EINSTEIN MADE EASY

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SPECIAL RELATIVITY

AT THE HEART OF SC PROGRAMS

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Office of Science
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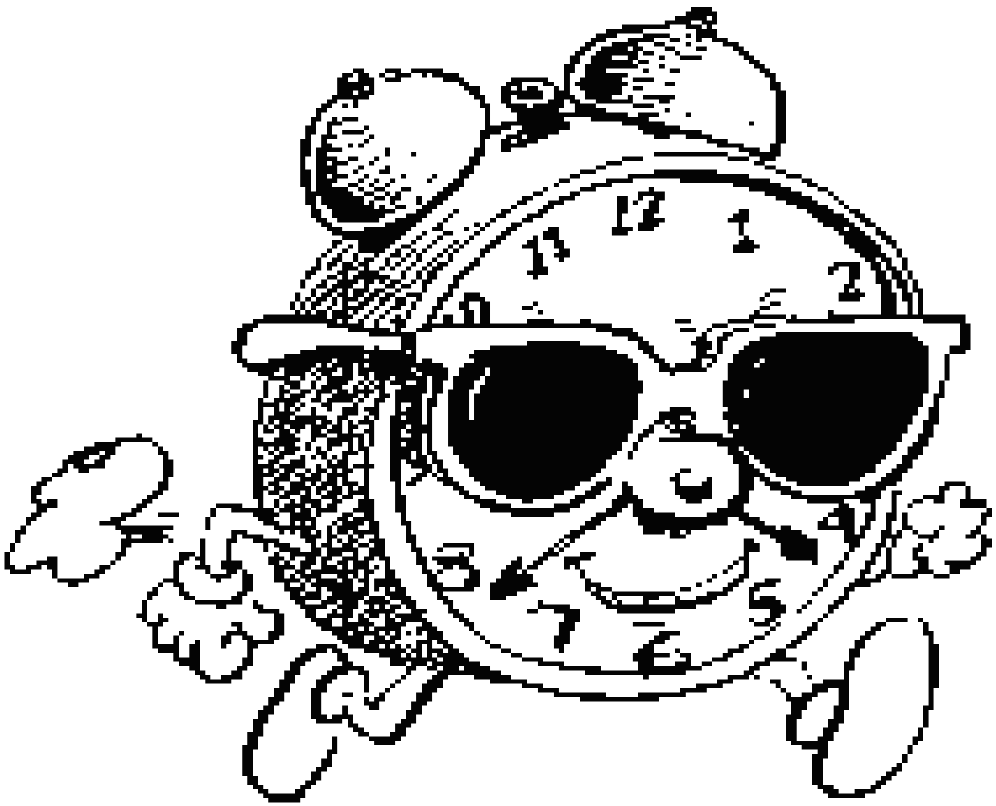
Motion and Gravity make clocks run slowly



Moving clocks run slowly

Time is of the Essence-1

- Prior to Einstein two great theories of physics
- Newtonian Mechanics and Gravity
- Maxwell’s unified theory of electricity and magnetism
- *These two theories imply different views of time*

Time is of the Essence-2

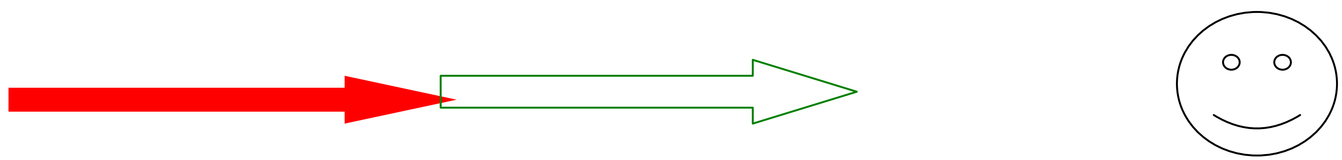
- For ***Newton***, time is an absolute, universal measure, ***"the river of time",*** the same for all observers, no matter whether they are at rest or traveling at high speed
- *This means that the speed of light measured by an observer will depend on the speed at which the source of light is traveling*

Time is of the Essence-3

- Bob standing on the corner of 7^{th} and Independence
- Alice is driving her auto down Independence towards the Capitol at 100 km/hr
- Alice sends a signal to Bob at 300km/hr
- What signal speed does Bob measure?

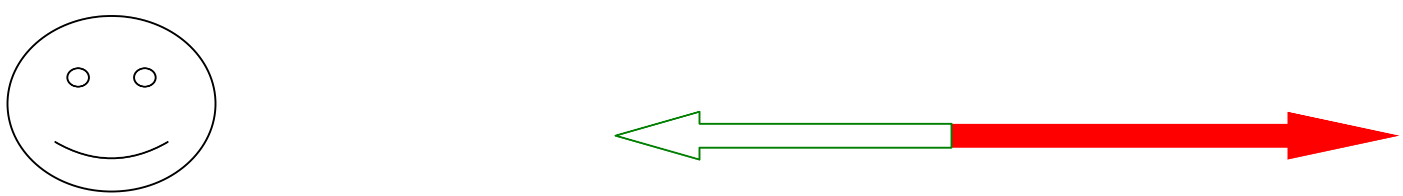
Newton and Relative Speed

- Alice at 100 km/hr; signal at 300;



