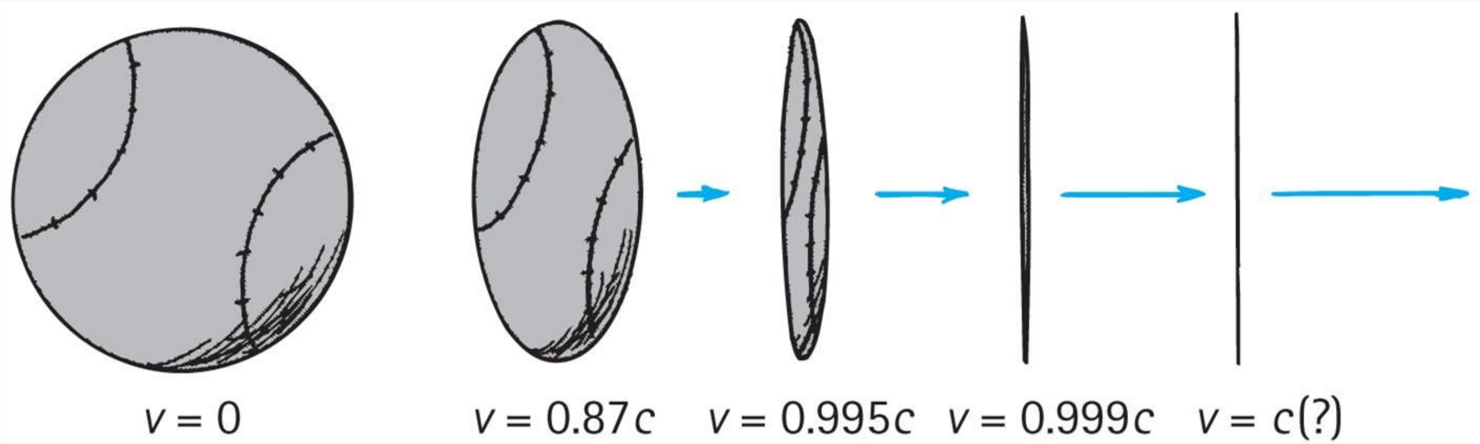
Gedankenexperiment



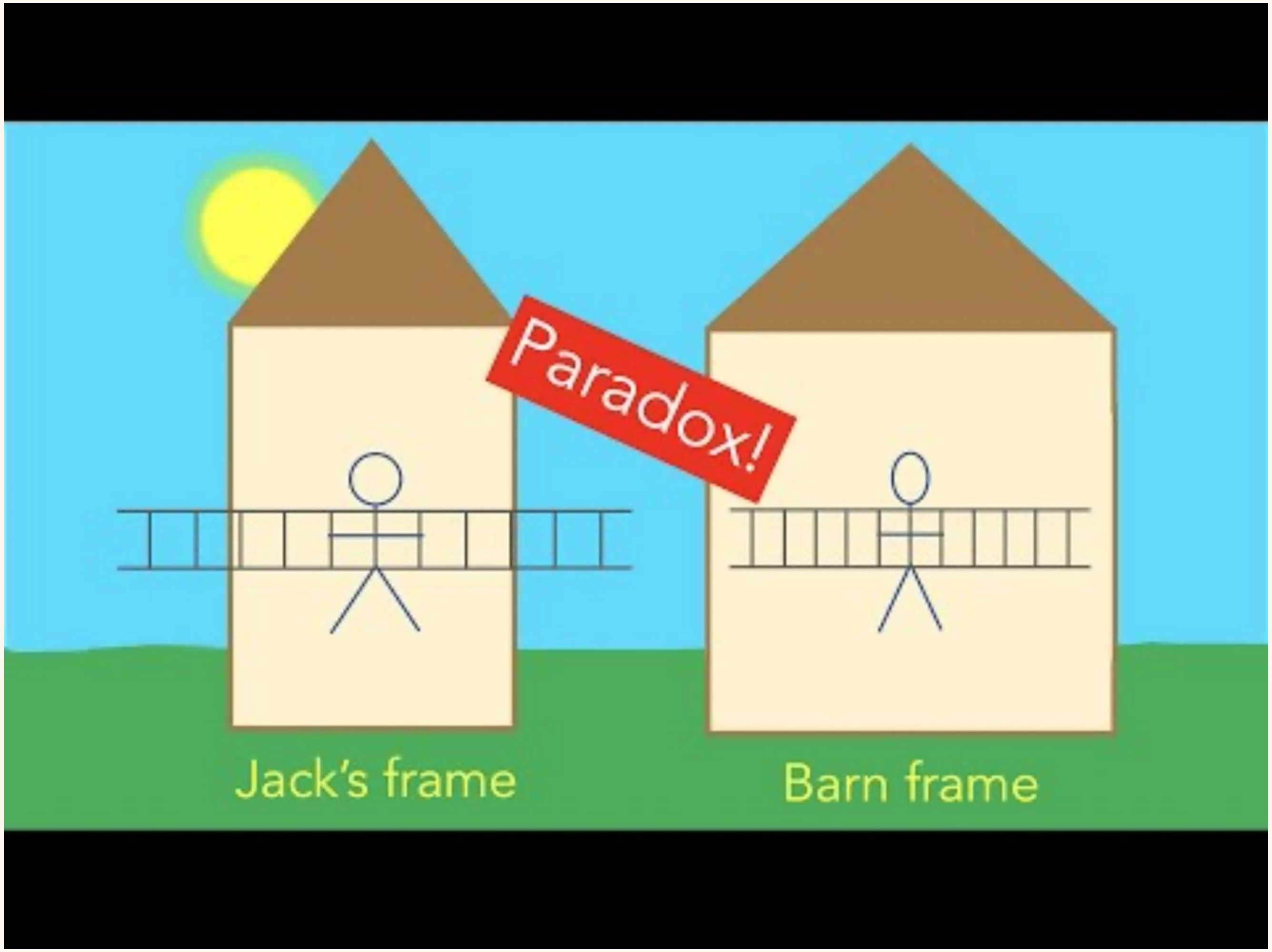
From the rod's perspective, the person moves to the right with relative speed v, and from the person's perspective, the rod moves to the left with the same relative speed v. Since the person measures a shorter time interval between the passing of both ends of the rod, they measure the rod to have shorter length compared to when it's at rest.

Length Contraction

- A moving object's length is measured to be shorter than its **proper length**, which is the length as measured in the object's own rest frame.
- Length contraction takes place only in the direction of travel. An object traveling horizontally experiences horizontal contraction but **not** vertical contraction.



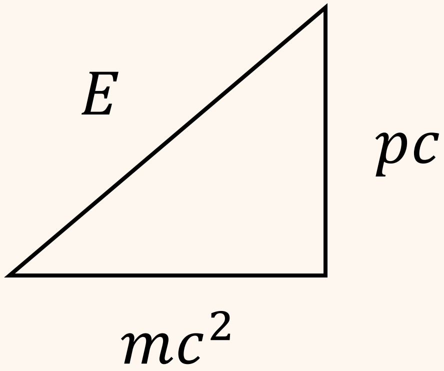
Einstein’s Ladder



Energy-Momentum Relation

- The postulates of special relativity call for revisions to the core concepts of Newtonian physics.
  - Force, momentum, and energy are all redefined so that **if energy and momentum are conserved in one inertial frame of reference, they are conserved in all inertial frames of reference.**
  - Just as space and time make up a single concept of spacetime, energy and momentum make up a single quantity composed of *relativistic energy* and *relativistic momentum*.
  - The mass of a single particle is a relativistic invariant, but the mass of a system of particles is not. The total mass depends on your frame of reference!

