Year 1 – Relativity
Lecture 2

Mitesh Patel

Overview of lectures

- Lecture 1: Introduction, concepts and classical results
- Lecture 2: The postulates of Relativity
- Lecture 3: Length contraction and simultaneity
- Lecture 4: The Lorentz transformations
- Lecture 5: Space-time diagrams and world lines
- Lecture 6: Four-vectors and causality
- Lecture 7: Energy and momentum
- Lecture 8: Rest mass energy and particle decays
- Lecture 9: Particle reactions
- Lecture 10: The relativistic Doppler effect

Previously on Relativity

- Looked at transformations between different coordinate measurement "frames"
  - Saw rotations and Galilean transformations
  - Galilean speed transformation: u' = u - v

- If the transformations correspond to a symmetry of physics
  - All observers must agree on what happened
  - Physical laws (e.g. Newton's) must hold in all frames
  - There is no way to define an "absolute" coordinate frame

What we will do today

- See how Maxwell's equations are inconsistent with the Galilean transformations
  - Maxwell's equations give a fixed speed for light
  - Appears to break the symmetry of Galilean frames
- Discuss the Michelson-Morley experiment
  - Failed to find any lack of a symmetry
- Present the postulates of Relativity
  - Assumes the symmetry is true, but Galileo is wrong
- See our first result derived from the postulates
  - Time dilation

Trigger warning

No (real) animals were harmed in the making of this lecture

Maxwell’s equations

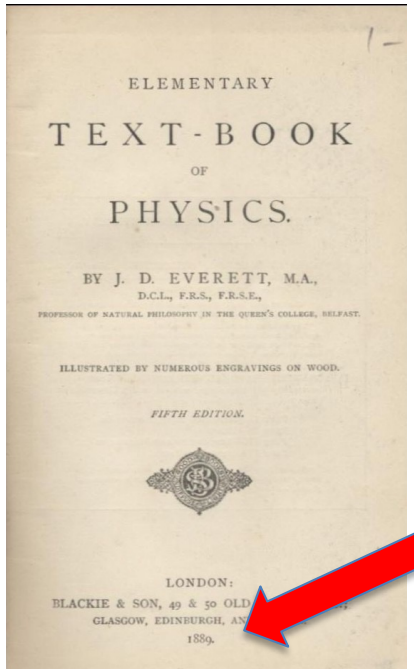
Analogy with sound

- Sound travels in a medium (i.e. air) with a fixed speed
  - If we do an experiment stationary relative to the air, sound travels at same speed in all directions
- But if the experimental apparatus is moving relative to the air, we effectively have a wind
  - Sound travels faster than expected in wind direction
  - And slower in the opposite direction
  - This breaks the symmetry of all frames being equal; we can tell if we are in a moving frame

Maybe light has a medium?

- The assumed medium for light was called the "aether" (or "ether")
  - Must occupy all space, including in vacuum
- If the Earth is not moving through the aether
  - Light will have a constant speed in all directions
- But if the Earth is moving through the aether
  - Light speed will depend on direction
- The aether stationary ("rest") frame is special
  - You can tell you are in this inertial frame
  - This breaks the inertial frame symmetry

The aether was a fact...


ELEMENTARY

TEXT-BOOK

OF

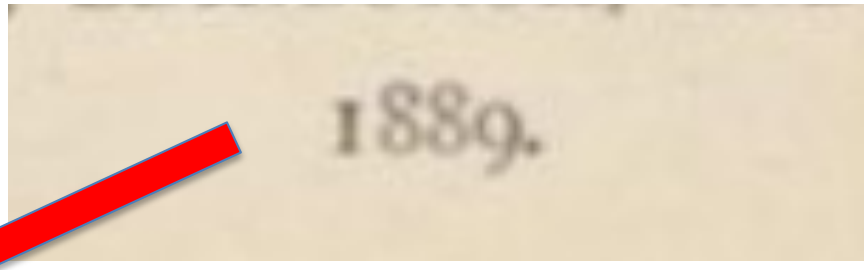
PHYSICS.

BY J. D. EVERETT, M.A.,
D.C.L., F.R.S., F.R.S.E.,
PROFESSOR OF NATURAL PHILOSOPHY IN THE QUEEN'S COLLEGE, BELFAST.

ILLUSTRATED BY NUMEROUS ENGRAVINGS ON WOOD.

FIFTH EDITION.

LONDON:
BLACKIE & SON, 49 & 50 OLD
GLASGOW, EDINBURGH, AN
1889.


1889.