Bob sees 300+100 above

Bob sees 300-100 below

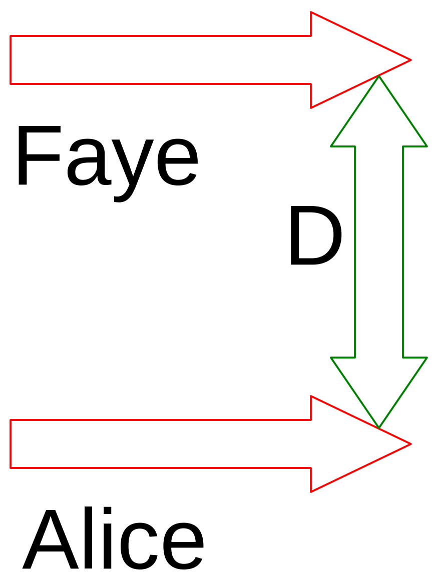


Maxwell and the Speed of Light

- ***Maxwell's*** theory implies that the speed of light, 300,000 km/sec is the same for ***ALL*** observers, no matter whether they are at rest or traveling with high speed
- ***Maxwell's*** theory also implies that people and objects cannot travel at speeds greater than the speed of light.
- ***Einstein*** explored the consequences of Maxwell's theory.

Einstein 1: Alice on Independence, Faye on Constitution, Bob with Alice

- Faye and Alice at 100 km/hr exchange a laser signal , Bob a passenger with Alice



time A to F to A = 2D/c

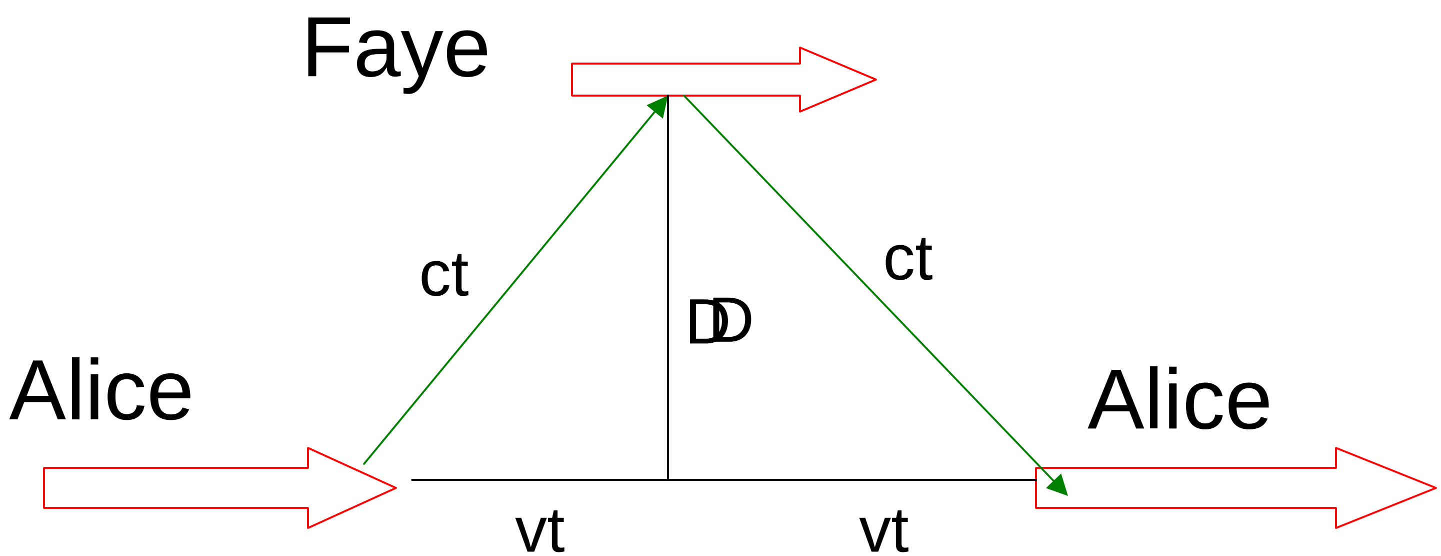
D = 0.6 km

c = 300,000 km/sec

call this time ***t(Alice)***

Einstein 2: Alice on Independence, Faye on Constitution, Bob at Rest

- Faye and Alice at 100 km/hr each,
- ***Bob standing on corner of 14th and Independence.***
- ***Time A to F to A = bigger Distance/c***



- ***Bob now sees a longer time!!***

Einstein 2': Alice on Independence, Faye on Constitution, Bob at Rest

- Pythagoras tells us the square on the hypotenuse = sum of squares on other two sides:

$$(ct)^2 = (vt)^2 + (D)^2$$

$$t = \gamma\,(D/c),$$

$$\gamma = 1/\sqrt{[1-(v/c)^2]} > 1$$

- **Time A to F to A = $\gamma(2D/c)$**
- Call this time ***t(Bob) = γt(Alice) > t(Alice)***

Einstein 2”: What does this mean for times measured by Alice moving and Bob at Rest ?