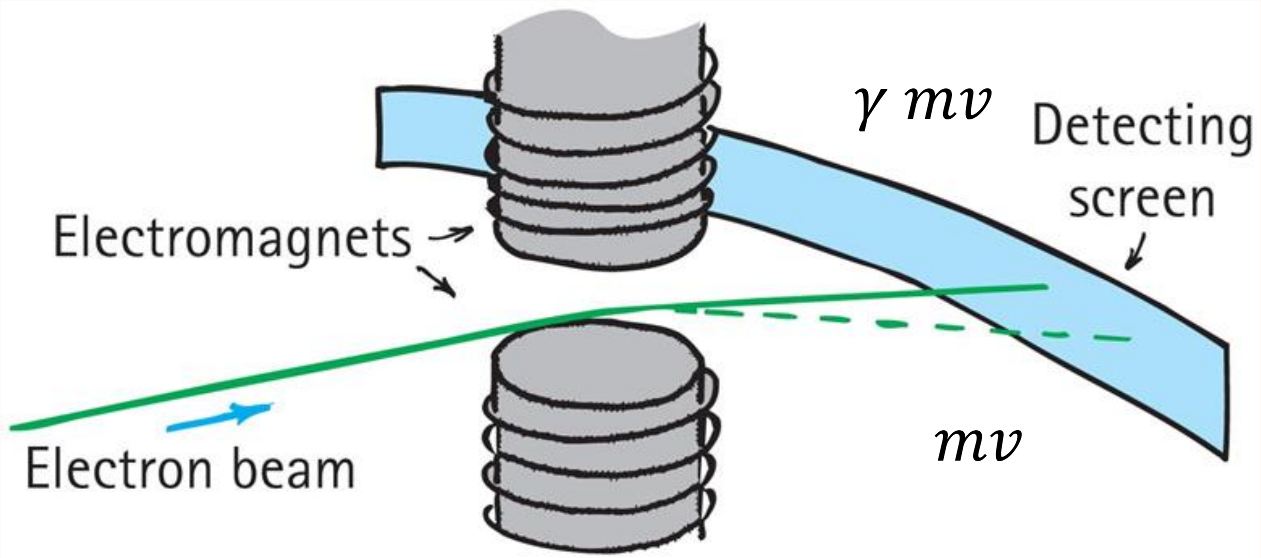
$$E^2 = (mc^2)^2 + (pc)^2$$



Relativistic Momentum

- Relativistic momentum is

$$p = \gamma\, mv = \frac{mv}{\sqrt{1 - v^2/c^2}}$$



Conceptual Question 9

When an object of mass m is pushed to relativistic speed v, its momentum is

A. greater than mv.

B. smaller than mv.

C. equal to mv.

Relativistic Energy

- The total energy of a particle or system taking into account its motion and mass.

$$E = \gamma\, mc^2 = \frac{mc^2}{\sqrt{1 - v^2/c^2}}$$

- When the speed of the particle is very small,

$$E \approx mc^2 + \frac{1}{2}mv^2$$

Rest Energy

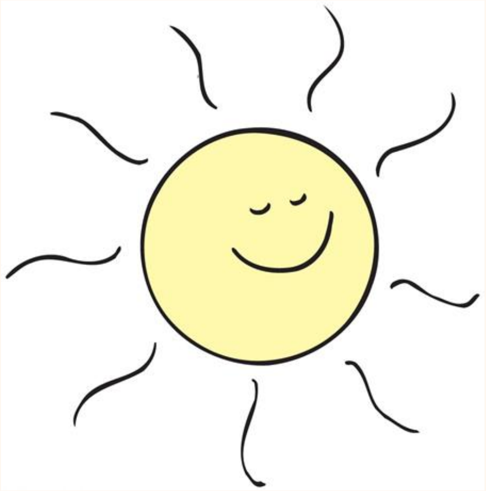
- A piece of matter, even at rest and not interacting with anything else, has **rest energy**.
- Einstein concluded that it takes energy to make mass and that energy is released if mass disappears.
- The amount of energy E is **related** to the amount of mass m **by the most celebrated equation of the 20th century**:

$$E = mc^2$$

Mass and Energy

- Saying that a power plant delivers 90 million megajoules of energy to its consumers is equivalent to saying that it delivers 1 gram of energy to its consumers because mass and energy are equivalent.

- In 1 second, 4.5 million tons of mass are converted to radiant energy in the Sun. The Sun is so massive, however, that in 1 million years only 1 ten-millionth of the Sun’s mass will have been converted to radiant energy.