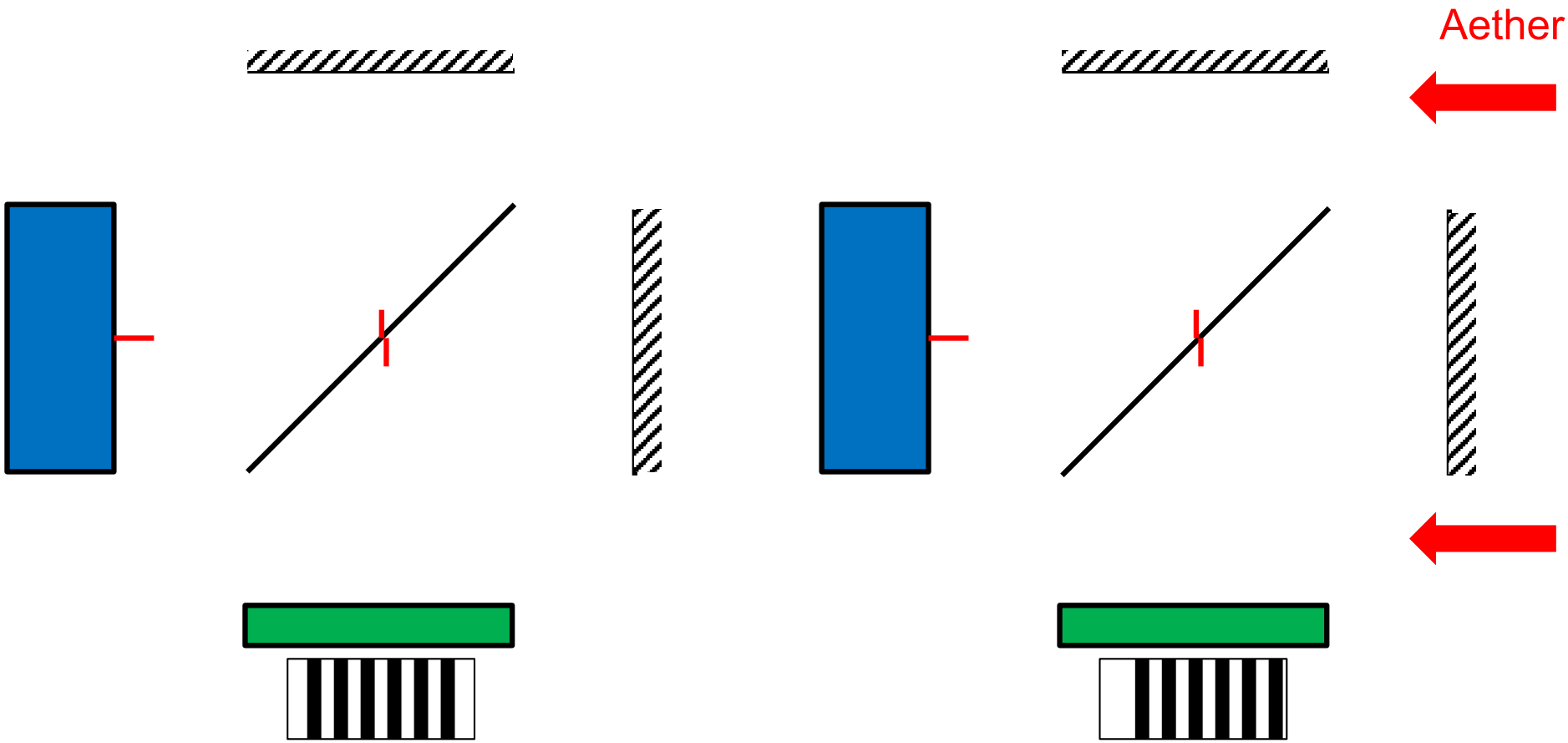
430. Sound cannot be propagated through a vacuum. Light, on the other hand, is propagated for immense distances through the interplanetary and interstellar spaces, which are more perfect vacua than any that can be artificially obtained. Hence it is inferred that light is propagated by the vibrations of some medium different from ordinary matter. The immense velocity of light shows that this medium is incomparably more resilient in proportion to its density than any of the forms of ordinary matter. This medium, whose existence is now universally accepted by physicists, is called the *luminiferous ether*.

If there is such an aether...

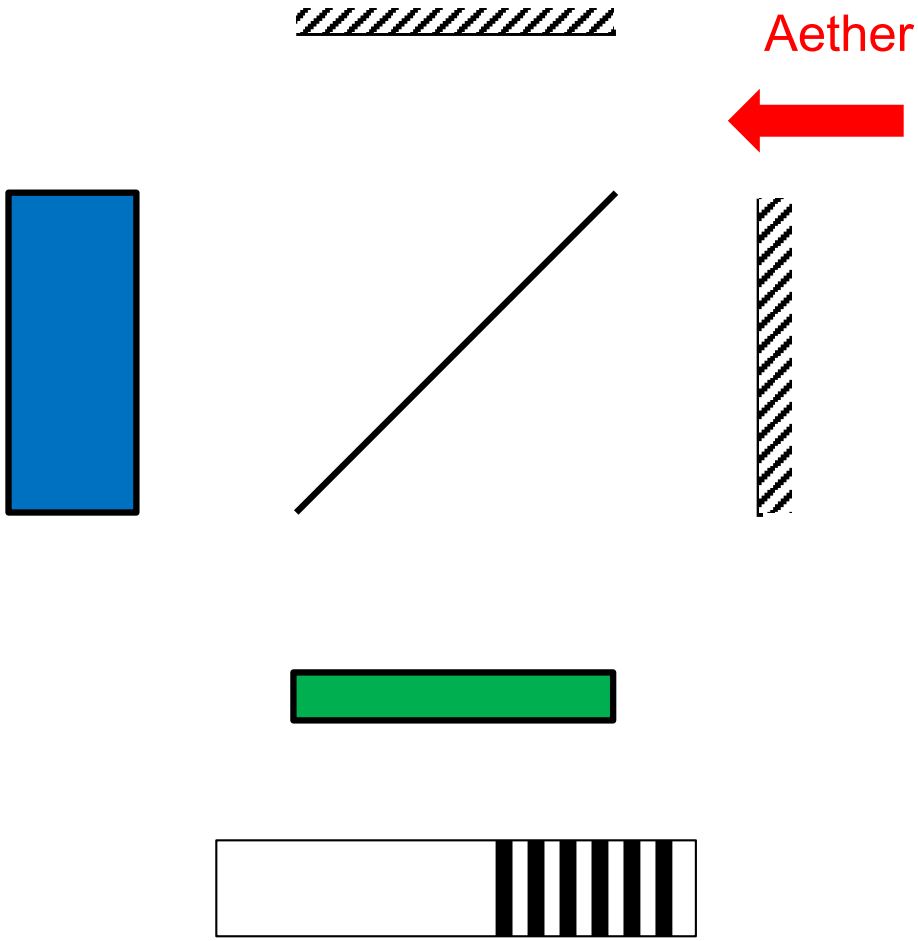
- As for sound, we would see a speed of light different to $1/\sqrt{\varepsilon_0\mu_0}$ if moving relative to the frame where the aether is stationary – speed observed would depend on the direction of travel – can test in an experiment... !

