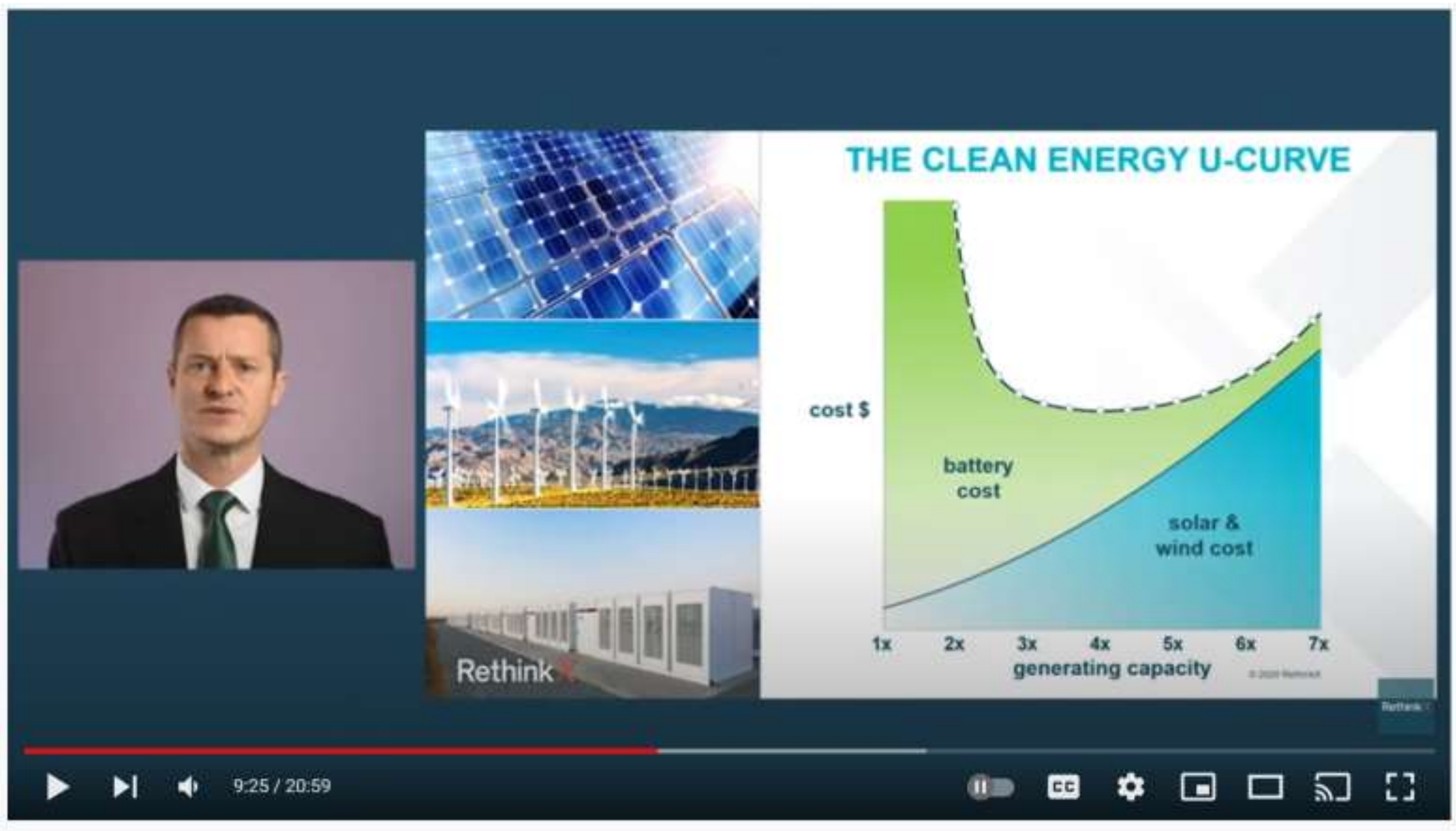
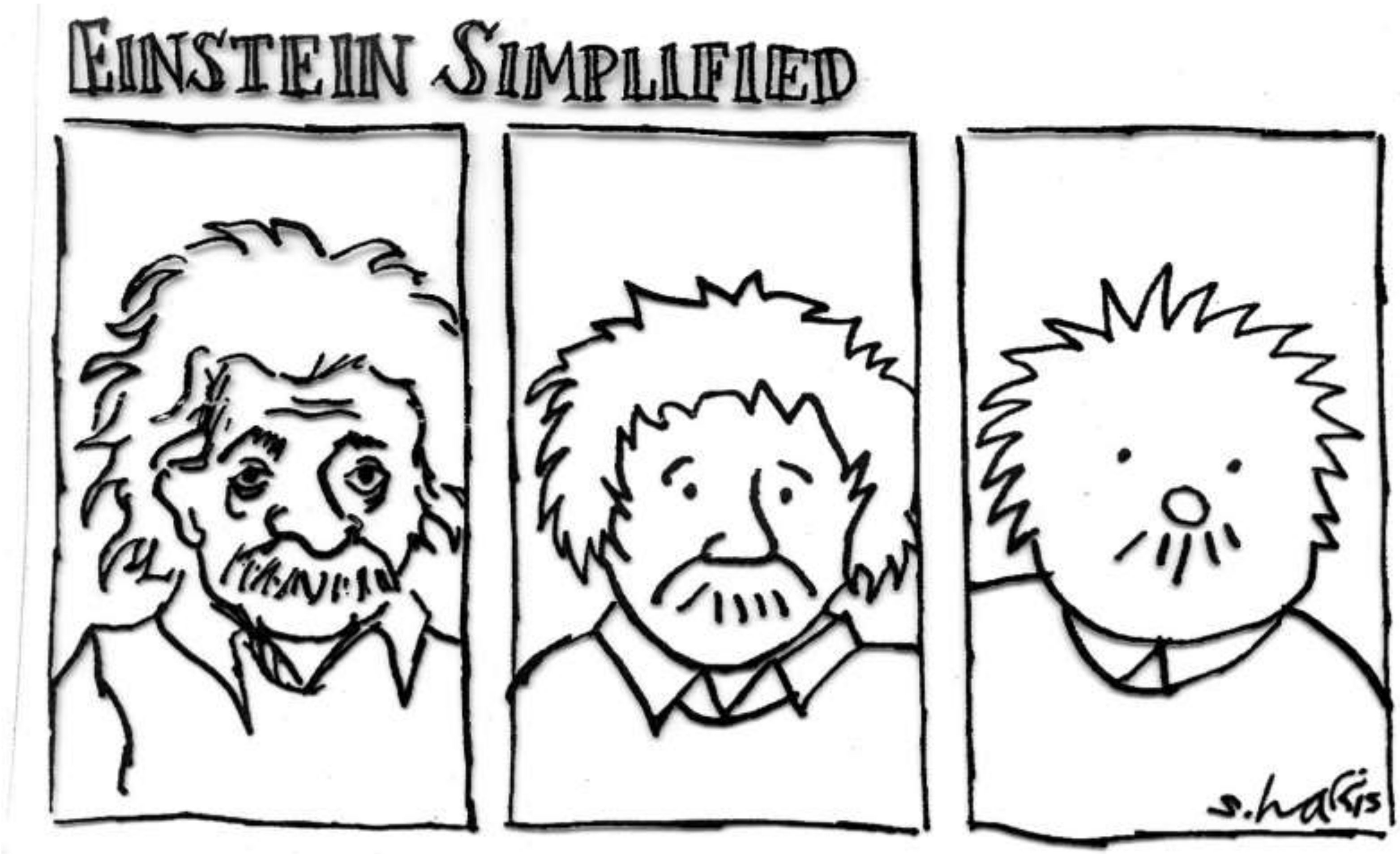
Reminder: Lab 2 due April 8!