- **Some typical values of γ:**
- v/c = 0.1, γ = 1.005; v/c = 0.9, γ = 2.29
- v/c = 0.01, γ = 1.00005; v/c = 0.99, γ = 7.09
- v/c = 0.001, γ = 1.0000005; v/c = 0.999, γ = 22.37
- ***Remember c = 300,000 km/sec =186,000 m/sec***

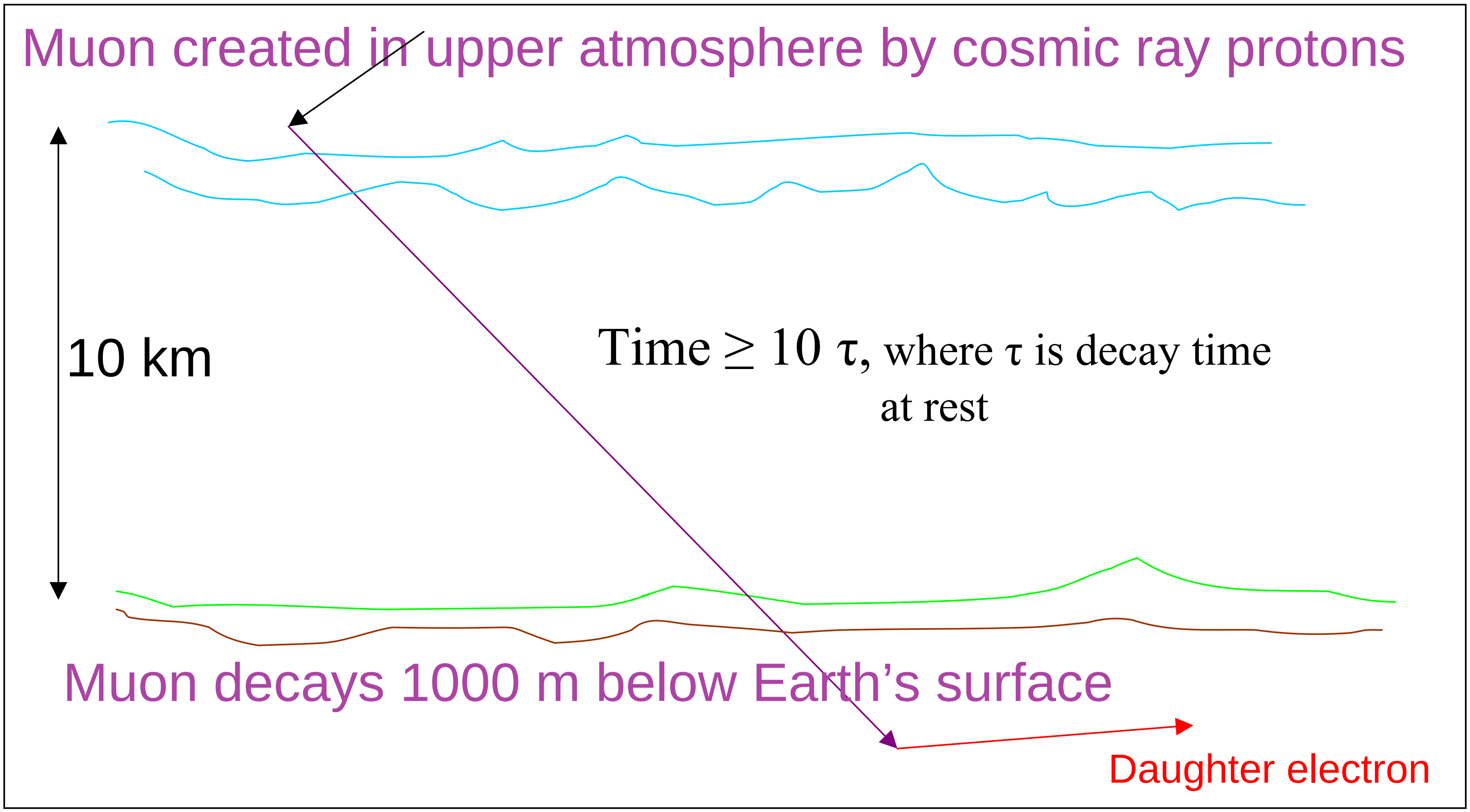
Einstein 2''': What does this mean for times measured by Alice and by Bob at Rest ?

- Alice says the time for the light signal to travel to Faye and come back is ***t(Alice).***
- Bob at rest says the time for the signal to go back and forth is ***t(Bob) = γ t(Alice)***
- Example:If Alice is driving at 0.9, or 0.99 c, then ***t(Bob) is 2.3, or 7.1 times t(Alice)***
- This phenomenon is called ***Time Dilation.*** *It means that, **relative to Bob**, moving clocks run more slowly than stationary ones.*

Einstein 3: Does time dilation occur in the real world? ***"Yes!"***

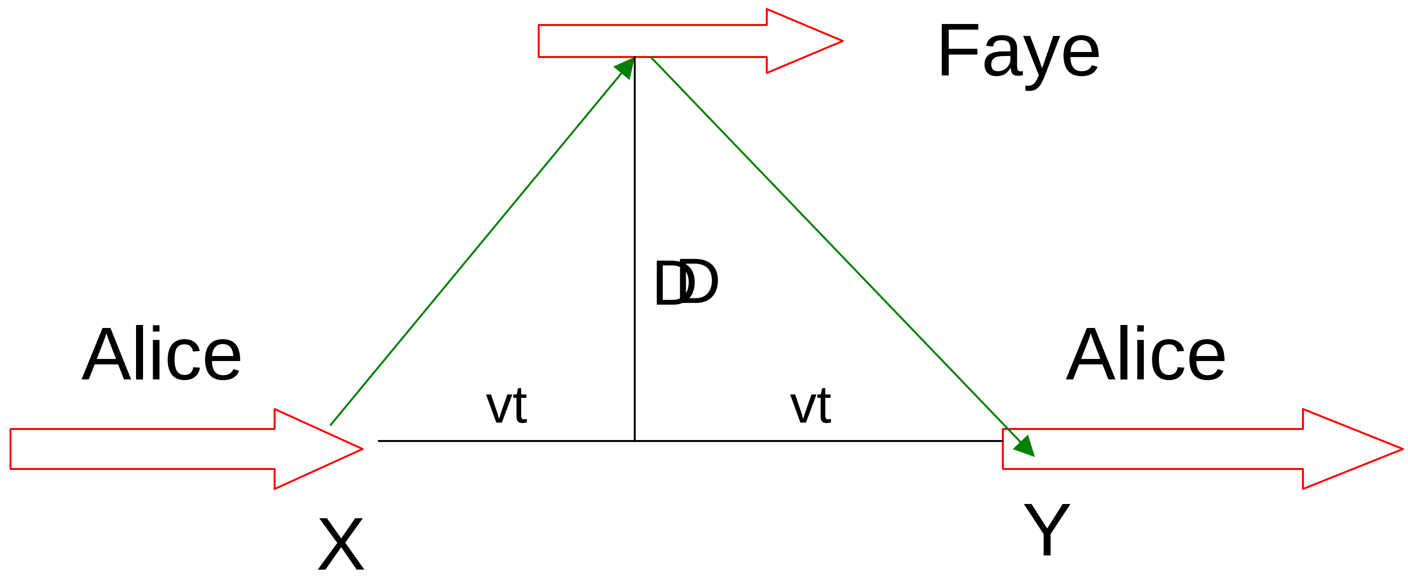
- ***One example is particles created by cosmic rays in the upper atmosphere which can penetrate a thousand meters or more below the surface of the Earth.***
- ***E.g. the muon which decays at rest in about 2 microseconds. At c, it could travel about 0.6 km. Because of time dilation, to us, it travels 10 km, or more!***

