Chapter 11

Relativity Theory

11.1 Homework

Readings – DV 22-23

Further readings:

- Albert Einstein *Relativity: The Special and the General Theory*: easy, clear, entertaining and ... cheap book written by Einstein himself.

- John Norton, *Eintein for Everyone*, ebook: `http://www.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/index.html`

Study Questions – Give a short answer to the following questions:

1. What are the three Newtonian core conceptual beliefs that the special theory of relativity (STR) shows to be mistaken?
2. What are the two postulates of the STR?
3. How are our notion of space, time and simultaneity modified in the STR?
4. What is an invariant? What were the invariants in Newton's theory? What is the invariant in the STR?
5. What are the two basic principles of the General Theory of Relativity (GTR)?
6. Explain how the principle of general covariance can be seen as a generalization of the principle of relativity?
7. What does the thought experiment about the elevator show? Compare with Galileo's thought experiment about the boat.
8. What evidence do we have to favor the GTR over Newton's theory of gravity?
9. DeWitt writes: "[...] Mars is simply moving in a straight line, but due to the curvature of spacetime, that "straight line" appears to be an ellipse about the sun". Explain

11.2 Introduction

The Newtonian worldview contains three conceptual beliefs: 1. Absolute Space

2. Absolute Time

3. Absolute Simultaneity

Holding these conceptual beliefs amounts to believe that the measures of length, duration and simultaneity are independent of the movement of the observer.

The Special Theory of Relativity (henceforth STR) shows that these beliefs are mistaken.

11.3 The Special Theory

Einstein and Relativity - Patent examiner in Bern: petty clerk but aware of most of the science of his time!

- Says he had been thinking about issues related to the theory since he was 16 – thought experiment: chasing the beam of light coming from the clock

- "On the Electrodynamics of Moving Bodies", June 1905

- His ideas come from:

1. Philosophical Reflexion

2. New evidence – Michelson and Morley experiment

3. Mostly: Foundations of Electro-magnetism

Einstein and philosophy of science : Importance of philosophy of science for developing freedom of thought – question the unquestionable: detect which facts may be "conceptual facts" . Here are a few quotations (taken from Don Howard, *Einstein's Philosophy of Science* in the Stanford Encyclopedia of Philosophy

> "Concepts that have proven useful in ordering things easily achieve such an authority over us that we forget their earthly origins and accept them as unalterable givens. Thus they come to be stamped as "necessities of thought," "a priori givens," etc. The path of scientific advance is often made impassable for a long time through such errors. For that reason, it is by no means an idle game if we become practiced in analyzing the long commonplace concepts and exhibiting those circumstances upon which their justification and usefulness depend, how they have grown up, individually, out of the givens of experience. By this means, their all-too-great authority will be broken. They will be removed if they cannot be properly legitimated, corrected if their correlation with given things be far too superfluous, replaced by others if a new system can be established that we prefer for whatever reason". (Einstein 1916 in a memorial note to Ernst mach, 106)

> It has often been said, and certainly not without justification, that the man of science is a poor philosopher. Why then should it not be the right thing for the physicist to let the philosopher do the philosophizing? Such might indeed be the right thing at a time when the physicist believes he has at his disposal a rigid system of fundamental concepts and fundamental laws which are so well established that waves of doubt can not reach them; but it can not be right at a time when the very foundations of physics itself have become problematic as they are now. At a time like the present, when experience forces us to seek a newer and more solid foundation, the physicist cannot simply surrender to the philosopher the critical contemplation of the theoretical foundations; for, he himself knows best, and feels more surely where the shoe pinches. In looking for a new foundation, he must try to make clear in his own mind just how far the concepts which he uses are justified, and are necessities. (Einstein 1936, "Physics and Reality", 349)

> "I fully agree with you about the significance and educational value of methodology as well as history and philosophy of science. So many people today – and even professional scientists – seem to me like somebody who has seen thousands of trees but has never seen a forest. A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is – in my opinion – the mark of distinction between a mere artisan or specialist and a real seeker after truth." (Einstein to Thornton, 7 December 1944, EA 61-574)

Einstein's view on the philosophy of science are still a matter of controversy among historians. That said, He was aware of Duhem's work on the underdetermination of theories by evidence.