Solar, Wind + Battery Storage for Electricity



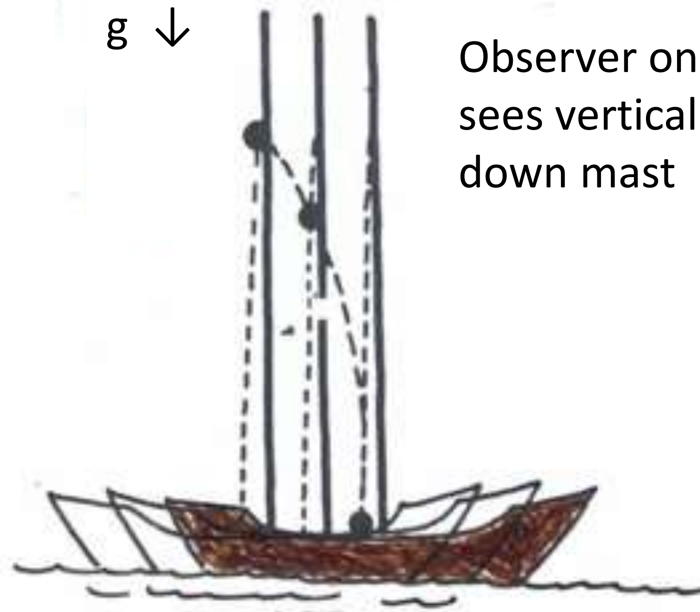
2:00 to 11:00

Theory of Special Relativity

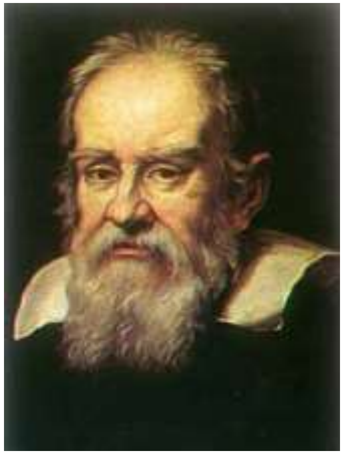


Ball dropped on moving ship

Observer with telescope sees parabolic path



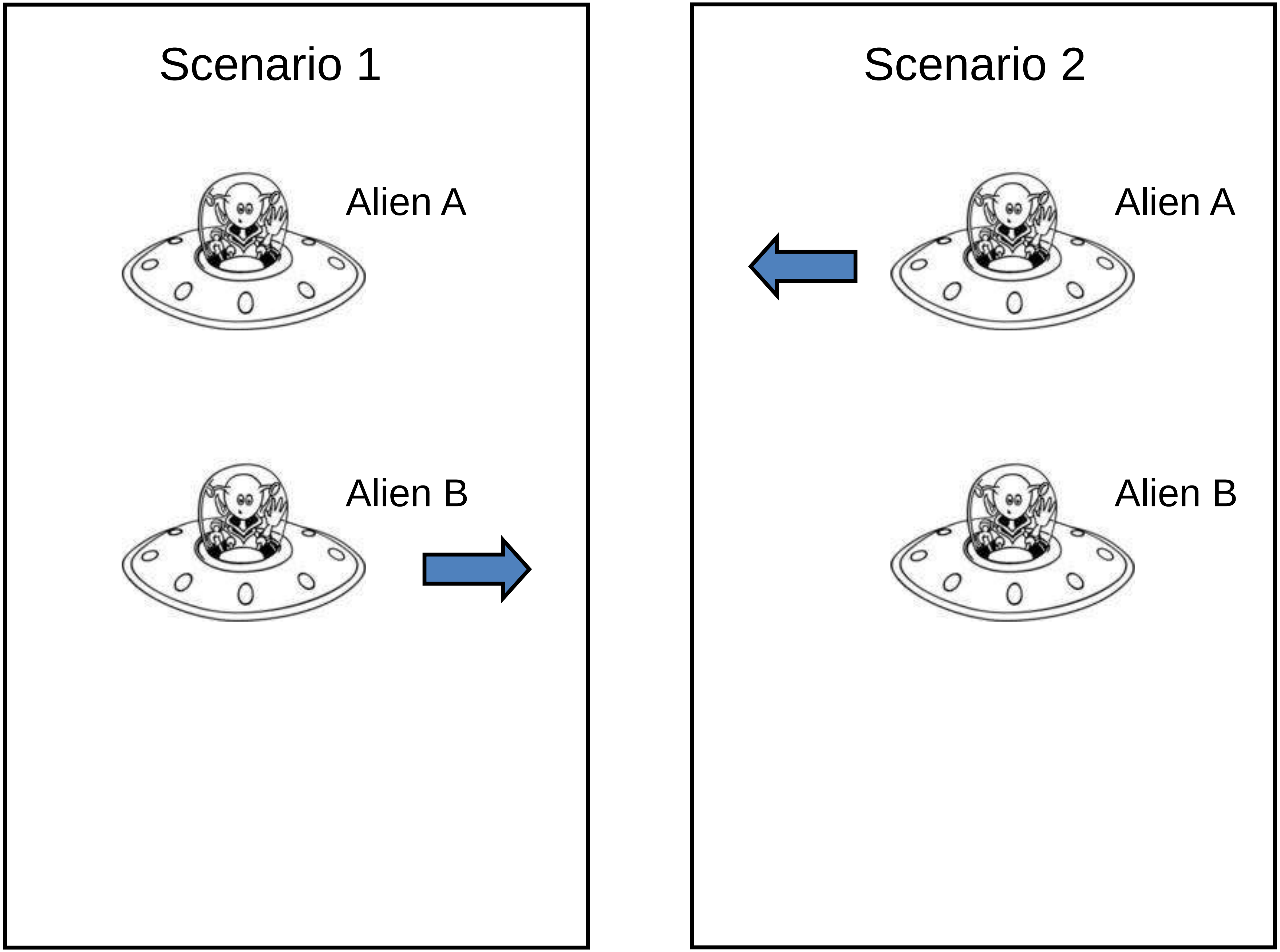
Observer on boat sees vertical fall down mast



Galileo, 1632

Principle of Relativity: there is no physical way to differentiate between a body moving at a constant speed and an immobile body.

Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully, have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still.[3]


Scenario 1
Alien A
Alien B
Scenario 2
Alien A
Alien B

Inertial reference frame

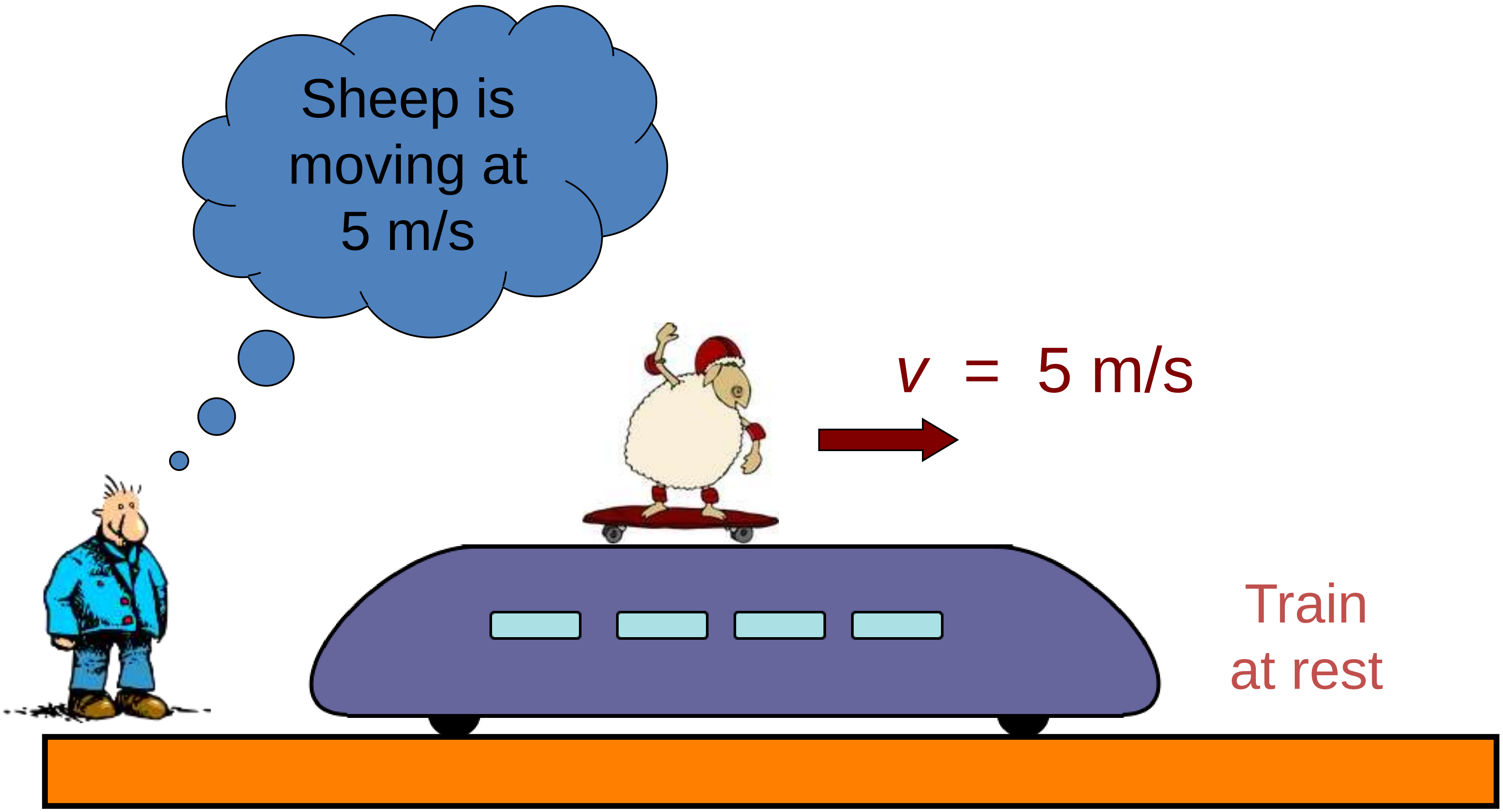
A viewpoint that is not accelerating. It can be stationary, or moving at a constant velocity.

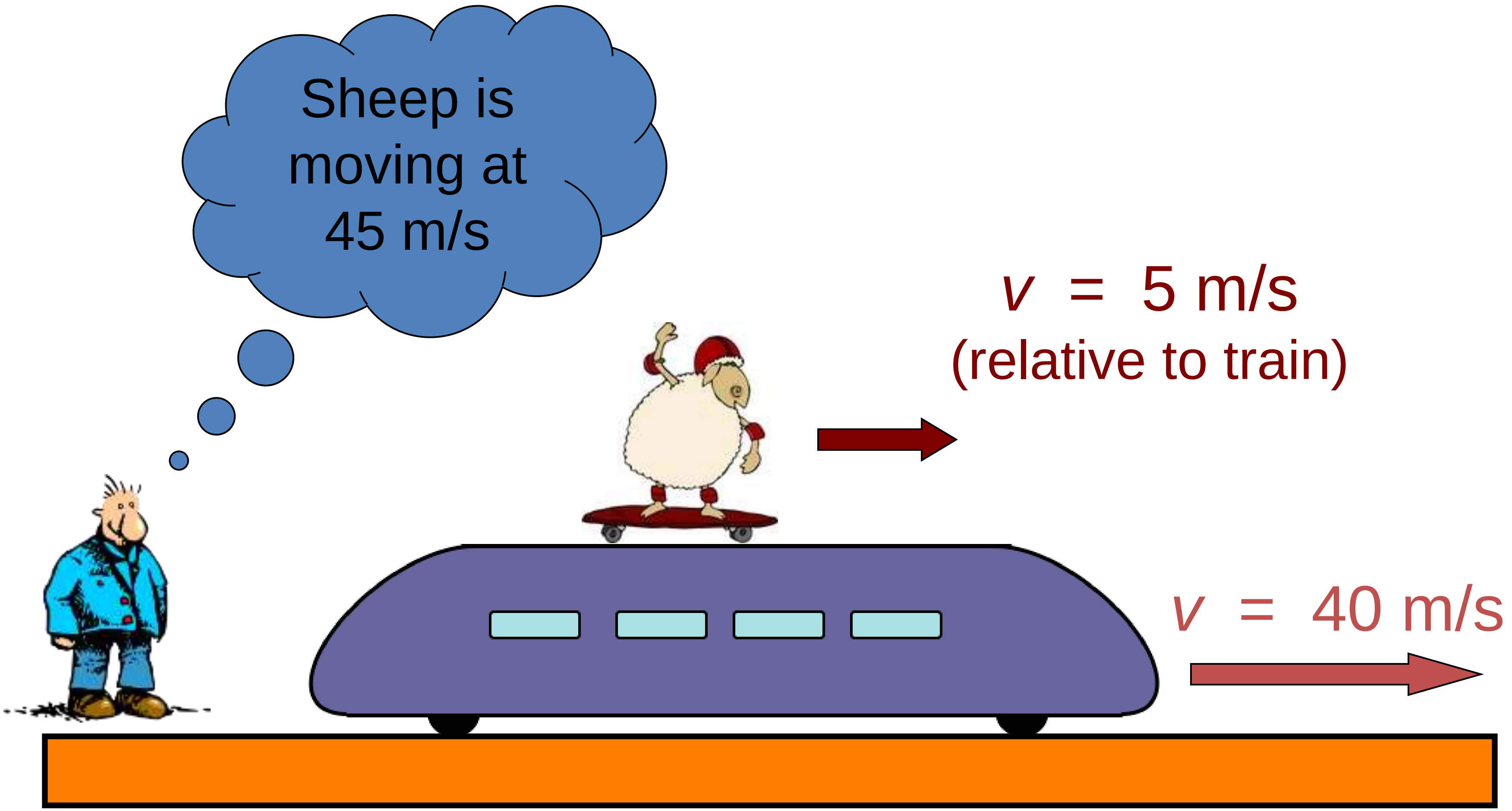
Q: Is an elevator an inertial reference frame?
A: Yes, but *only* when it is going up or down at a *constant* speed