Decay of Atmospheric Muons



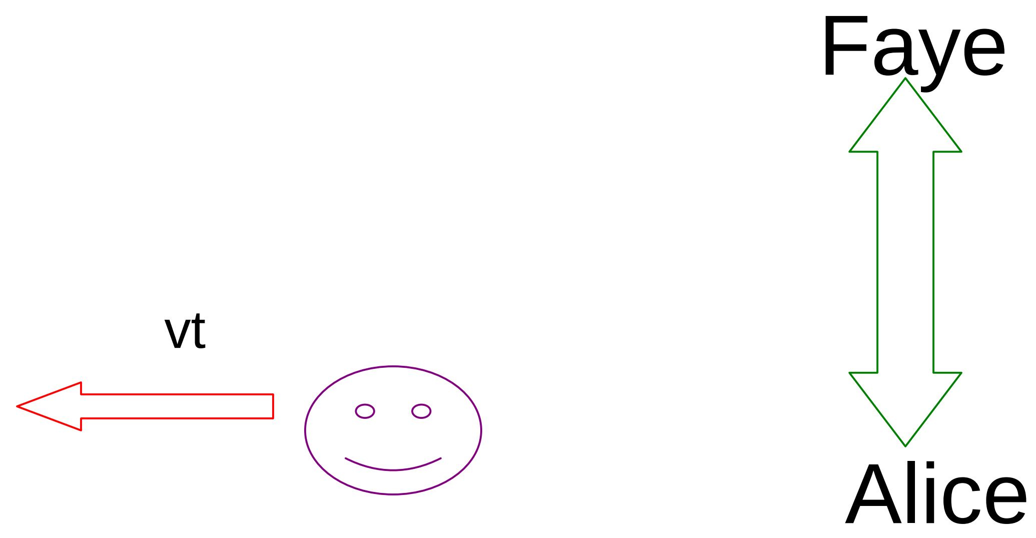
Length Contraction—the other side of Time Dilation 1

- ***Alice makes marks X and Y on Independence Avenue when laser signal comes back to her.***
- ***Bob at rest says distance from X to Y as 2vt(Bob)***



Length Contraction—the other side of Time Dilation 2

- From Alice's point of view, Bob is receding with speed v as she exchanges laser signal with Faye,



- Alice sees Bob recede distance v***t(Alice)***

Length Contraction—the other side of Time Dilation 3

- Bob, at rest with respect to X and Y, measures distance to be **L(Bob)=2vt(Bob)=2vγt(Alice)**
- Alice, moving with respect to X and Y, measures a **shorter distance** **L(Alice)=2vt(Alice)**
- This is length contraction, also called Lorentz contraction: **L(Alice)=(1/ γ) L(Bob) ≤ L(Bob)**

Length Contraction—the other side of Time Dilation 4

- **Important caveat**:
- Lengths parallel to relative motion appear contracted, but
- Lengths perpendicular to relative motion are not contracted.
- This can be shown by another "thought experiment"

What does Special Relativity do to Newton's Laws of Motion? 1

- We use Newton's Laws every day and at the speeds that humans can achieve (the fastest jet plane does well below 1 km/sec) they work exceedingly well.
- The basic law is:

Force = Rate of change of momentum

Momentum = mass X velocity

- Einstein Found he could preserve this law by making a simple change in the definition of mass and energy

What does Special Relativity do to Newton's Laws of Motion? 2

- Replace mass by $m = m_o \gamma$
- Define energy as $E = mc^2 = m_0 c^2 \gamma$
- For small velocities $E \approx m_0 c^2 + (1/2) m_0 v^2$ where $v << c$. Second term is kinetic energy.
- Whence the famous formula $E = mc^2$

Gravity: Newton's Problem

- *"That gravity should be innate, inherent, and essential to matter,* ***so that one body may act upon another, at a distance through vacuum, without the mediation of anything else, by and through their action and force may be conveyed from one to another, is to me so great an absurdity****, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it."*

Einstein had a Similar Problem

- ***How can the force of gravity be instantaneous if nothing can travel faster than the speed of light?***
- Other forces of Nature that we know are propagated by “mediator particles”:
  - The photon for electromagnetic forces
  - The gluon for strong nuclear forces
  - The W and Z bosons for “weak decay forces”

Einstein’s Inspired Insight—a man falling from the roof of a house!