Theories of Light around 1900 :

The rise of wave theories :

- Newton: corpuscular theory of light.

- Fresnel: Wave behavior of light

Wave behavior :

1. Interference – See Figure 11.1

2. Diffraction – see Figure 11.2

A consequence: Poisson vs. Arago on the black spot

The Ether :

1. The medium through which light waves move: natural assumption. That said, problematic properties:

- Because light propagates very fast, the ether must be extremely rigid

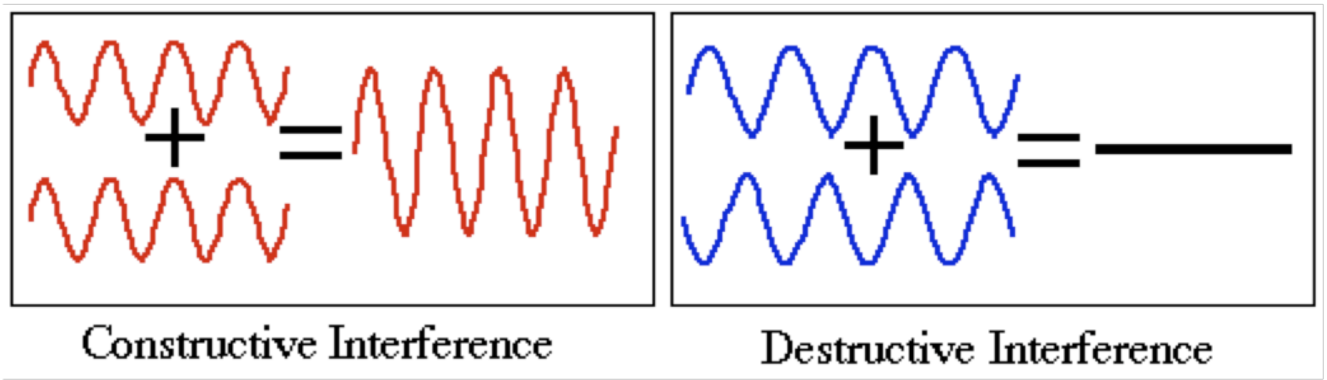

Figure 11.1: Wave Behavior: Interefence (from Prof. DiSalle)

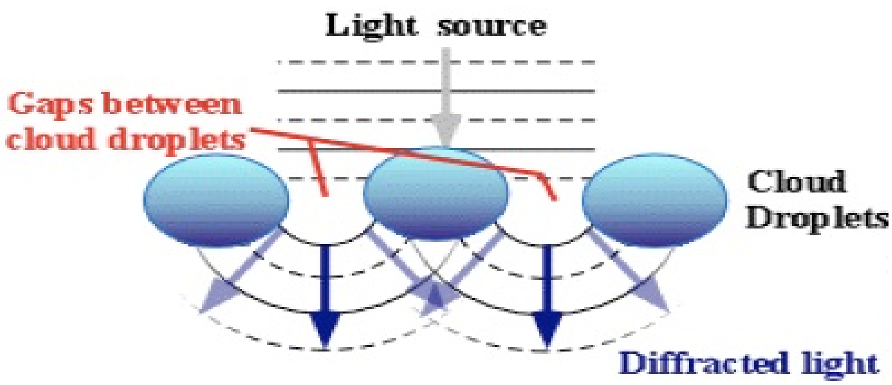

Figure 11.2: Wave Behavior: Diffraction (from Prof. DiSalle)

- Because light goes everywhere, the ether must be extremely tenuous

Hard to conceive !