Conceptual Question 10

According to the equation $E = mc^2$

A. mass and energy travel at the speed of light squared.

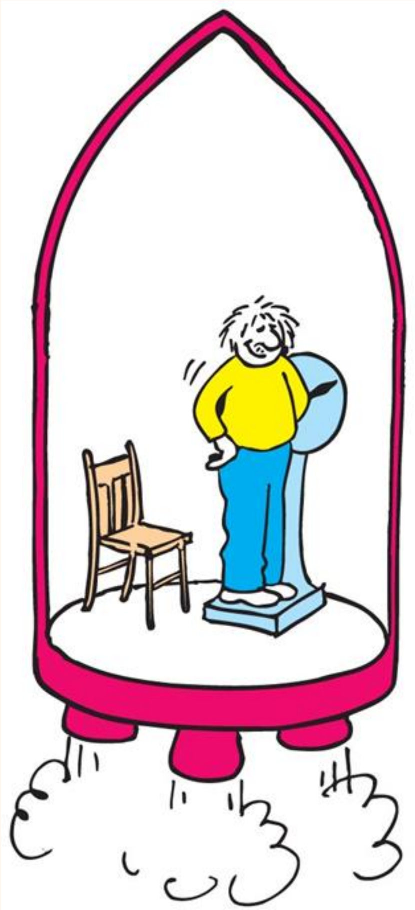
B. energy is actually mass traveling at the speed of light squared.

C. mass and energy travel at twice the speed of light.

D. mass and energy are related.

E. none of the above

Gedankenexperiment



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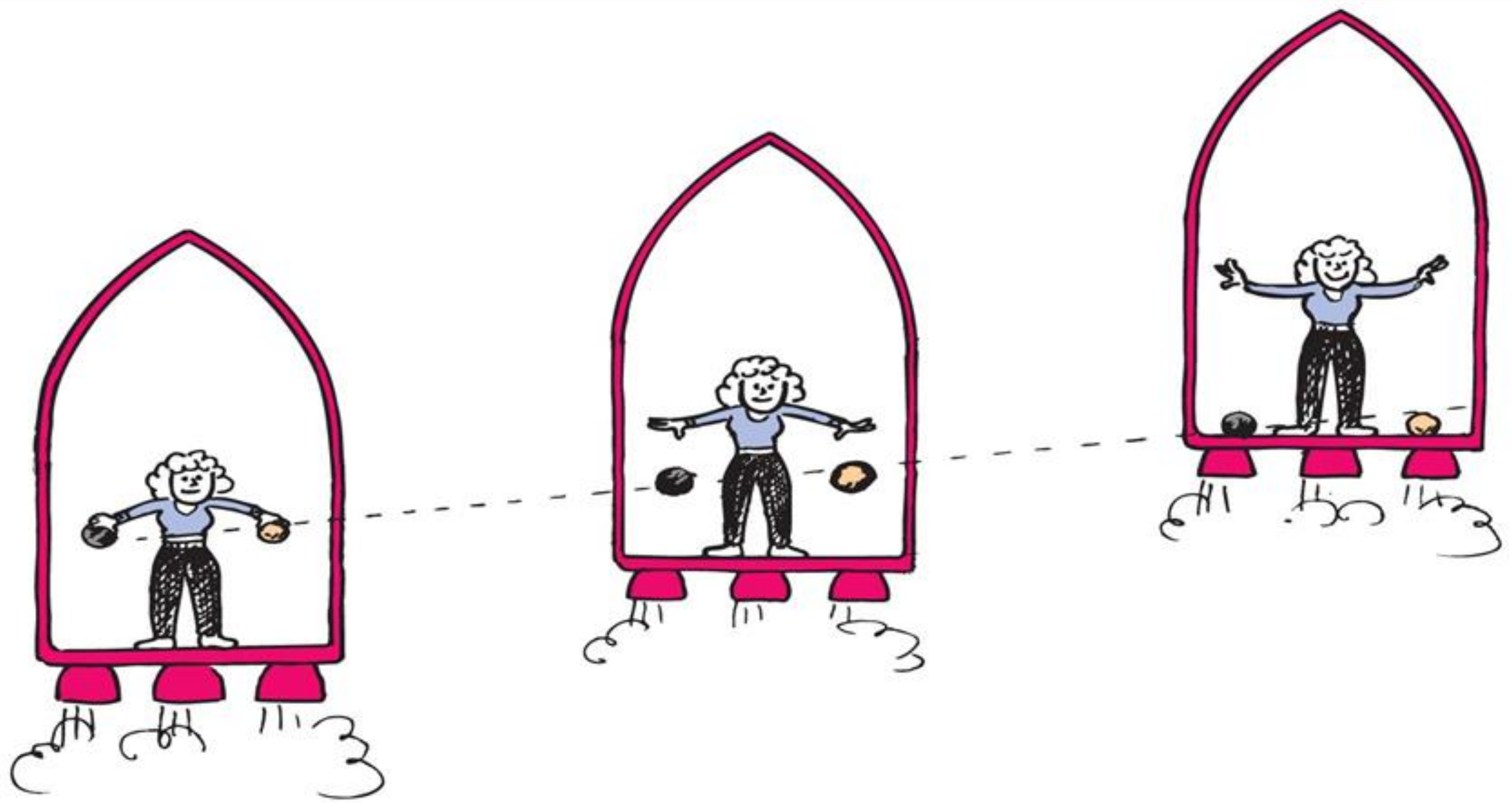
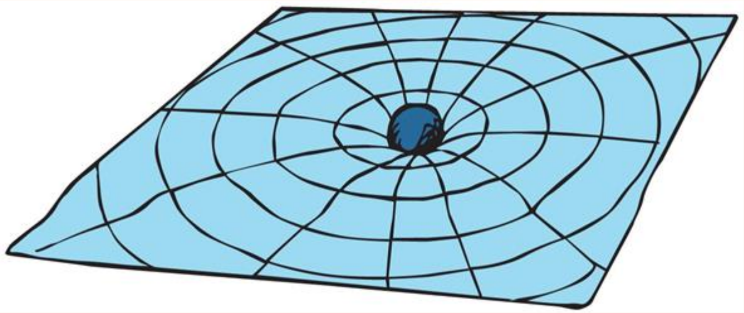