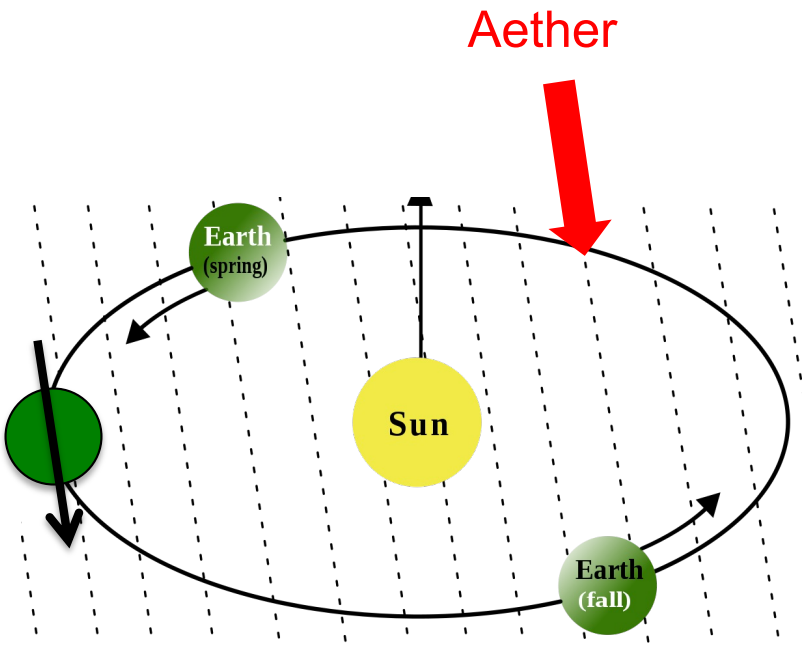
- (incorrectly) Assumes the Galilean transformations are correct but the equation for the speed, and hence Maxwell's equations, only hold in one frame

The Michelson-Morley experiment



Rotate the whole experiment



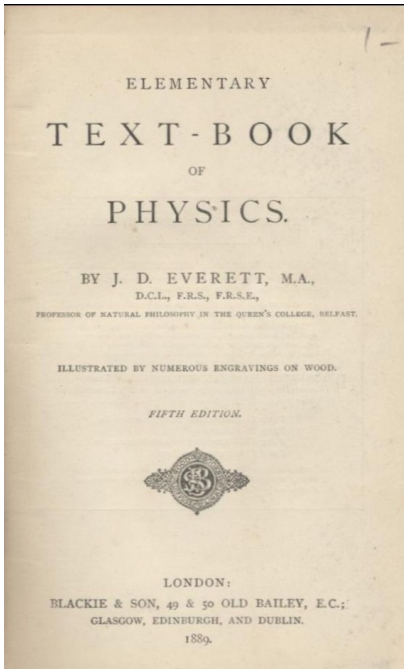


No shift seen

Still no shift seen

The value of experiments (1)

- There is merit in measuring (to high precision) quantities where the answer is already in textbooks


ELEMENTARY

TEXT-BOOK

OF

PHYSICS.

BY J. D. EVERETT, M.A.,
D.C.L., F.R.S., F.R.S.E.,
PROFESSOR OF NATURAL PHILOSOPHY IN THE QUEEN'S COLLEGE, BELFAST.

ILLUSTRATED BY NUMEROUS ENGRAVINGS ON WOOD.

FIFTH EDITION.

LONDON:
BLACKIE & SON, 49 & 50 OLD BAILEY, E.C.;
GLASGOW, EDINBURGH, AND DUBLIN.
1889.

The Nobel Prize in Physics 1907

Photo from the Nobel Foundation archive.