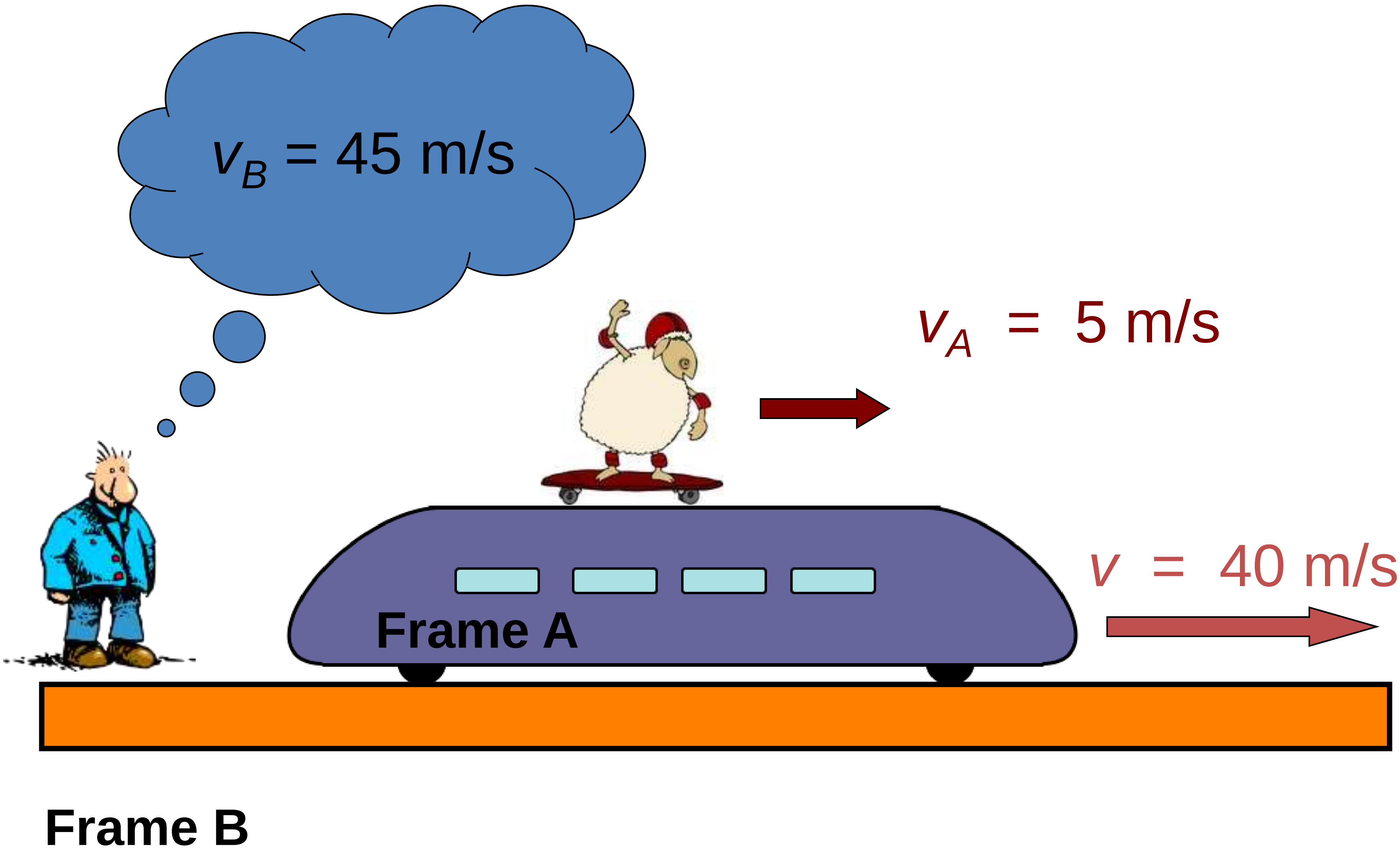
Relativity principle

A scientific principle stating that **the laws of physics are the same in all inertial reference frames**

Video: Frames of Reference


Sheep is moving at 5 m/s
v = 5 m/s
Train at rest


Sheep is moving at 45 m/s
v = 5 m/s
(relative to train)
v = 40 m/s



Frame A: Speed of sheep relative to train
Frame B: Speed of sheep relative to observer

Galilean relativity

- Let v_A be speed of object measured in frame A
- Let v be speed of frame A with respect to frame B
- Then speed of object measured in frame B is

$$v_B = v + v_A$$

Galilean relativity

- Let (x,t) be position and time measured in frame A
- Let (x',t') be position and time measured in frame B
- Then