- **Einstein:** *“Why is this force, gravity, different from all other known forces?*
- **His Answer:** *“There came to me the happiest thought of my life…if one considers an observer in free fall, for example from the roof of a house, there exists for him no gravitational field---at least in his immediate vicinity.”*
- You only “feel” gravity when the Earth pushes on you as your weight.

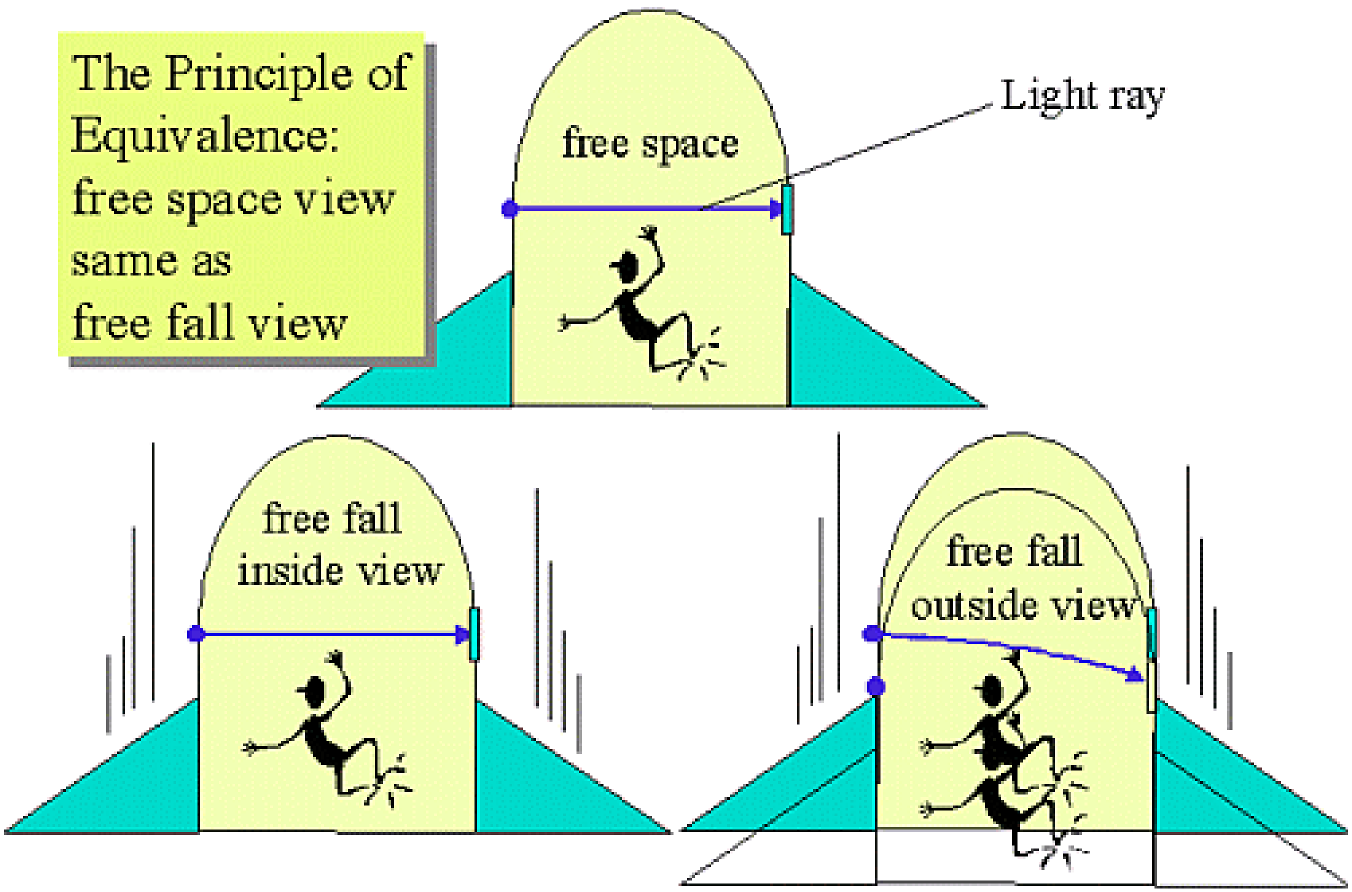
Einstein's Equivalence Principle 1

- ***All experiments will give the same results in a local frame of reference in free fall and in a local frame of reference far removed from gravitational influences.***
- This leads to gravitational effects on time and the curvature of space-time
- Relationship of gravity and acceleration

Einstein's Equivalence Principle 2

- Consider the figure below. In a rocket in free space (somewhere far away from stars and planets) a laser beam is emitted from one side of the rocket to a light detector on the opposite side. The astronaut sees the laser beam travel in a straight line from one side to the other. Now consider the same rocket in free fall near a planet. According to the equivalence principle the astronaut will again see the laser beam travel in a straight line across the cabin. So far, nothing strange! But now consider the same experiment viewed from the vantage point of someone who is at rest relative to the planet. The stationary