Albert Abraham Michelson

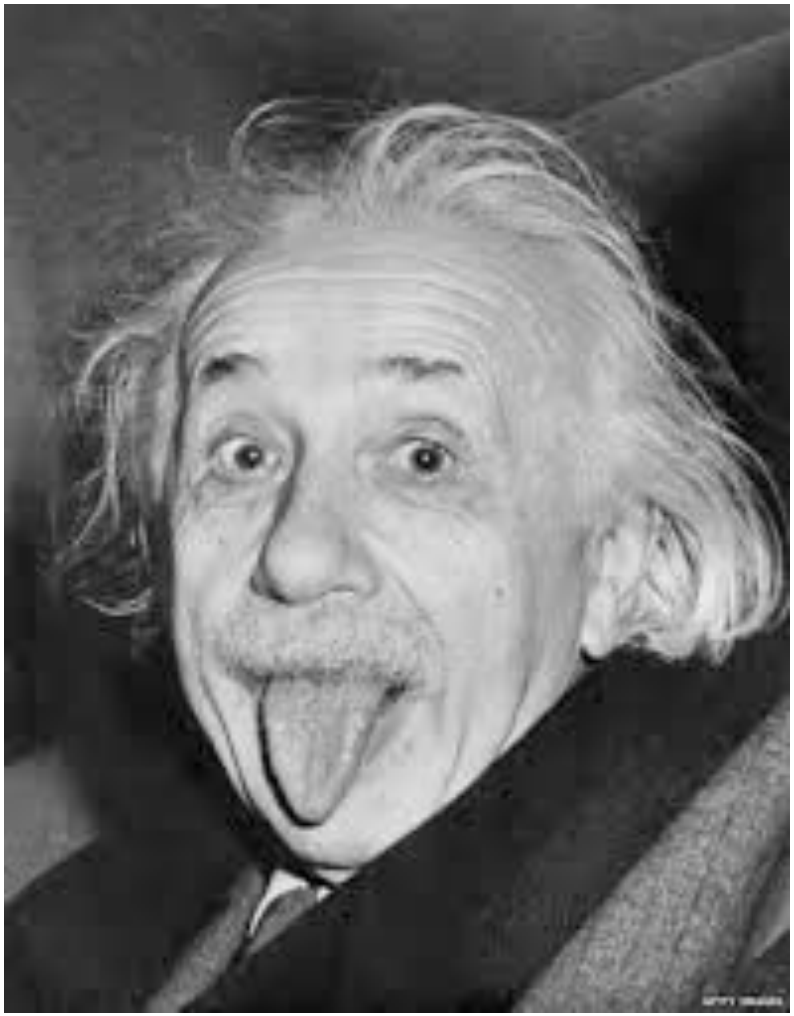
Prize share: 1/1

The Nobel Prize in Physics 1907 was awarded to Albert Abraham Michelson "for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid."

- A single ("failed" !) experiment can change everything!

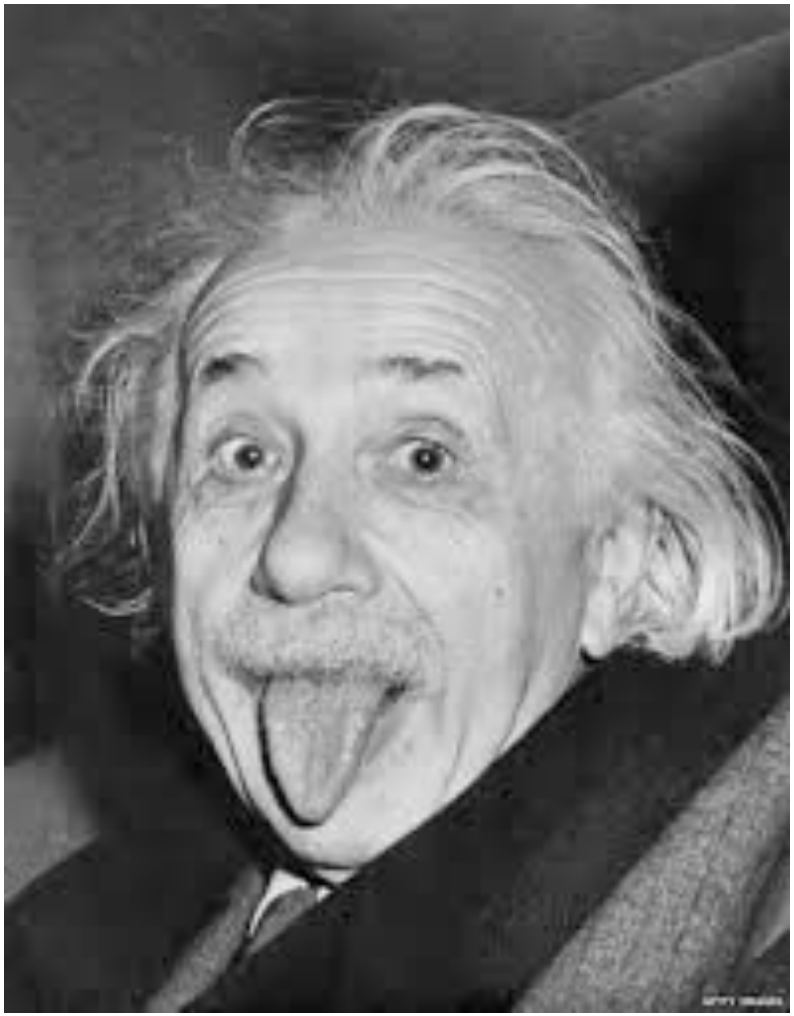
Enter Einstein

- Einstein's genius was to realise that the resolution to this dilemma was the other way round
  - Maxwell's equations were correct, c=constant for all observers
  - The Galilean transformation equations which were "wrong" (i.e. the low energy limit of their SR equivalent)