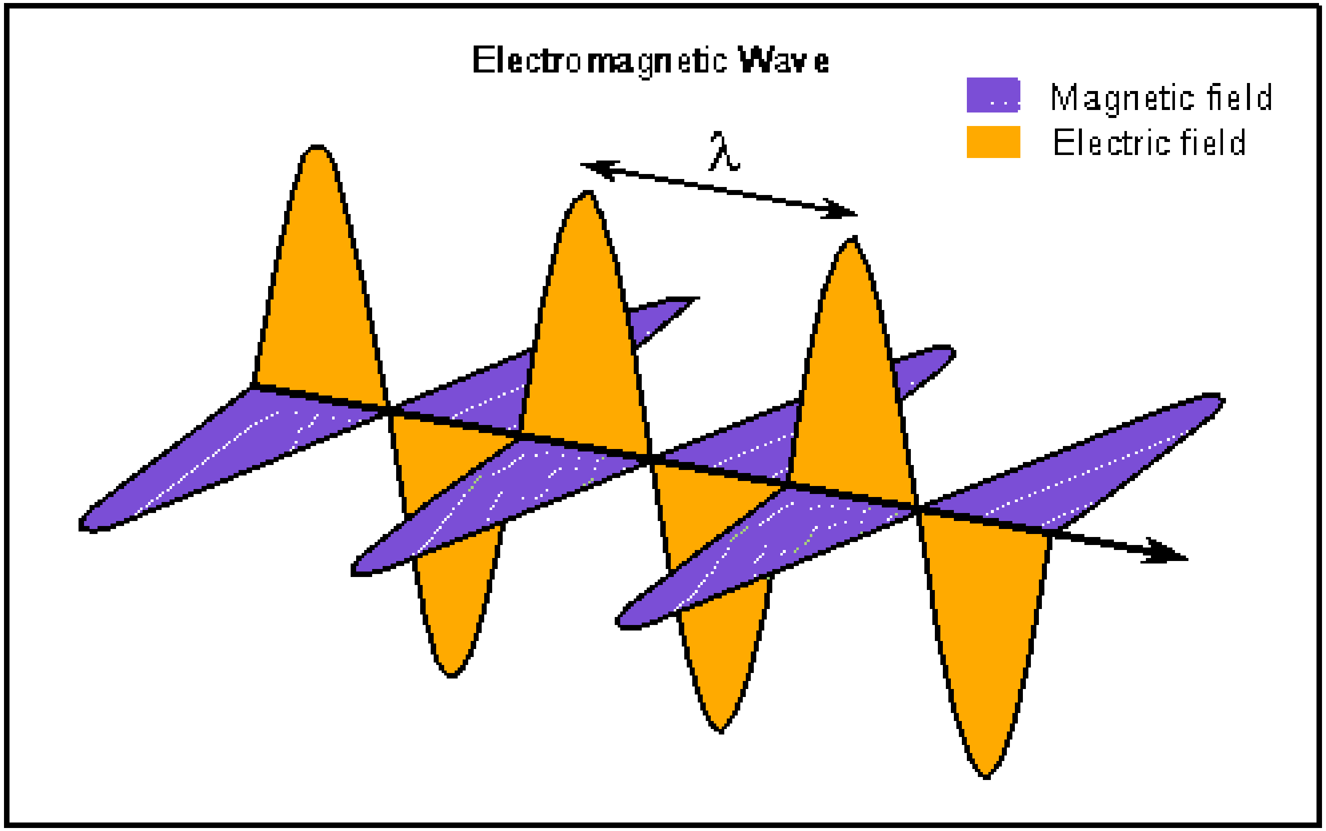
$$x' = x + v\,t$$

$$t' = t$$

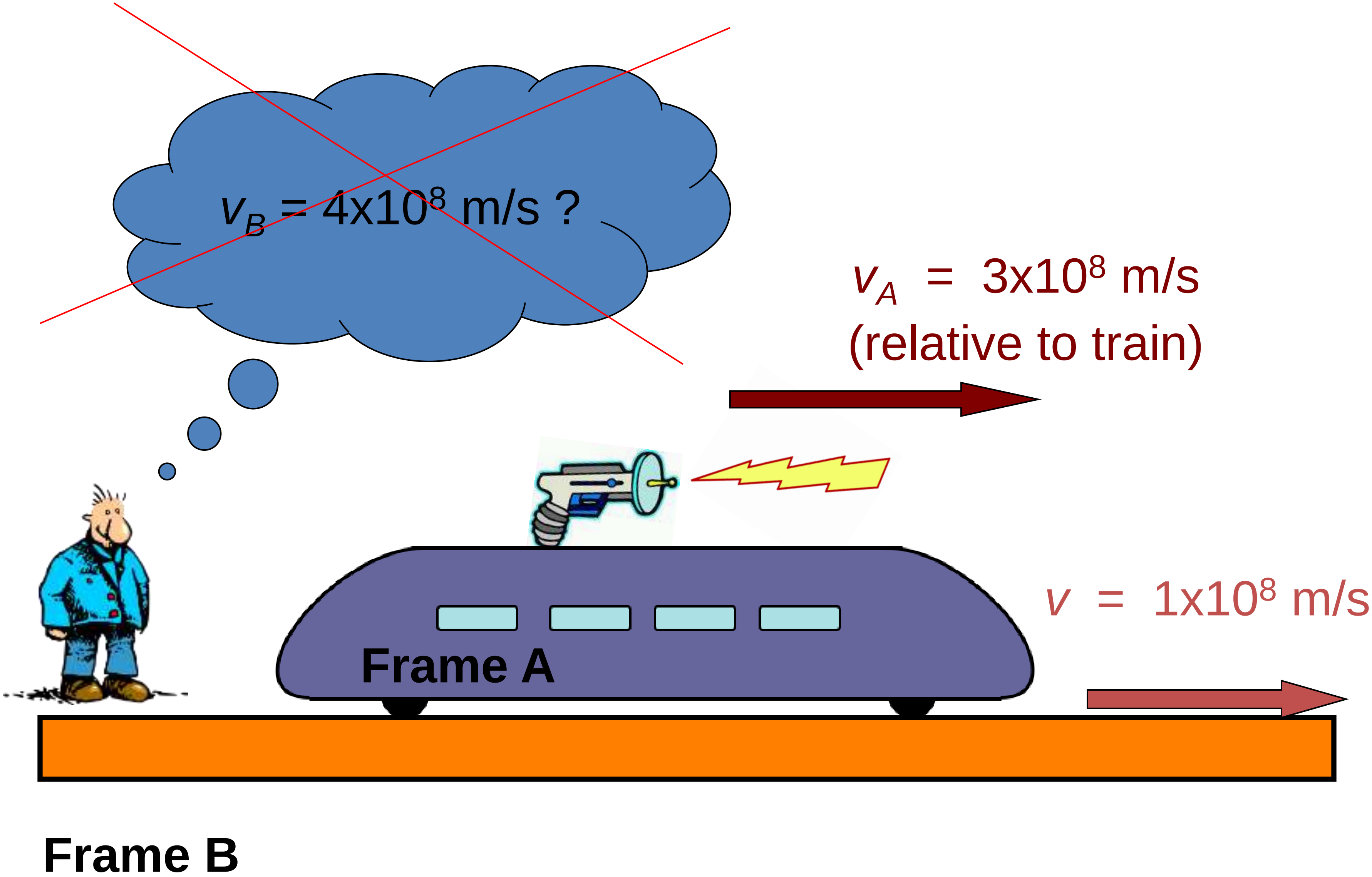
Status in 1900

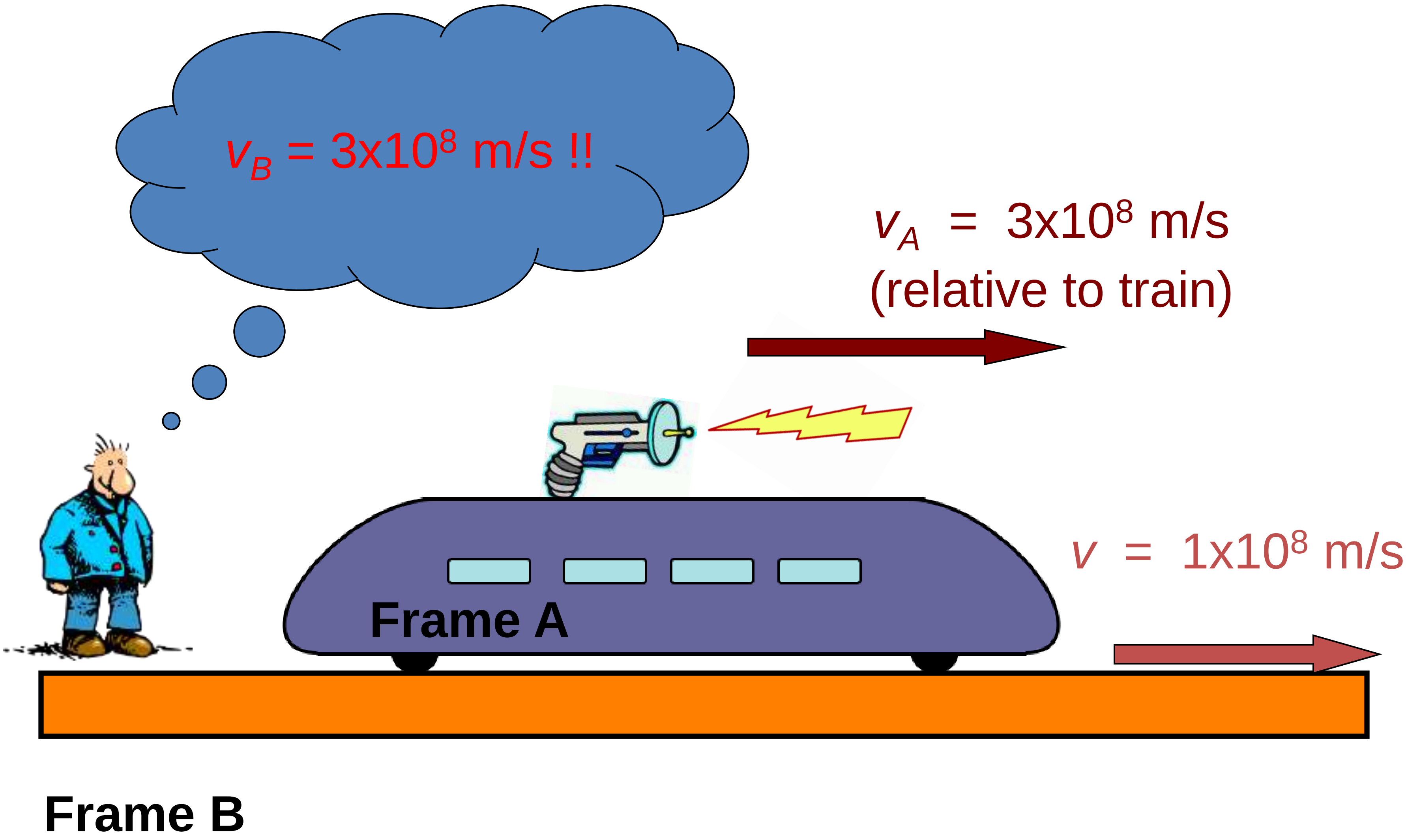
- Newton's laws of motion are *exactly* consistent with Galilean relativity
- Maxwell's laws of electromagnetism are *approximately, but not exactly,* consistent with Galilean relativity

Maxwell: Electromagnetic waves



Speed = $3x10^8$ m/s


~~$v_B = 4 \times 10^8$ m/s ?~~
$v_A = 3 \times 10^8$ m/s
(relative to train)
$v = 1 \times 10^8$ m/s
Frame A
Frame B



v_B = 3x10^8 m/s !!
v_A = 3x10^8 m/s
(relative to train)
v = 1x10^8 m/s
Frame A
Frame B

Status in 1900

- Newton's laws of motion are *exactly* consistent with Galilean relativity
- Maxwell's laws of electromagnetism are *approximately, but not exactly,* consistent with Galilean relativity
- General opinion: Maxwell's theory needs some slight fixing up?

Einstein 1905

- The relativity principle is *exactly correct.*
- Theory of electromagnetism predicts waves traveling at 3.0×10^8 m/s in my reference frame
- It also predicts the same speed in *any* inertial reference frame!
- This is not just some weird idea, it is confirmed experimentally.
- So something is wrong with Galilean relativity. What should we replace it with?

The Principle of Relativity

Every <u>nonaccelerated observer</u> observes the same laws of nature.

In other words, no experiment performed within a sealed room moving at an unchanging speed and direction can tell you whether you are standing still or moving.

The Constancy of Lightspeed

Remember that the speed of electromagnetic waves (speed of light) is built into the electromagnetic theory. If the laws of physics are the same in any *unaccelerated* reference frame, what does this mean for the speed of light?

It means that the speed of light should be the same to any observer.

Viewpoint of Einstein, 1905

- The real problem is not with mechanics, electricity, magnetism, etc.
- Nor is it with our understanding of the properties of objects such as baseballs and atoms.
- If something is wrong with Galileo's velocity addition formula, then there is a problem in how we have conceived of space and time themselves!!!

Clicker

We know from the Doppler blue shift of the light from the Andromeda galaxy, that the galaxy is approaching us at a speed of about 100 km/s. With respect to an alien observer, the light was emitted at a speed of 299800 km/s. What is the speed of that same light as it arrives at the Earth, with respect to the Earth?

A. 299700 km/s
B. 299800 km/s
C. 299900 km/s
D. Unknowable, since all is relative

Clicker

We know from the Doppler blue shift of the light from the Andromeda galaxy, that the galaxy is approaching us at a speed of about 100 km/s. With respect to an alien observer, the light was emitted at a speed of 299800 km/s. What is the speed of that same light as it arrives at the Earth, with respect to the Earth?

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Time

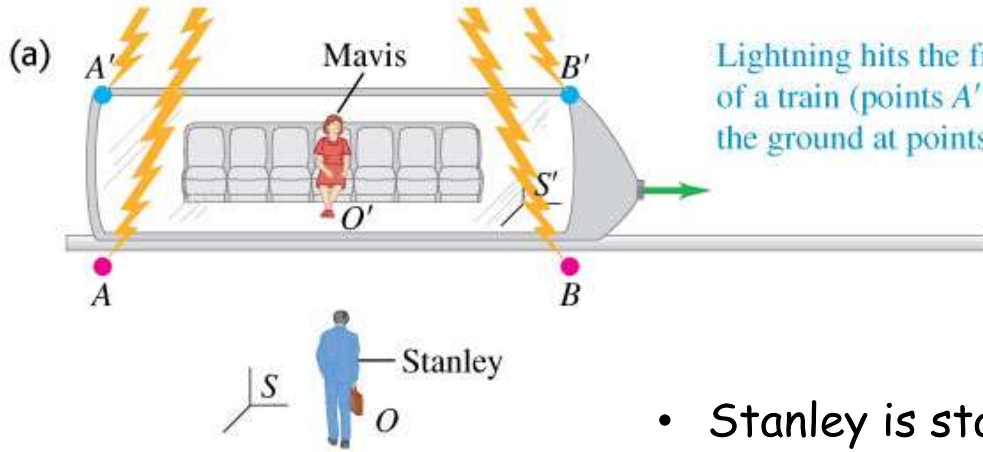
Einstein traced the root of the problem to a false assumption about time:

~~"All observers will agree about the simultaneity of events"~~

WRONG !

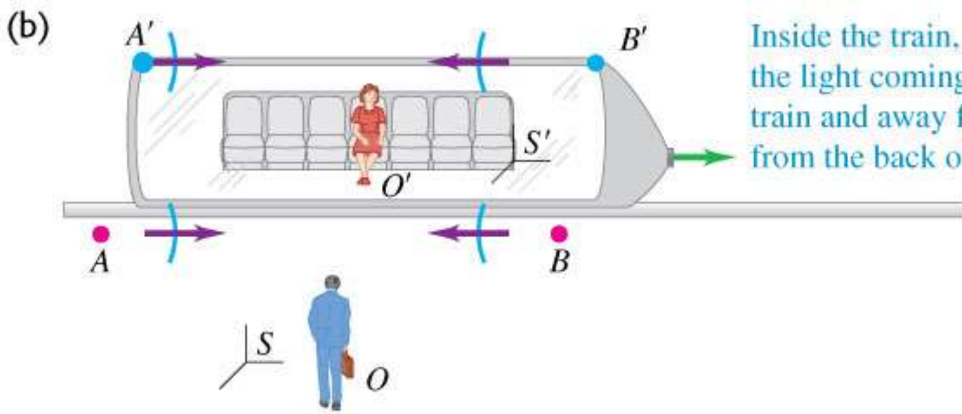
Video: Simultaneity

Simultaneity of Events



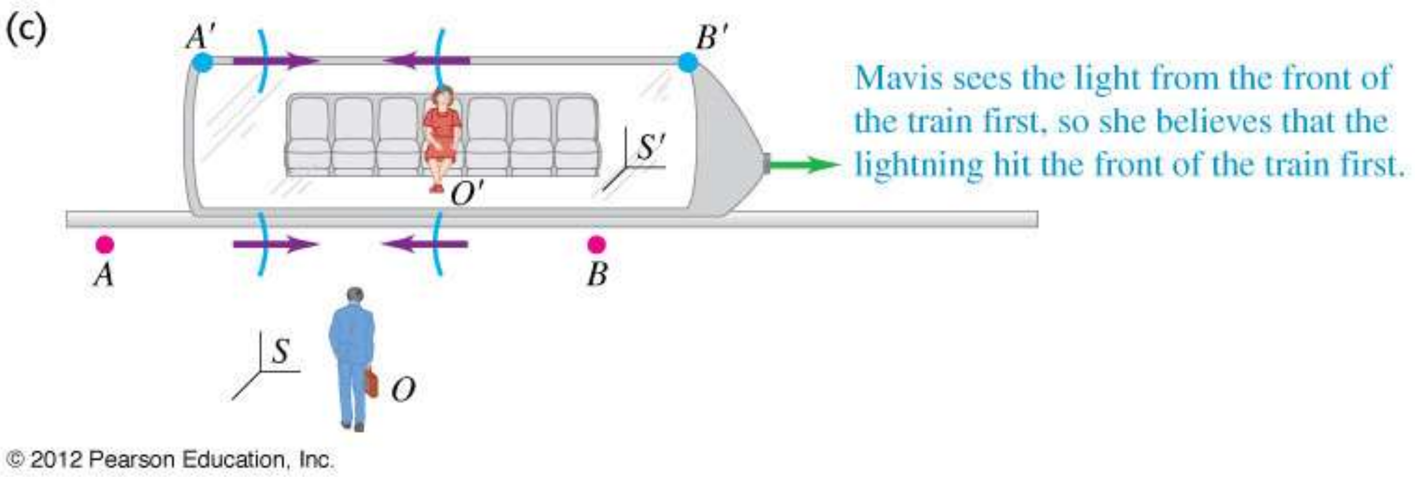
Lightning hits the front and back of a train (points A' and B') and hits the ground at points A and B.