Principle of Equivalence

- There is no local experiment that can distinguish between uniform acceleration and a uniform gravitational field.
- This is a foundational concept in the theory of general relativity, which describes gravity as a curvature of spacetime. An object with energy curves the spacetime around itself, and the geometry of spacetime determines how objects with energy move.



Conceptual Question 11

If you drop a ball inside a spaceship at rest on a launching pad, you'll see it accelerate to the floor. Far away from Earth, how else could you see the ball do the same?

A. Spaceship should stay at rest.

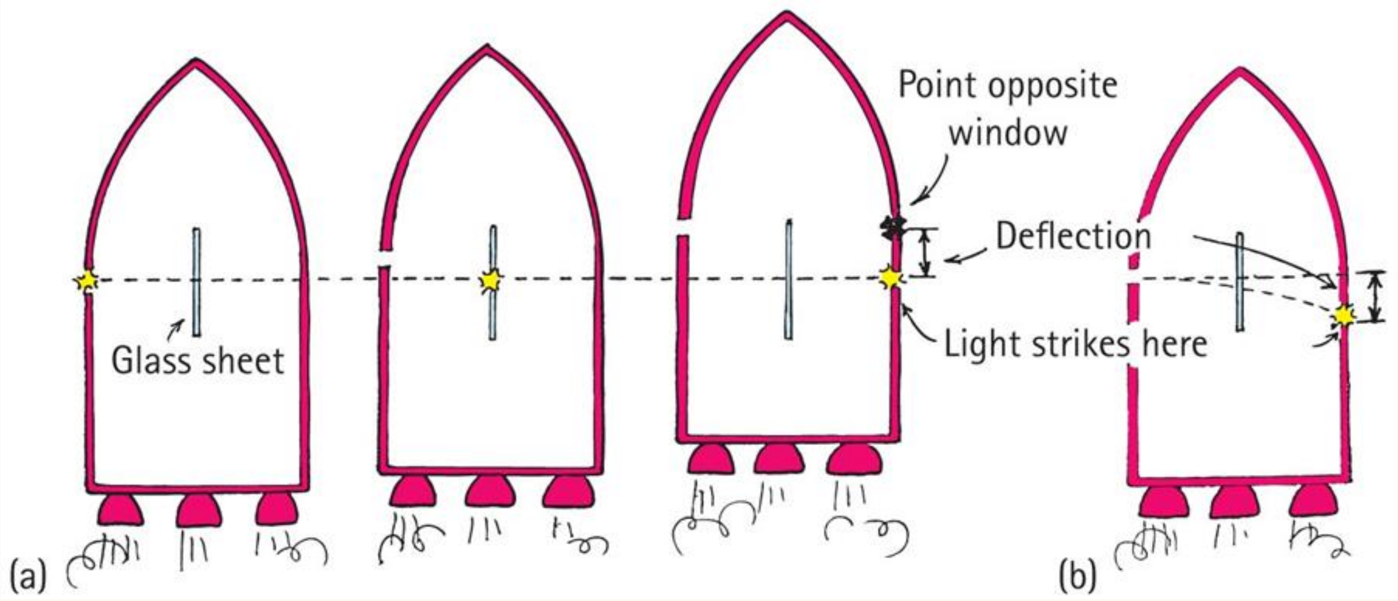
B. Spaceship should move at a constant velocity.