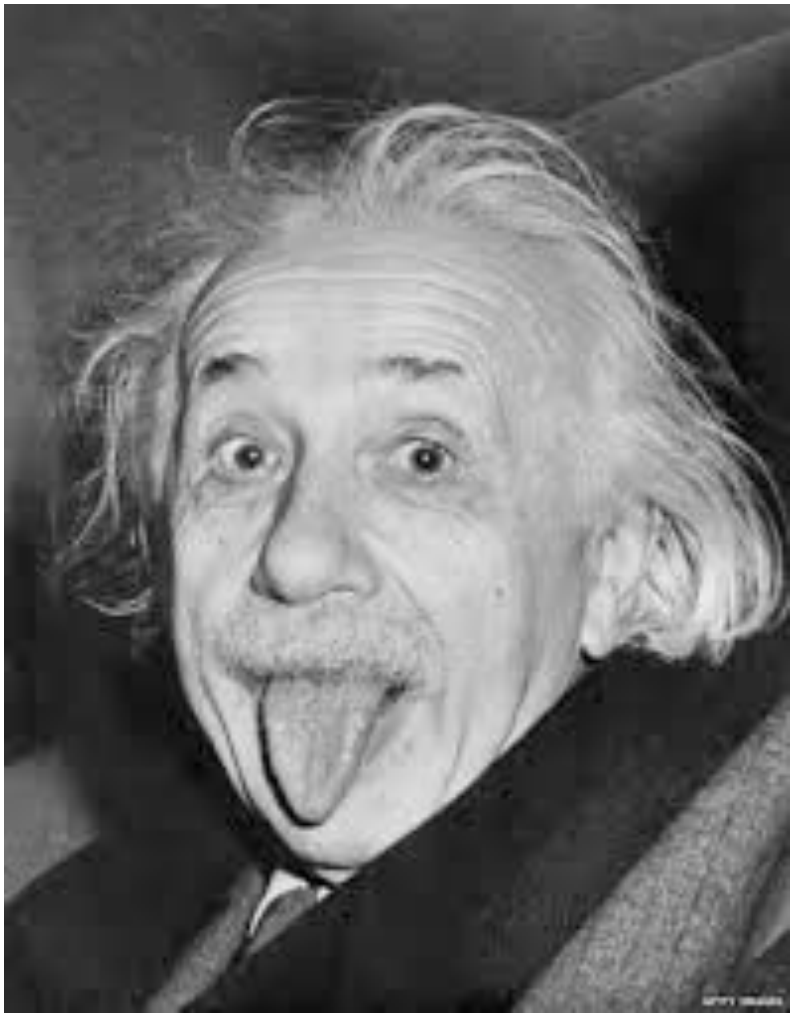
Enter Einstein

- Achieved this by allowing time to be different between different frames
- Changing time in just the right way means that the speed of light can be constant in all frames
- Extraordinary change for our concept of reality



The value of experiments (2)

- If you want to revolutionise theory and our concept of time-and-space, the bar is Einstein (Newton, Maxwell... ?)
- At least if you're an experimentalist, you might just get lucky!