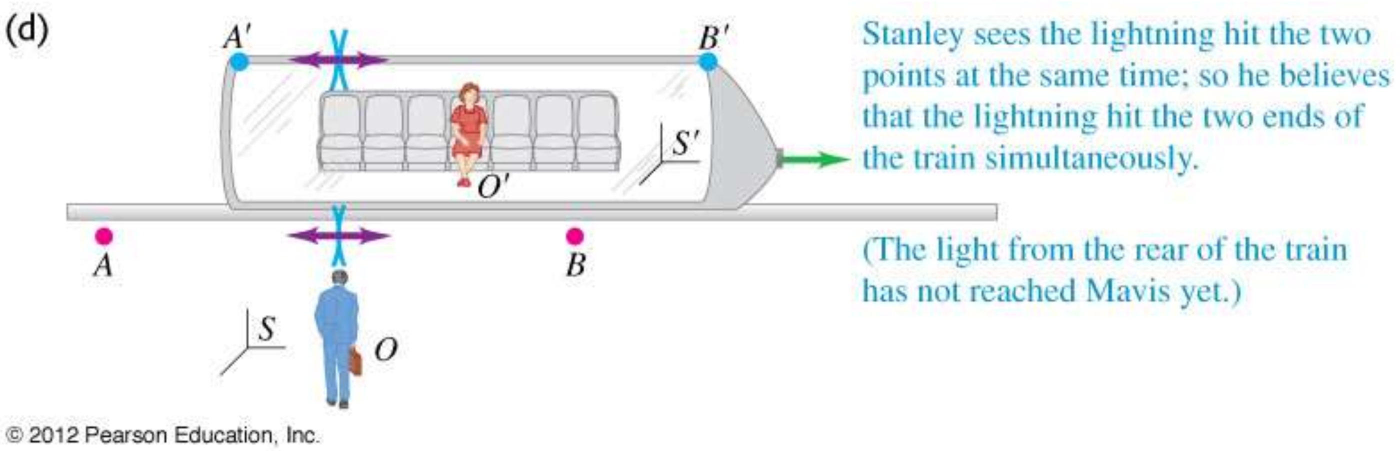
- Stanley is standing half-way between the points A and B.
- Mavis is sitting half-way between the points A′ and B′.



Inside the train, Mavis moves toward the light coming from the front of the train and away from the light coming from the back of the train.

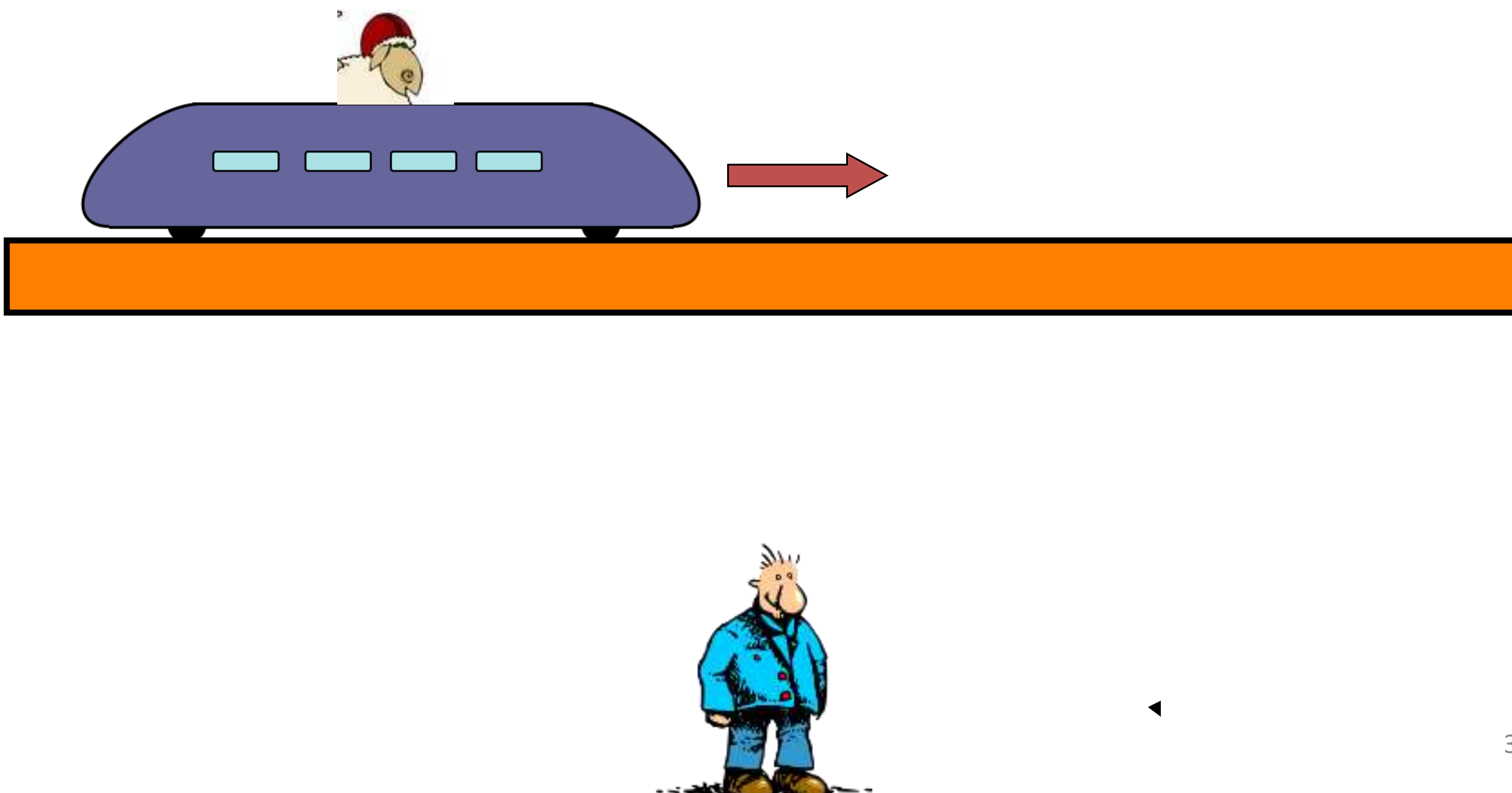
Simultaneity of Events



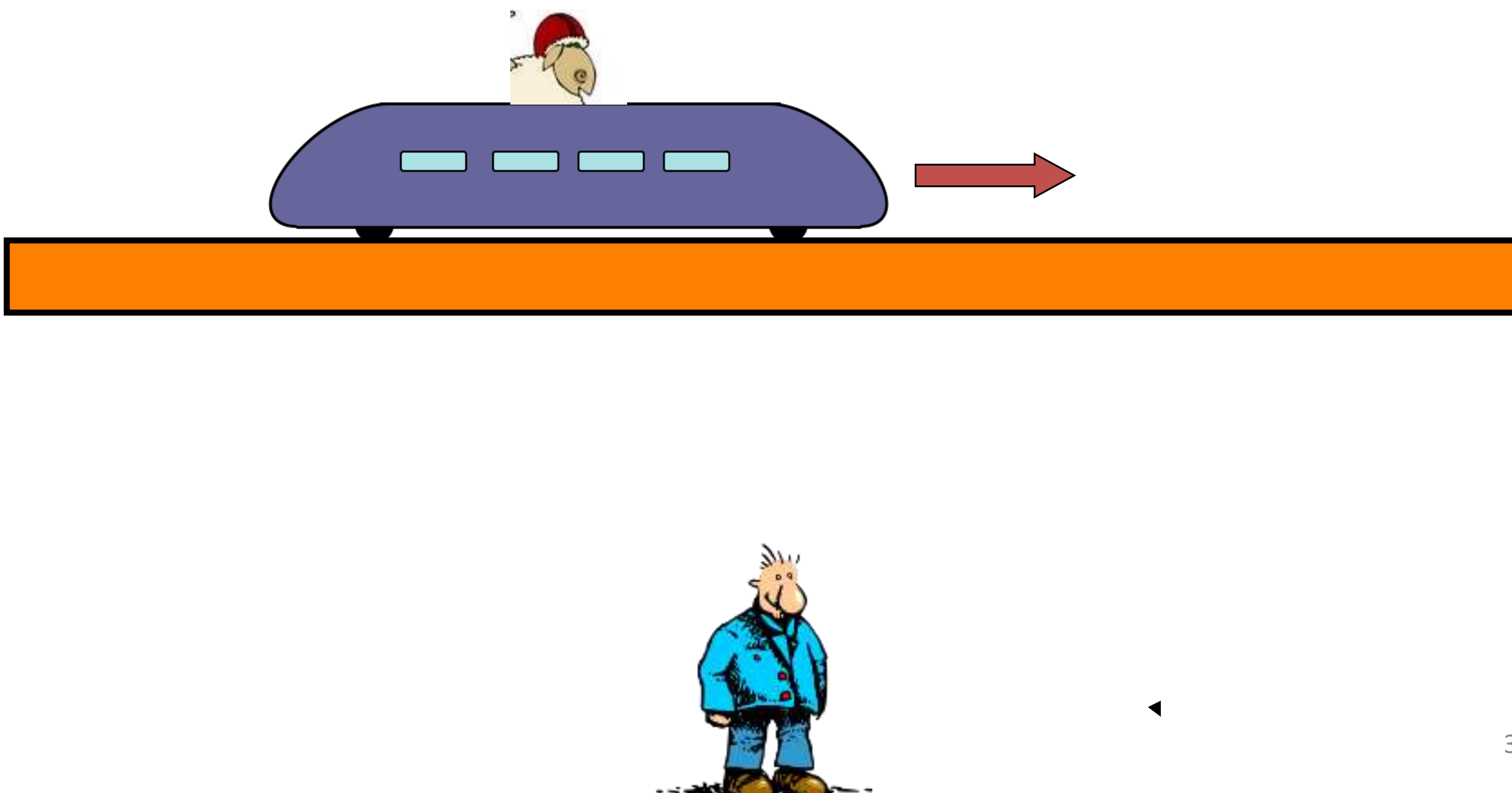


- Stanley concludes that the lightning strikes occurred simultaneously.
- Mavis concludes that the front lightning strike occurred before the rear strike.