Einstein's Equivalence Principle 3



Einstein’s Equivalence Principle 4

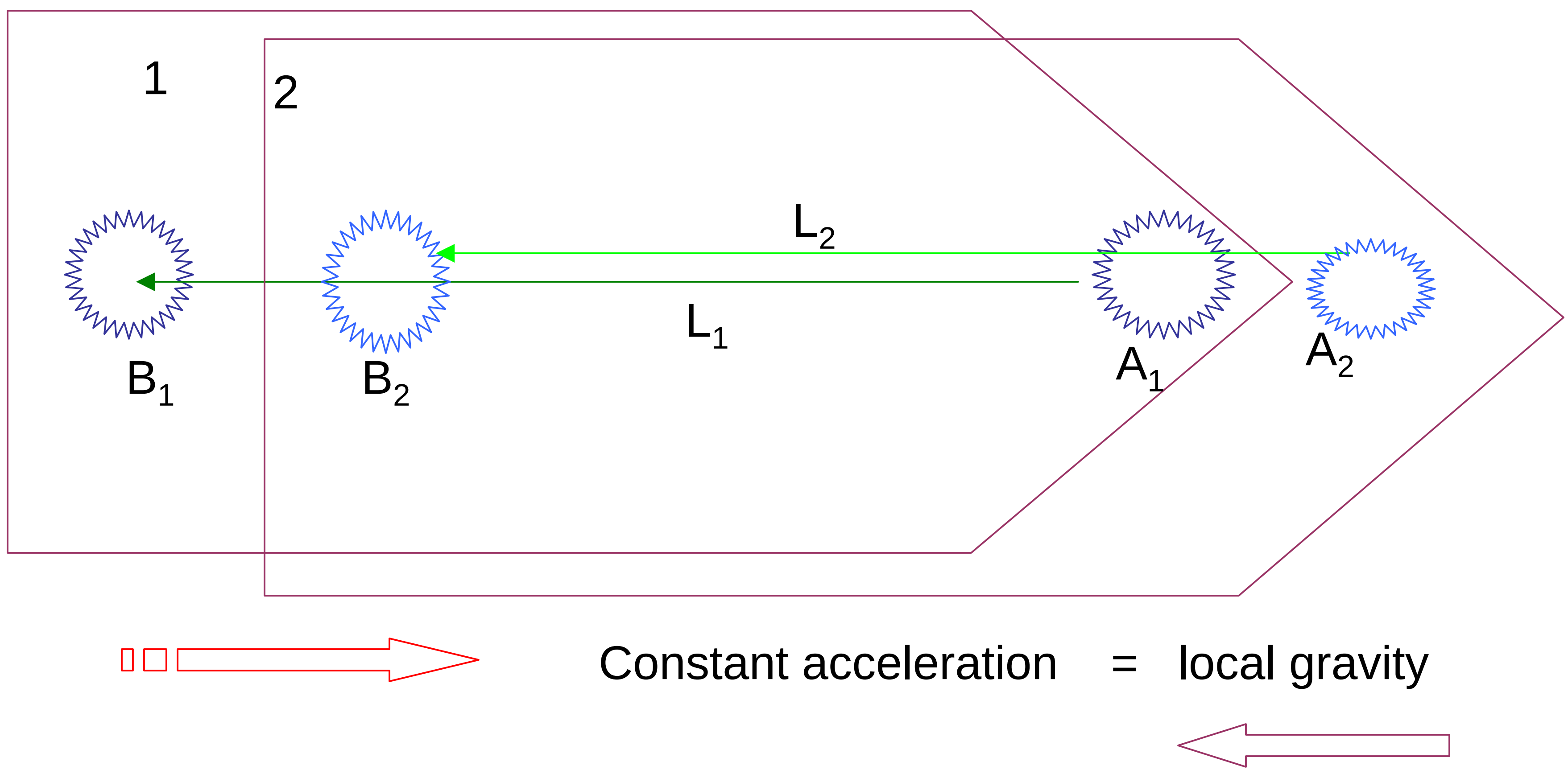
- observer also sees the event: *laser beam hitting the light detector*. (Events can't be changed just by changing your point of view!) But, by the time the light beam has crossed the cabin, the rocket and the light detector will have fallen a small distance. So the observer who is stationary with respect to the planet will see the laser beam follow a *curved path*.
- Since the stationary observer believes herself to be in a gravitational field (because she feels her weight) she will conclude that gravity bends light. Einstein assumed that light, nonetheless, travels in as straight a line as possible. The fact that light's natural motion is curved could be understood if the spacetime through which it traveled were itself curved. Similar reasoning led Einstein to the further conclusion that clocks in a gravitational field run slower than clocks far from gravitational influences. Einstein sought to explain these effects as consequences of natural (that is, unforced) motion in curved spacetime.
- Einstein's equations