C. Spaceship should accelerate at g.

D. None of the above is correct.

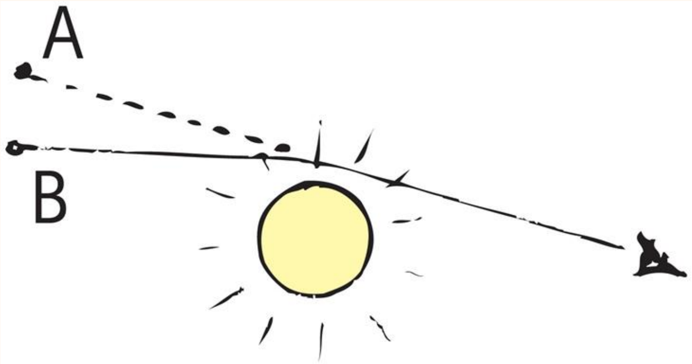
Bending of Light

- Light has energy, so it can be affected by gravity according to general relativity.



Gravitational Lensing

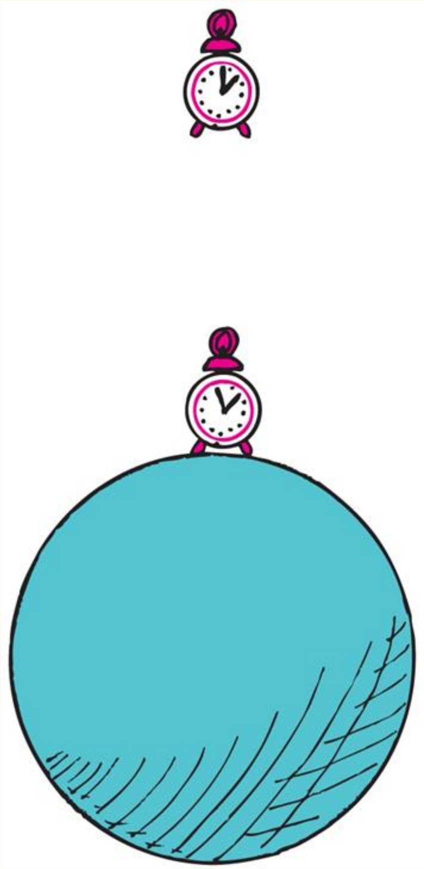
- Einstein predicted that starlight passing close to the Sun would be deflected by an angle of 1.75 seconds of arc—large enough to be measured.
- Although stars are not visible when the Sun is in the sky, the deflection of starlight can be observed during an eclipse of the Sun.
- Starlight bends as it grazes the Sun. Point A shows the apparent position; point B shows the true position.



Gravitational Lensing

Gravitational Time Dilation

- According to Einstein's general theory of relativity, gravitation causes time to slow down.
- If you move in the direction in which the gravitational force acts, time will run slower at the point you reach than at the point you left behind.
- If you move from a distant point down to the surface of Earth, you move in the direction in which the gravitational force acts—toward a location where clocks run more slowly. **A clock at the surface of Earth runs slower than a clock farther away.**



Conceptual Question 12

Who will age less, a person at the top of a skyscraper or a person in the basement?