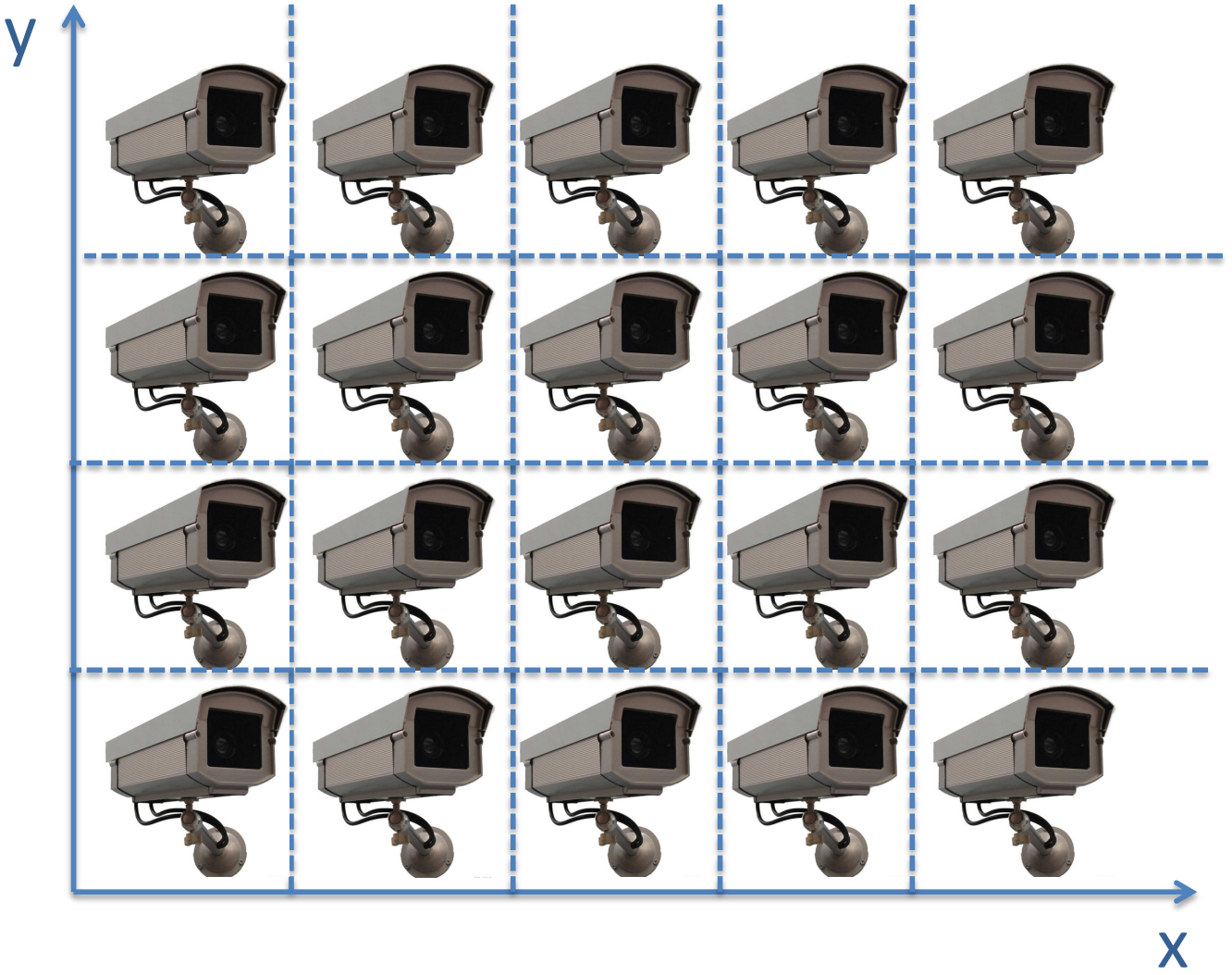


The postulates of Relativity

- There are only two postulates = assumptions
  1. The laws of physics are the same in all inertial frames, i.e. coordinate frames moving uniformly relative to each other
  2. The speed of light c in vacuum is independent of the speed of the light source and has the same value for all inertial observers

- No violation of the postulates has ever been seen experimentally

The all-seeing observer



Relative motion

- Rashid is a traffic cop at Rest by a hyperway
- Sam is Superfast going at 2.9×10^8 m/s
- Beth is a light Beam emitted by Sam

- Go to www.menti.com
- Question 1: What speed does Rashid observe Beth moving at?
- Question 2: What speed does Sam observe Beth moving at?
- Question 3: What speed does Sam observe Rashid moving at?