Einstein's Equivalence Principle 5

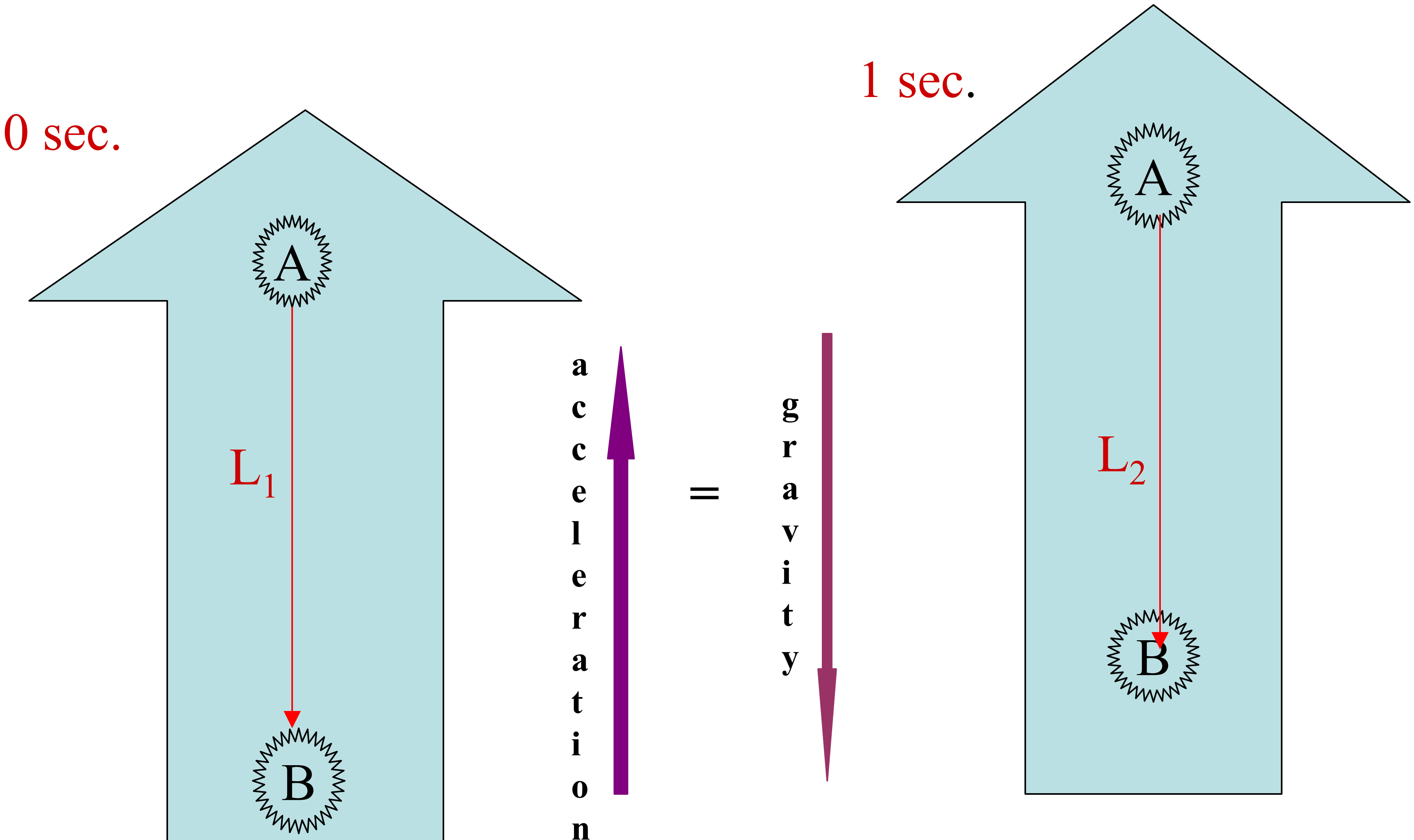
- After ten years of arduous intellectual searching, in 1915, Einstein succeeded, finally, in translating his profound physical intuition about Nature into a rigorous mathematical theory of free motion in curved spacetimes. Thus was born the **general theory of relativity.**

Time and Acceleration 1

- 1 is first laser flash, 2 is second



$L_1 > L_2$: clock A runs faster than clock B



Time and Acceleration 2

- Clock A emits first laser flash, which travels distance L_1 to Clock B
- Clock A emits second laser flash one second later, and travels distance L_2 to B
- Acceleration makes L_2 shorter than L_1 and to B the time between flashes is less than one second.
- Thus Clock A appears to run faster than Clock B.