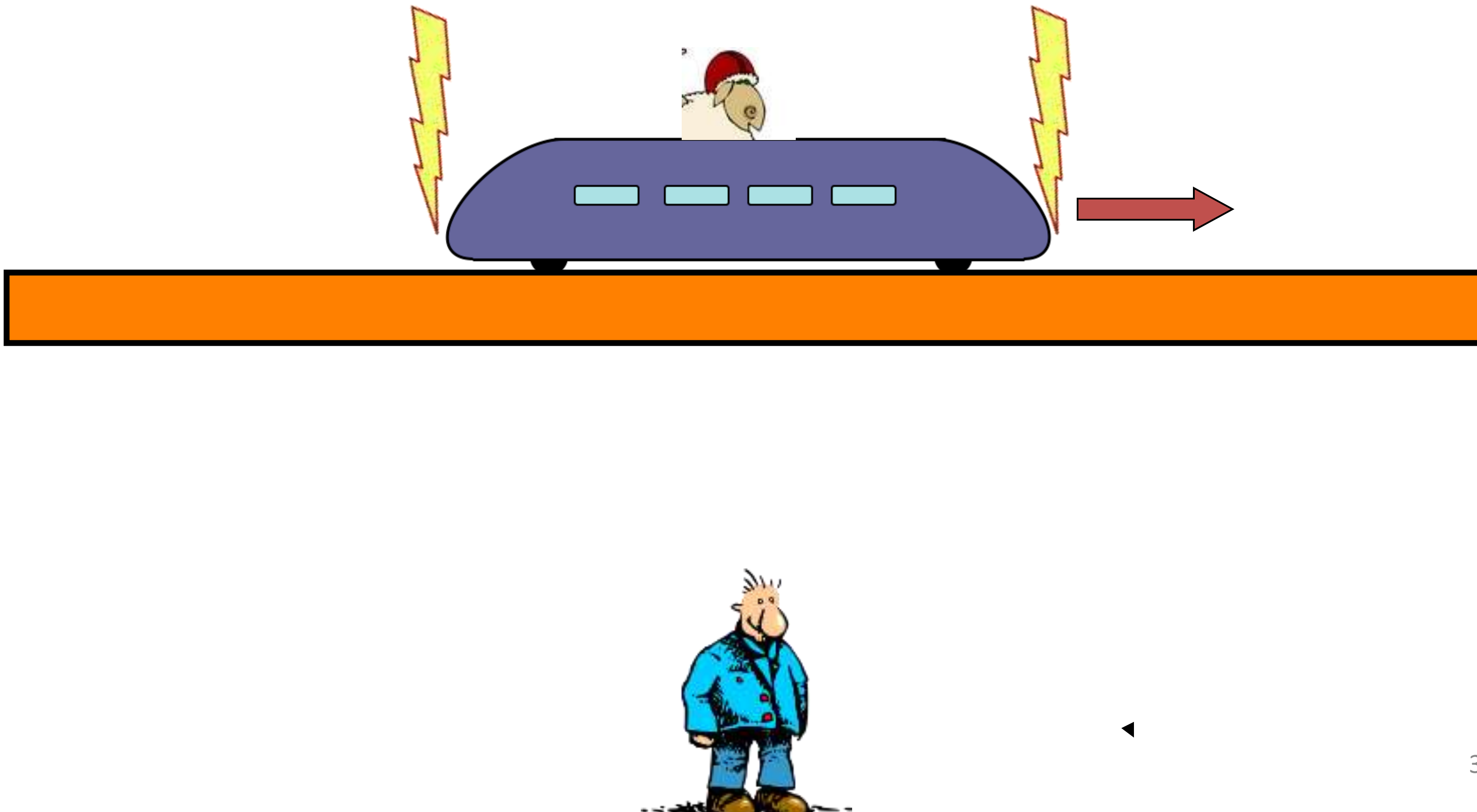
Events: frame of the guy



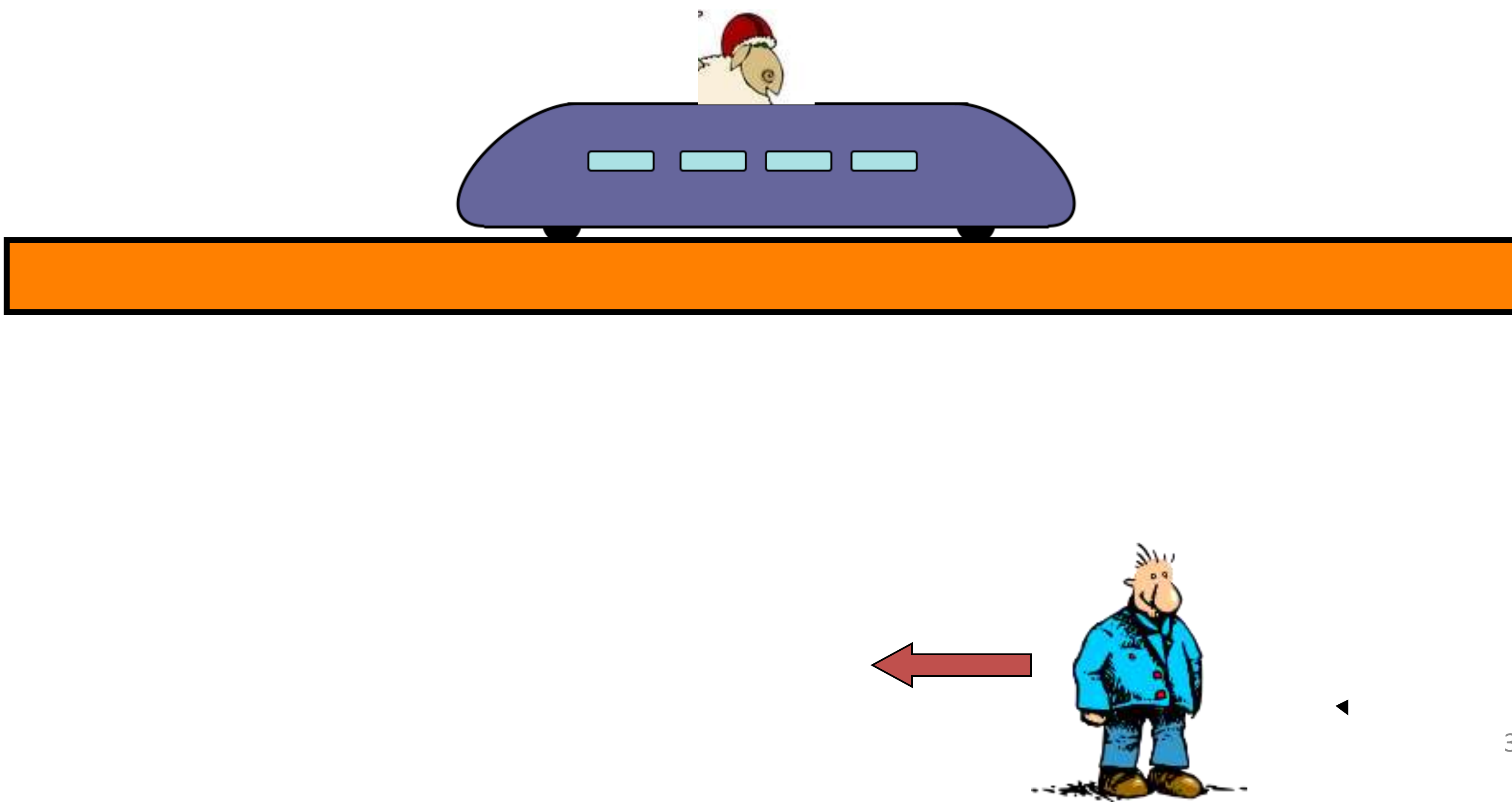
Events: frame of the guy



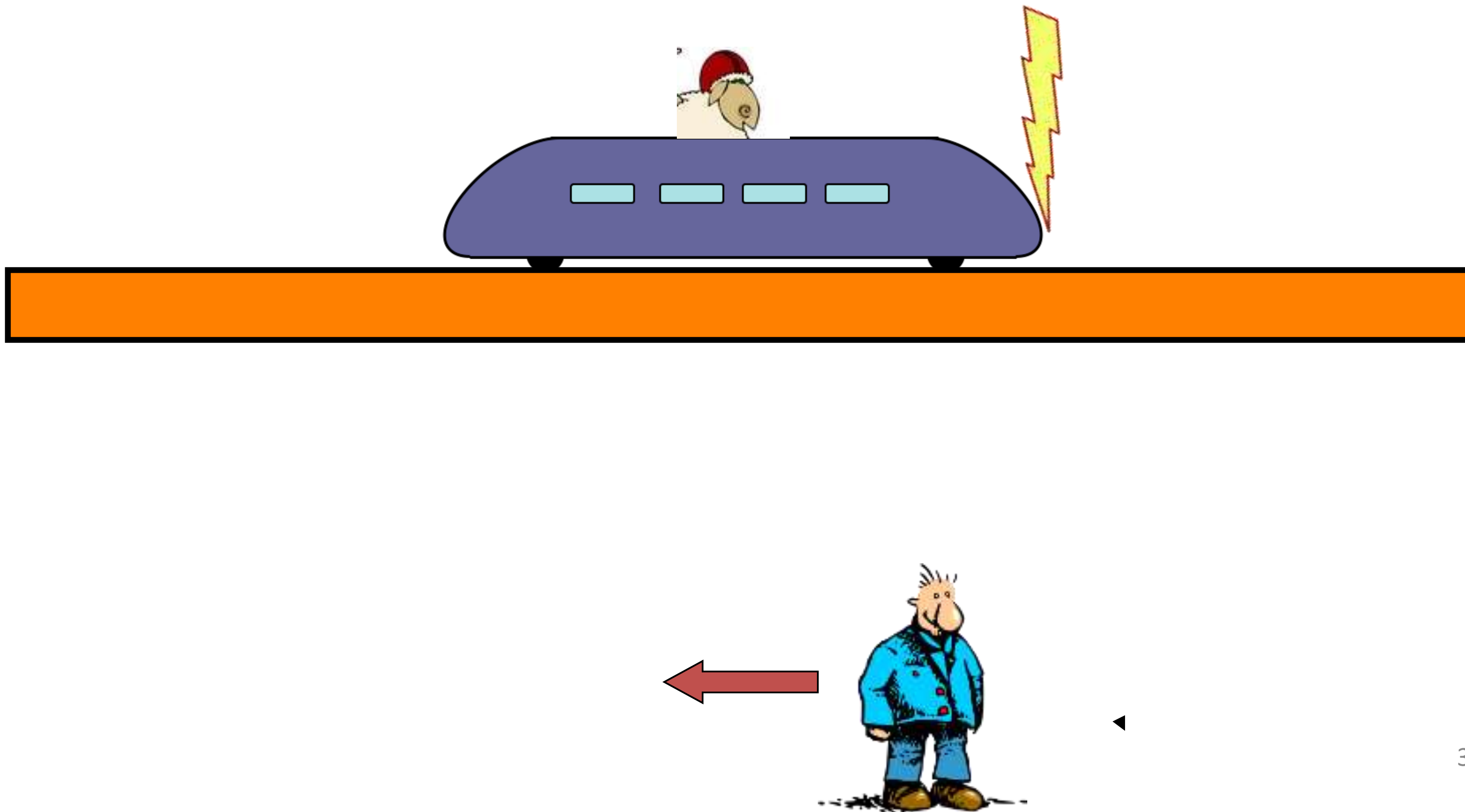
Events: Frame of the guy



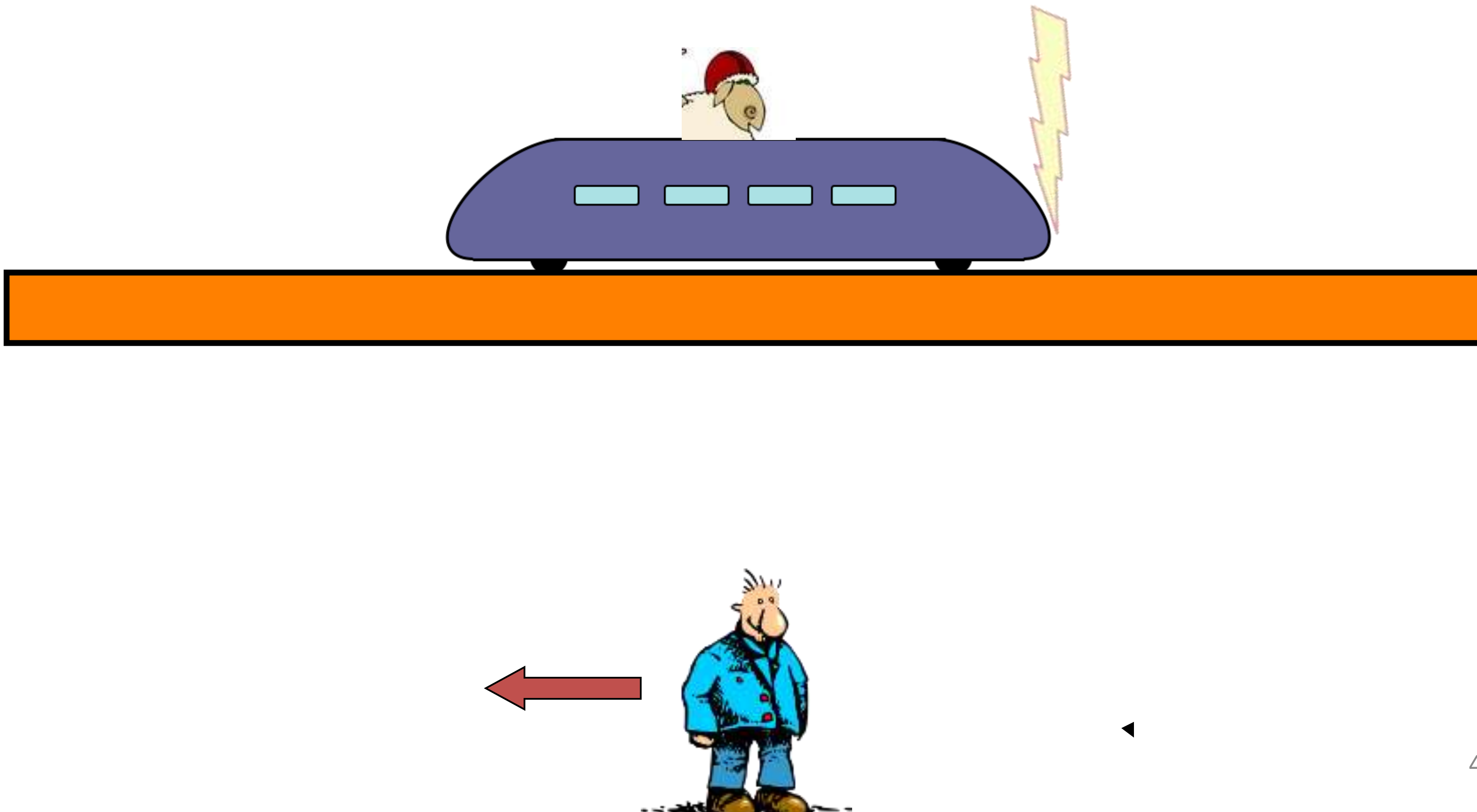
Events: Frame of the <u>sheep</u>



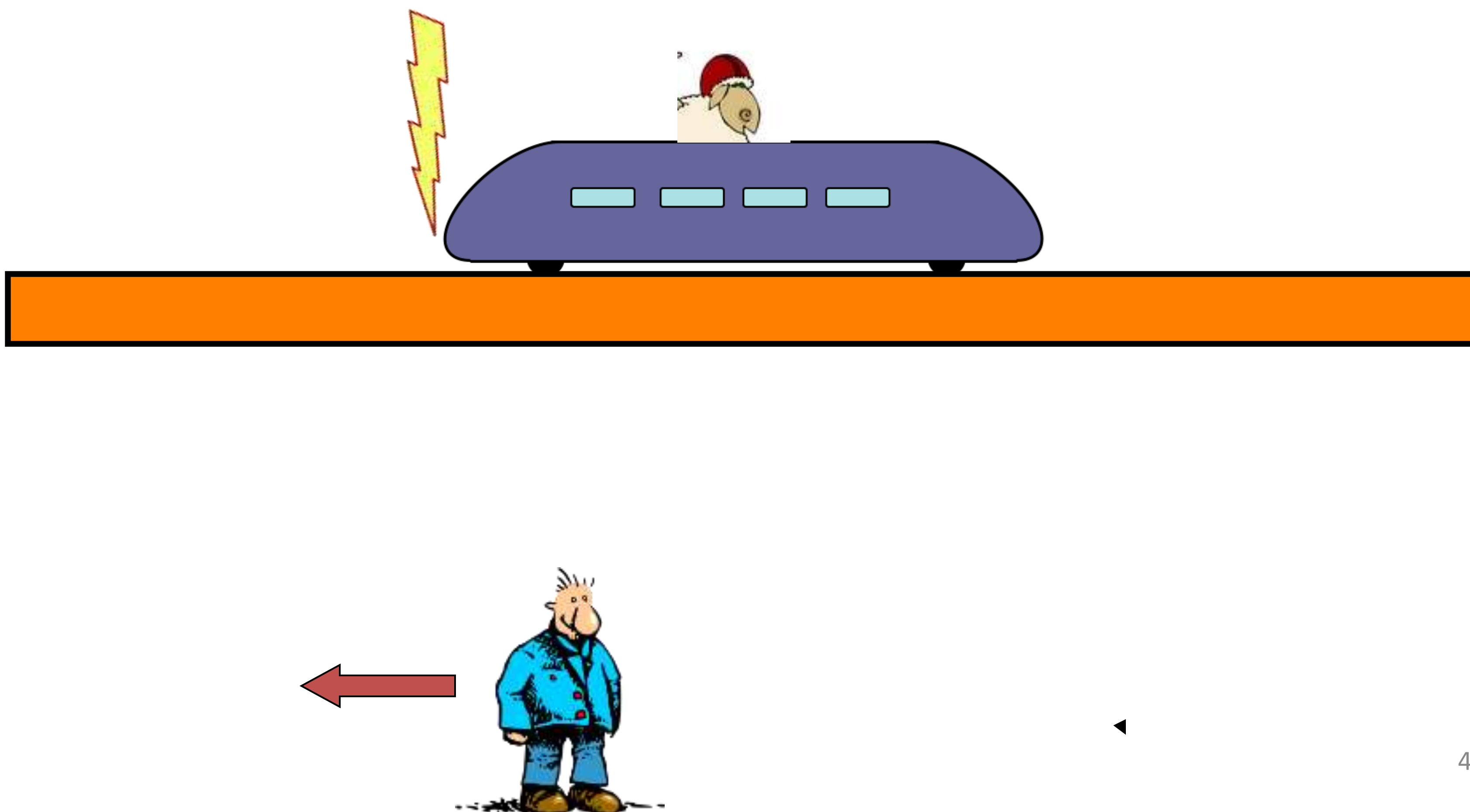
Events: Frame of the sheep



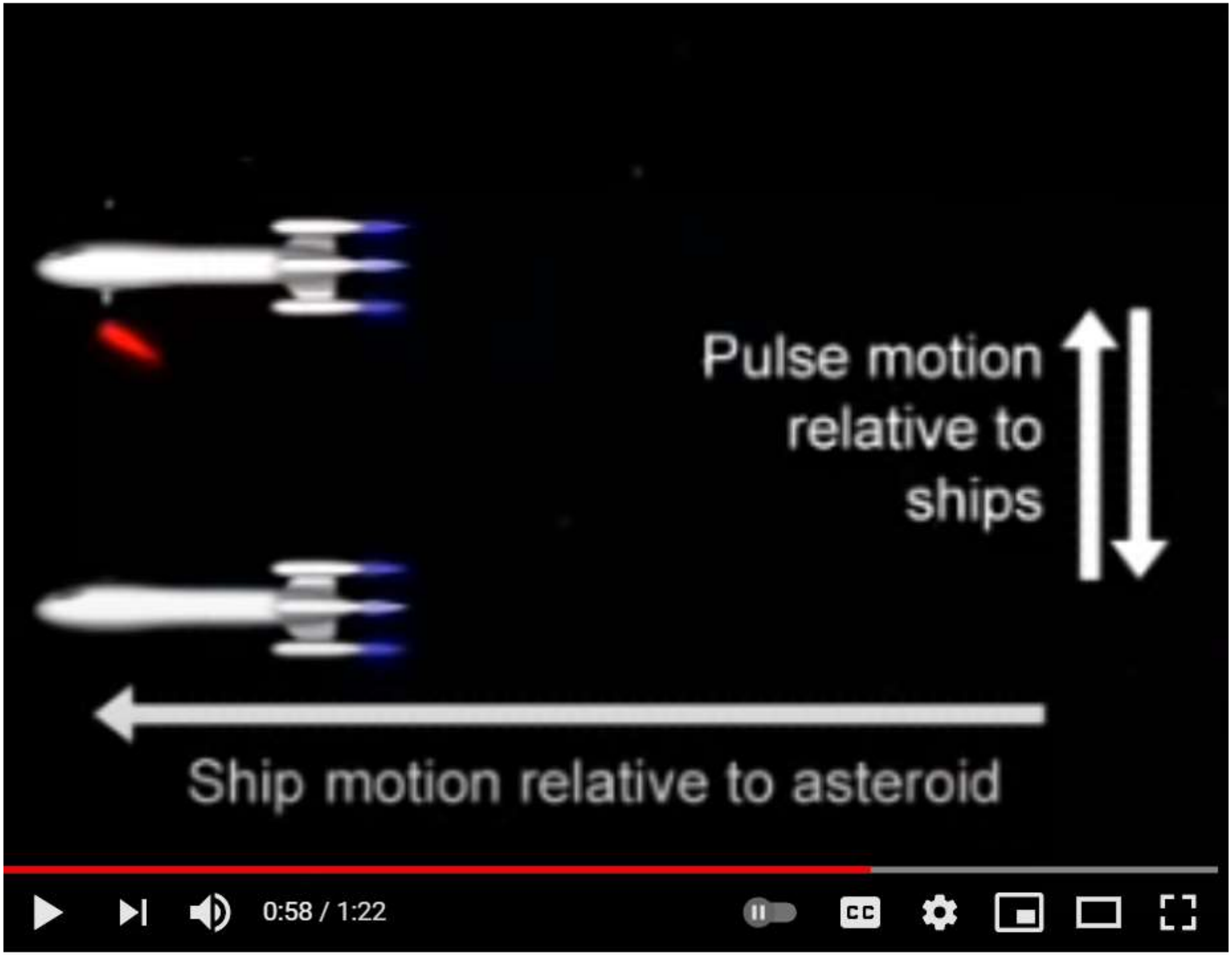
Events: Frame of the sheep



Events: Frame of the sheep



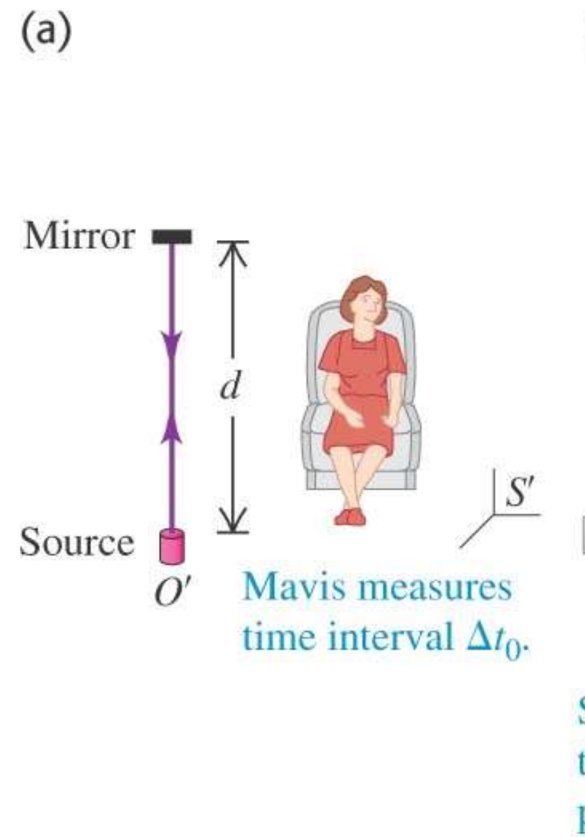
[Video: Time dilation]



A Light-Clock

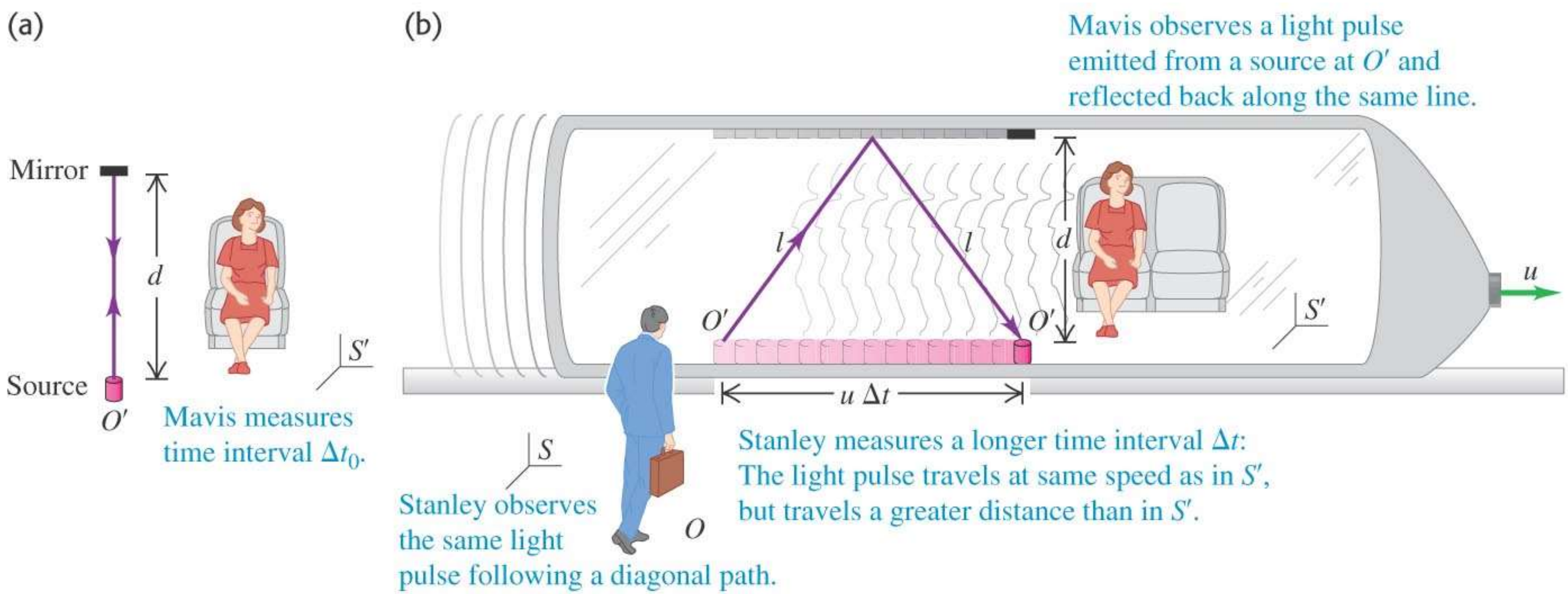
Mavis builds a clock, using a flash of light bouncing back and forth between two mirrors on the train. If the distance between the mirrors is d, the light clearly bounces from a mirror every d/c seconds.

The round-trip time for the light pulse (tic-toc) observed by Mavis is 2d/c.



A Light-Clock

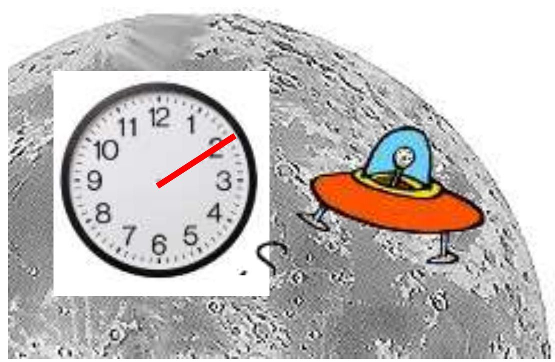
Stanley, on the platform, sees the train rushing by as the light bounces back and forth. For him, the light pulse travels in a zig-zag path, along diagonal lines, and thus travels a greater distance than what Mavis observes!
Consequently, Stanley observes a longer round-trip time than what Mavis observes.



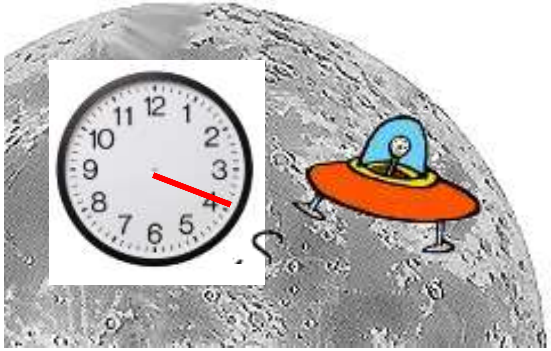
Time dilation

- In any given frame, observers will conclude that clocks run **slow** in all other frames
- The faster the relative motion, the bigger the effect!

Frame of alien on planet



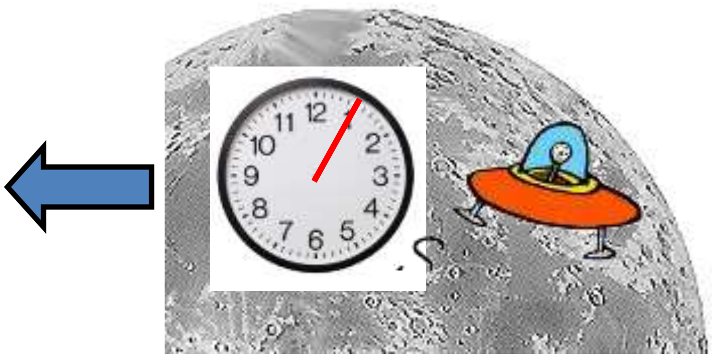