A. Person at the top of the skyscraper

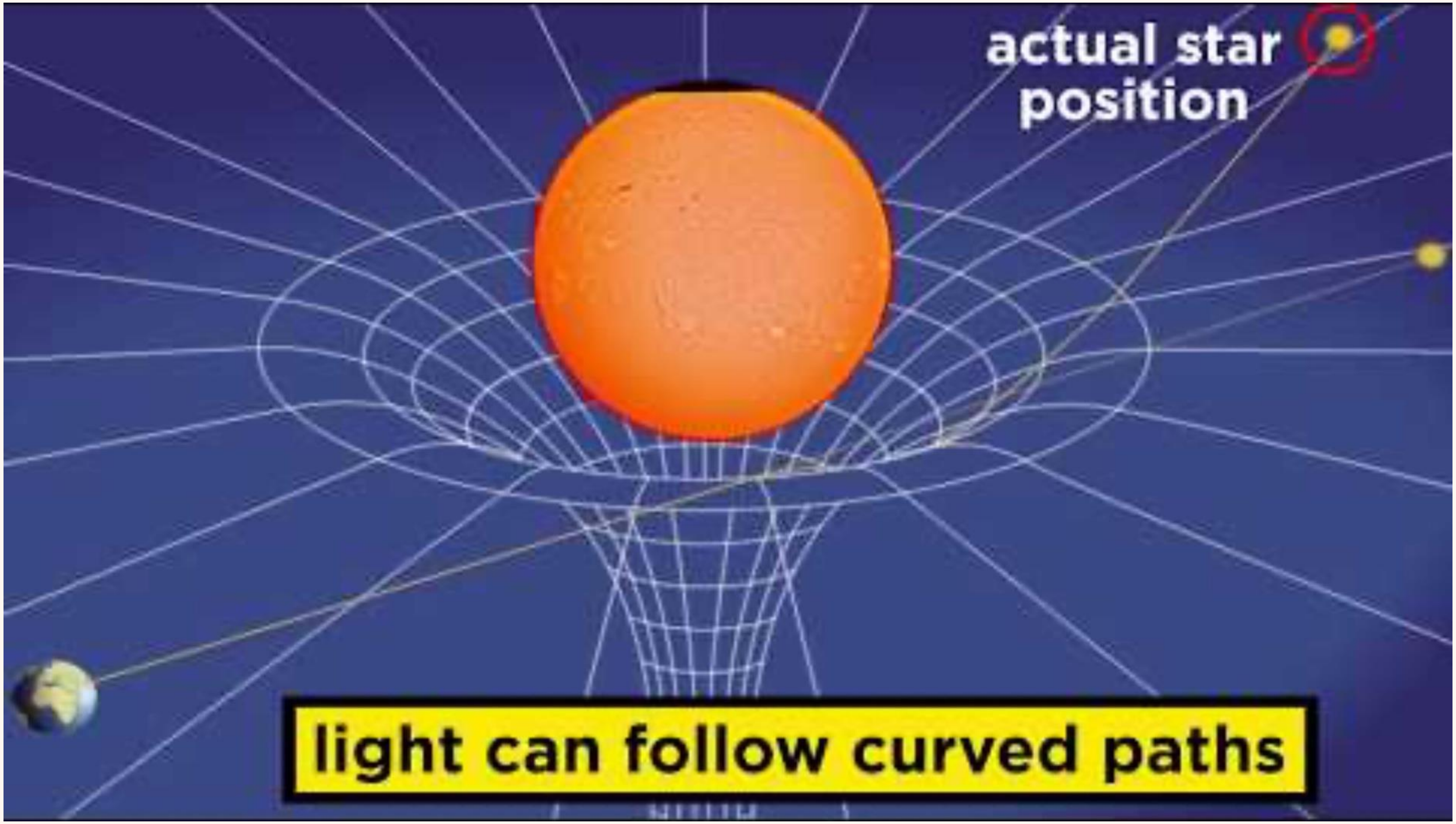
B. Person in the basement

C. They will both age equally.

D. Neither of them will age.

Mercury's Anomalous Orbit

Geometry of Spacetime



Gravitational Waves