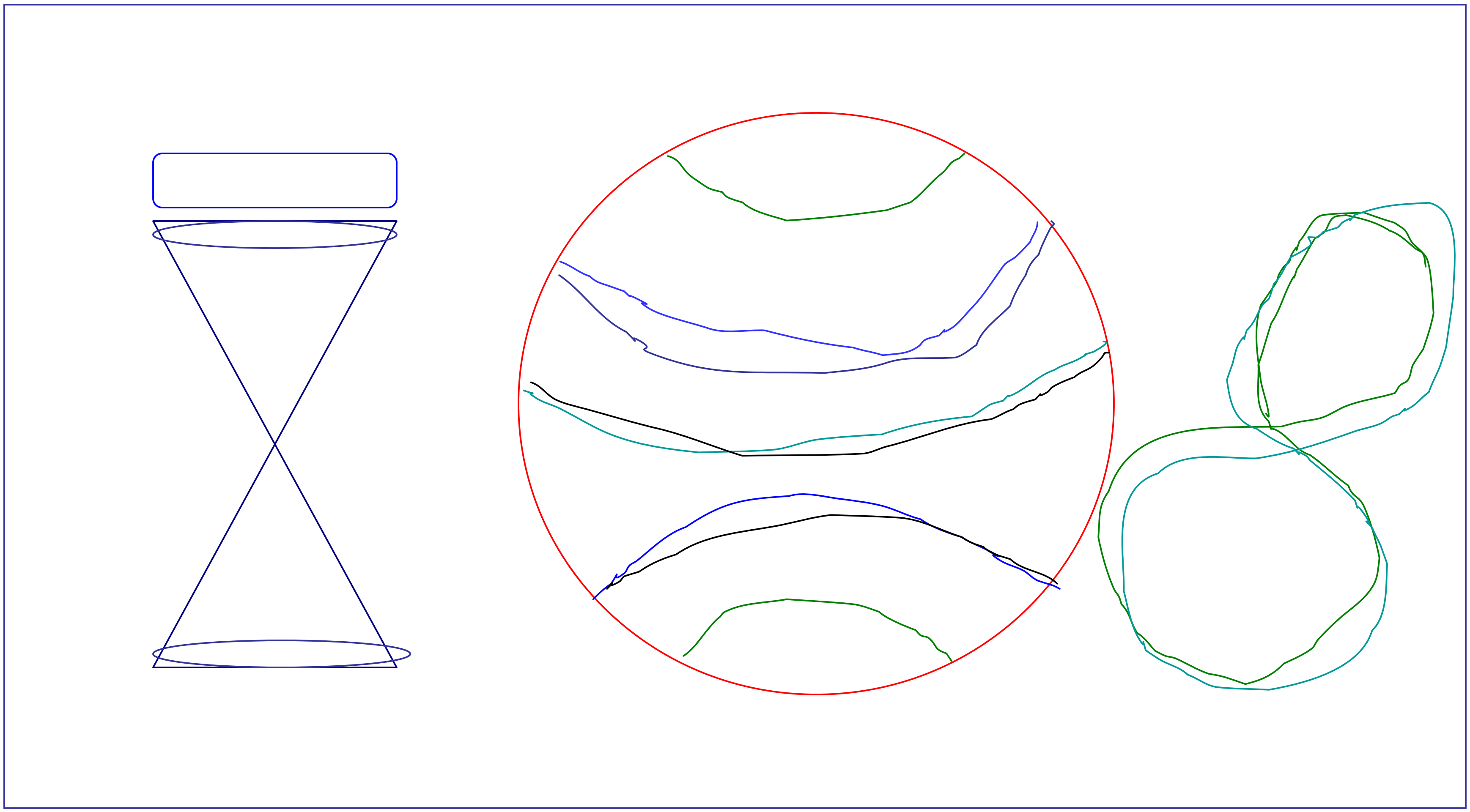
Time and Acceleration 3

- More generally, ***clocks in stronger gravitational field run slower than clocks in weaker gravitational field.*** Time stops altogether in a black hole.
- Demonstrated experimentally by Pound and Rebka at 21.6 m Jefferson Tower Harvard in 1960, and by flights of atomic clocks at 10,000m altitude
- Gravitational redshift of radiation from sources of intense gravity, such as black holes, quasars, pulsars etc.

Curvature of Spacetime

- Einstein interpreted these effects and the bending of starlight by the Sun as being due to the ***curvature of spacetime***. Light seeks the shortest path, but if spacetime is curved, the shortest distance us not a straight line.
- Examples of curved space---orbits around the Earth.

Curvature of Spacetime



Final Comment

- In his 1905 paper on Brownian Motion, Einstein gave conclusive support to the corpuscular view of matter over the view of matter as a continuous medium, the corpuscles being atoms, molecules, etc.
- In his 1915 General Relativity, he introduced spacetime as the medium in which we live.
- Question: Is Spacetime Corpuscular?

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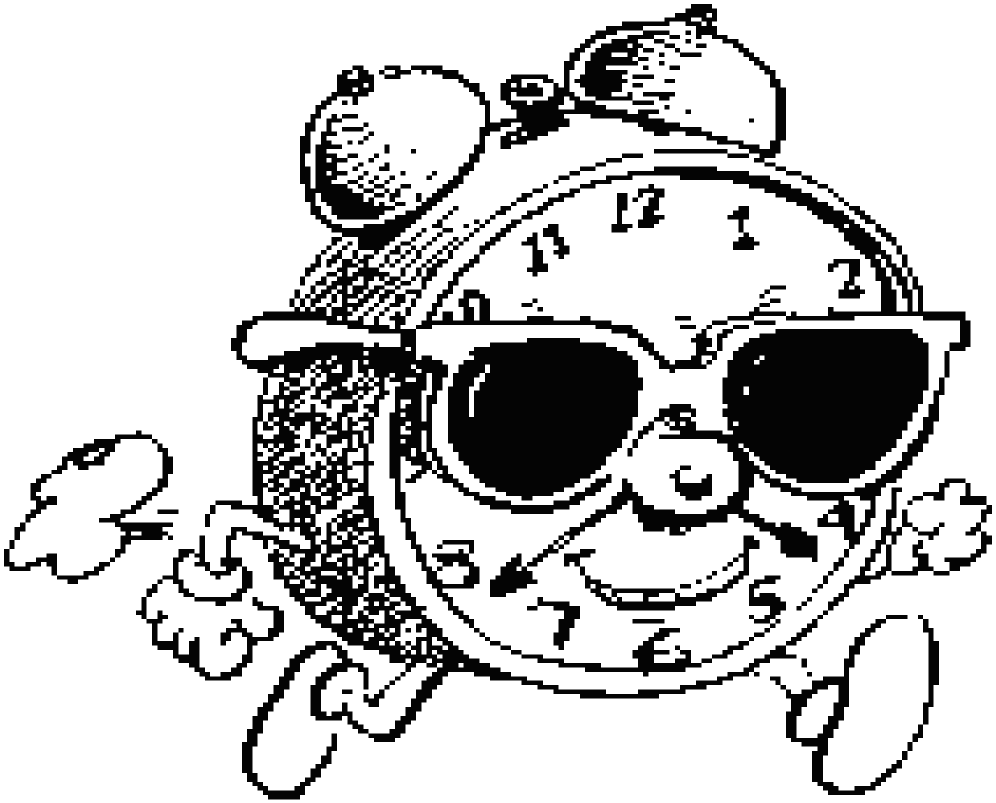

Moving clocks run slowly