Frame of alien on planet



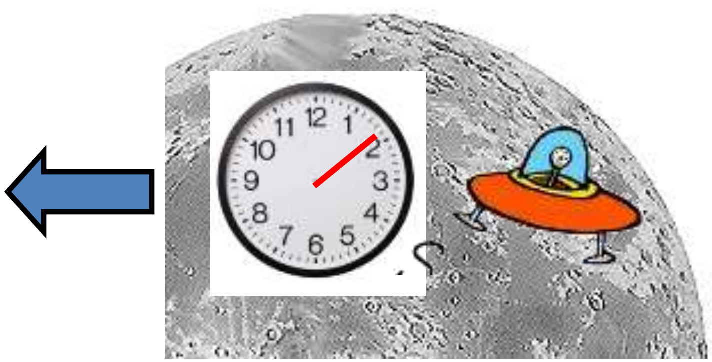
Frame of alien on planet

Frame of aliens on spaceship

Frame of aliens on spaceship



Frame of aliens on spaceship



But wait…

- Who is really right? Whose clock is really running slower?
  - Both are right! There is no absolute notion of time in Einstein's theory!

But wait…

- I can look at my clock and see if it is running slow or not. Then I'll know if I'm at rest or not.
  - Wrong! Your brain is running slow too! It will look to you like the clock is ticking at a normal rate!

But wait…

- I can stop my rocket ship, dock on the asteroid, and compare the two clocks side by side. Then I'll know which is running slower!
  - Well, but then they'll be running at the same rate! Only when one is moving with respect to the other do they run at different rates.

But wait…

- Who is really right? Whose clock is really running slower?
  - Both are right! There is no absolute notion of time in Einstein’s theory!
  - Really!

Time dilation

Table 10.1

The relativity of time: some quantitative predictions

To give you a feel for these speeds: 0.3 km/s is a typical subsonic jet plane speed, 3 km/s is twice the speed of a high-powered rifle bullet, at 3000 km/s you could cross the United States in 1 second, and at 30,000 km/s you could circle the globe in 1 second. Clearly, relativistic effects are small until the speed becomes very large!

Relative speed (km/s)	Relative speed as a fraction of lightspeed (c)	Duration of one "tick" on a moving clock, as measured by an observer past whom the clock is moving (s)