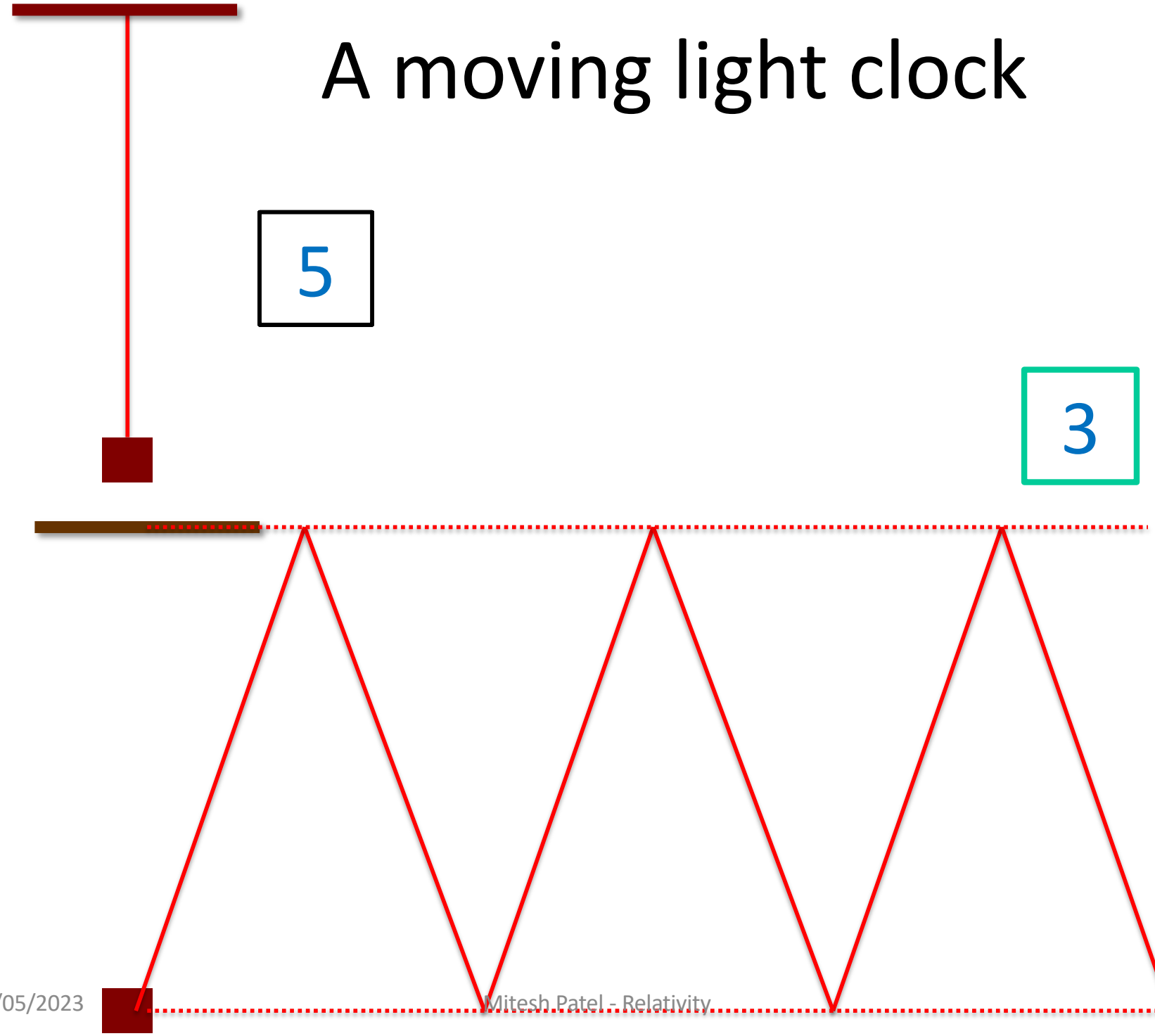
Relative motion

- Qus 1&2: Rashid and Sam both see Beth moving at $c = 3.0 \times 10^8$ m/s
  - The second postulate says this must be true
- Qu 3: Sam sees Rashid moving at -2.9×10^8 m/s
  - If they did not agree on their relative speed, there would have to be some other difference between the two frames
  - But the first postulate says all inertial frames are equivalent