0.3	10^{-6}	1.000 000 000 000 5
3	10^{-5}	1.000 000 000 5
30	10^{-4}	1.000 000 005
300	0.001	1.000 000 5
3000	0.01	1.000 05
30,000	0.1	1.005
75,000	0.25	1.03
150,000	0.5	1.15
225,000	0.75	1.5
270,000	0.9	2.3
297,000	0.99	7.1
299,700	0.999	22.4

Time dilation

- *t* = the time measured in the frame where the clock (or observer) is at rest (also called proper time)
- *t'* = the time measured by stationary observer of the moving clock
- *v* = relative speed of two frames
- *c* = speed of light

$$t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Clicker

A spaceship passes me at 2/3 of the speed of light. What do I observe about what is occurring on board?

A) Clocks run slow
B) Chemical reactions occur more slowly than usual
C) Molecules vibrate more slowly than usual
D) Passengers think more slowly than usual
E) All of the above

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Clicker

Velma passes Mort at a high speed. According to Mort, his clock progresses by 1 hour while Velma's clock progresses by only 40 minutes. Velma observes that:

A. Mort's clock progresses by 40 minutes while hers progresses by 1 hour.
B. Mort's clock progresses by 1 hour while hers progresses by 40 minutes.
C. Mort's clock progresses by one hour while hers progresses by 80 minutes.
D. Both clocks progress by 1 hour.
E. We can't say because we don't know Velma's speed.

Clicker

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