A stationary light clock

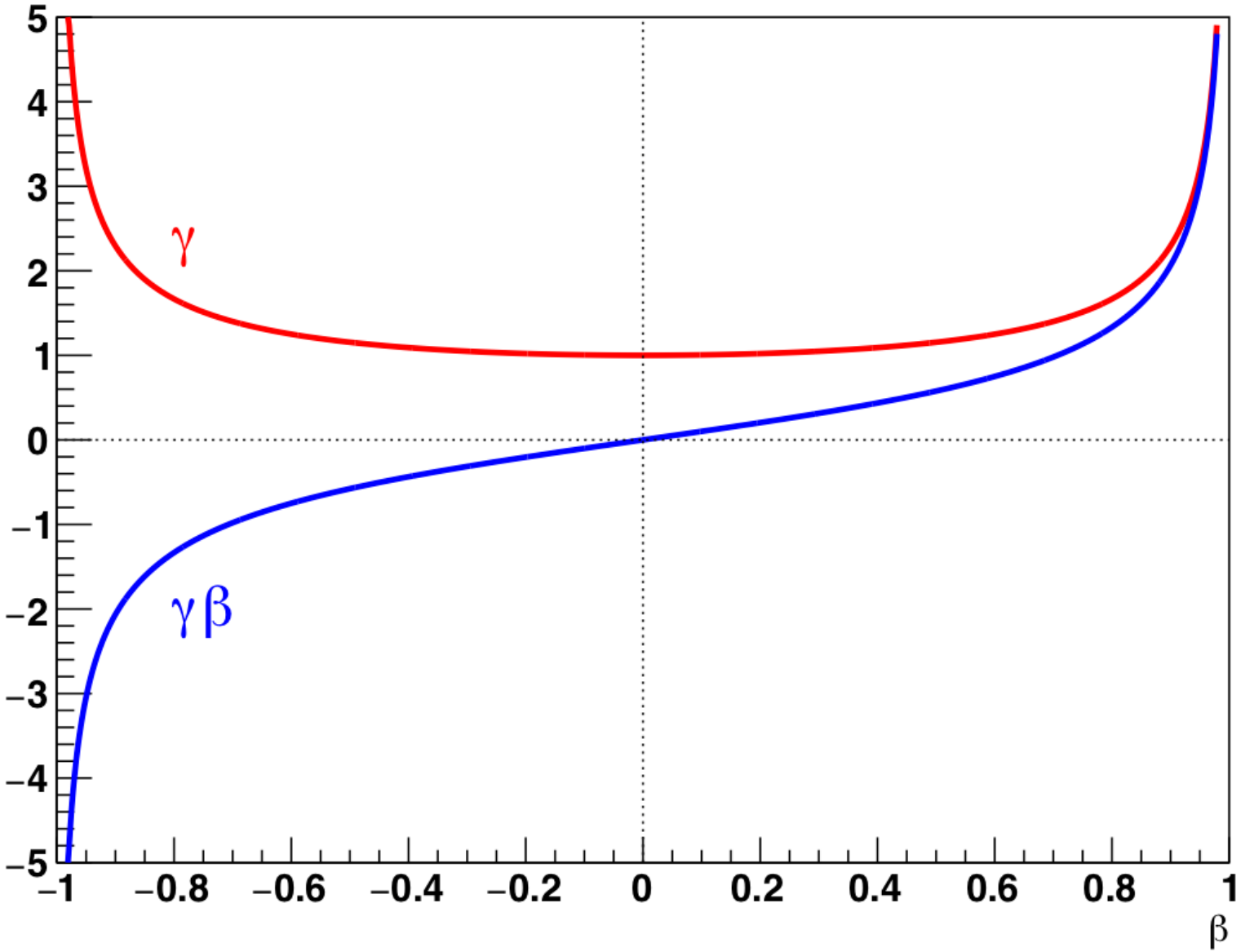
A moving light clock

A moving light clock



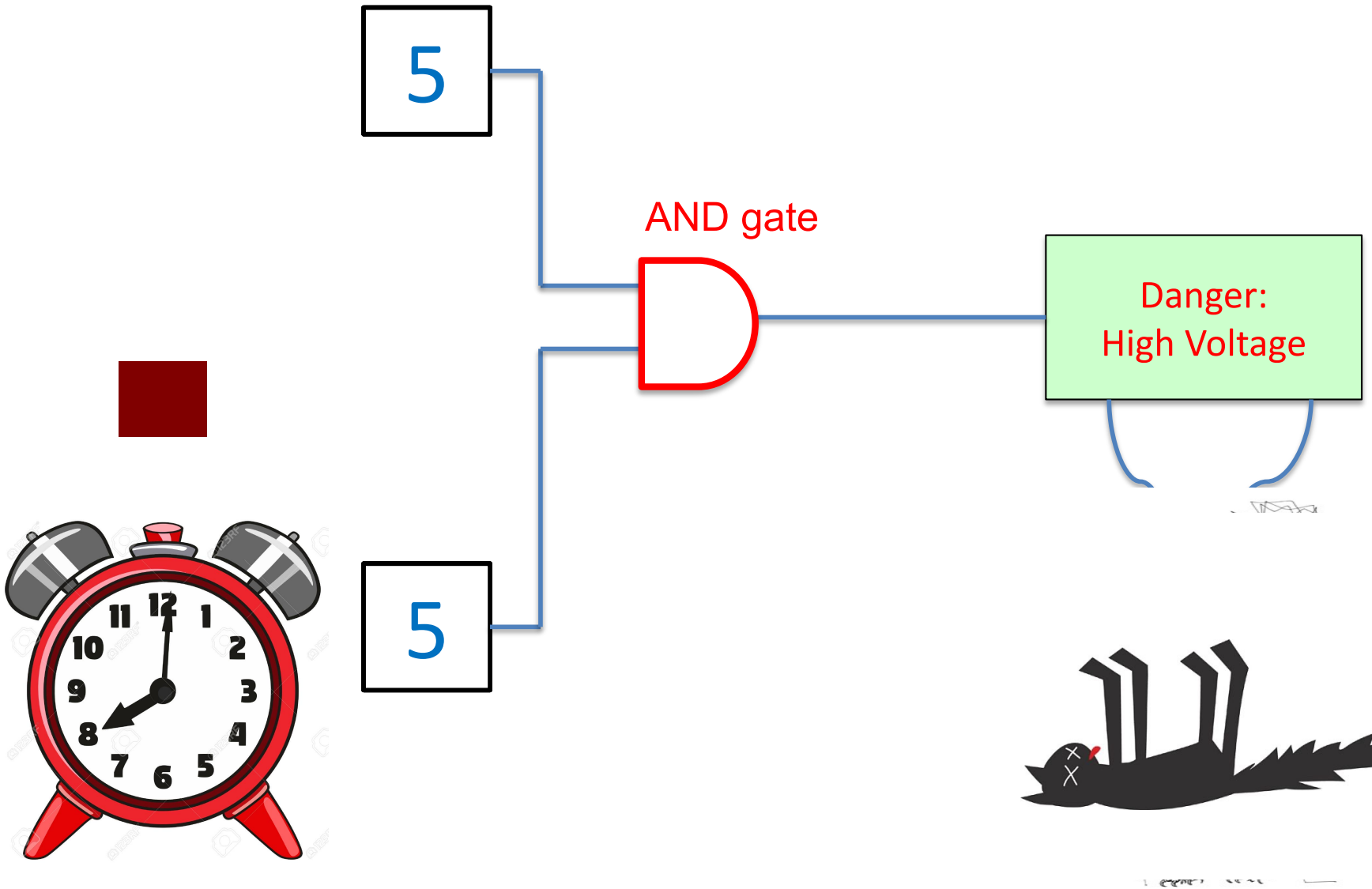
The light clock and time dilation

γ and $\gamma\beta$ vs β



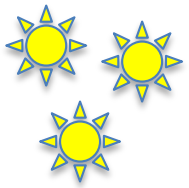
Time Dilation

Comparing clocks



Time dilation and the twins

- Ali and Ed are twins
  - Ali goes to Alpha Centauri, Ed stays on Earth

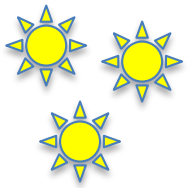


- If they both carry clocks, does Ed, stationary on Earth, see Ali's clock run …
  - Fast
  - Slow
  - It depends

Go to www.menti.com

The twins “paradox”

- Ali and Ed are twins
  - Ali goes to Alpha Centauri, Ed stays on Earth



- Ed sees Ali’s time runs slowly when moving
  - On the way out and back
  - She is younger than him when she returns
- Why doesn’t Ali see Ed get younger than her?

Time dilation works both ways

- All inertial frames are equivalent
  - Rashid sees Sam's clock run slower than his watch

  - Sam sees Rashid's watch run slower than his clock!!!

Resolution: time depends not just on relative speed, but also on position (lecture 4)

What we did today

- Saw that Maxwell's equations predict a constant speed of light
  - Requires the Galilean transformations to be modified
- Presented the postulates of Relativity
  - All inertial frames are equivalent
  - The speed of light is constant for all observers
- Saw our first result derived from the postulates
  - Time dilation; time for an object slows down when it is moving by a factor of $\gamma = 1/\sqrt{[1-(v/c)^2]}$