2. Helps in Mechanics as well: Field theories vs. Newtonian's action at a distance – The gravitational force is but the manifestation of a preexisting state of the space: the gravitational field. Gravitational attraction is everywhere, all the time, as a *disposition*. It manifest itself under the appropriate circumstances.

Definition 19 – ***Disposition***

A disposition *is a property which manifest itself only under specific circumstances.*

Example: Fragility

Velocity of light and Ether :

- The velocity of light is considered a constant *with respect to the ether*

- Otherwise, the velocity of light satisfies *the law of the addition of speed*: the velocity measured by an observer O should depend on the O's velocity with respect to the ether

See Figures 11.3, 11.4, 11.5, 11.6

Michelson and Morley – 1887 – See Figure 11.7, 11.8

Given the above, it should be clear that a sufficiently precise measurement should allow for measuring the movement of the earth through the ether, in measuring the difference in the speed of light.

The result of the historical experiment: no difference in speed!!

What could have gone wrong ???

Lorentz' contraction :

- The only thing that could have gone wrong is our apparatuses...

- We measure speed in measuring :

1. length
2. time

$$v = l/t \longrightarrow t = l/v$$

Lorentz:

- We need a difference in speed

- There is no difference in time

- It must be because of differences in length

$\longrightarrow$ *All bodies contract when moving through the ether – Hence, there is no way to detect the movement of the earth through the ether with our apparatuses!*

Note that this is not as crazy as it seems: if the ether is the milieu of electromagnetic waves, and if electromagnetic waves are what brings material bodies together, then it is no surprise that the constitution of bodies varies when they are moving through the ether.

Einstein will have a different interpretation: the speed of light is a constant but simultaneity is relative

Two postulates :

1. **Speed of light** is constant – 186,000 miles per second / 300,000 km/s

While it is a law in Maxwell's theory, Einstein takes it as a postulate in STR.

2. **Principle of Relativity**: the law of physics are the same in *all inertial frames*

Frame of reference: the reference to our measure (Earth, Laboratory etc). We usually define a coordinate system in the frame of reference

Inertial Frames: all frames of references in uniform rectilinear motion respective to one another: *everything except accelerated frames*

Are these two postulates consistent? – Not as easy as it would seem: the constant speed of light vs. the law of addition of speed:

- Take someone on a spaceship shooting a beam of light: according to the law of addition of speed, the light should go faster for an observer floating at rest in space.

- But then there would be a way in which we can distinguish between rest and uniform rectilinear motion, which is forbidden by the Principle of Relativity!

- SO: fundamental changes are needed if we want to make the two postulates consistent.

Consequences on space, time, and simultaneity :

1. **Time dilation** :

   A moving clock slows down (twin paradox): or else... we would have a means to distinguish between rest and uniform rectilinear motion

   John Norton's light clock – perpendicular to motion – see how time slows down (more to cover) – See Figure 11.9

2. **Space Contraction** :

   Similarly, take the light clock moving horizontally: the clock must shrink or else.... we would have a means to distinguish between rest and uniform rectilinear motion

   Indeed, put two clocks together (one horizontal, one veritcal) : they must "tick" at hte same rate. The problem is that, when the clocks are moving, the beam of light has to chase the other side of the clock... it should take a very long time to get there!

   Solution: the horizontal clock shrinks (Figures 11.10, 11.11, 11.12)

3. **Relativity of Simultaneity** : (harder to get) inertial observers (observers on inertial frames) disagree as to the timing of distant events

   Same reasoning again: Something must change, or else we have a means to distinguish between rest and uniform rectilinear motion

   Figure 11.13 : The platform

   - Jim on the platform at rest, Linda on the side, moving toward the left
   - From Jim's the point of view: the two flashes are simultaneous: *Note that Jim judges that two events are simultaneous when we receive the light beams at the same instant*
   - From Linda's point of view, the two flashes must also arrive on Jim at the same time (otherwise...)
   - The problem is : from Linda's point of view, the platform moves, and hence the beam coming from the left has a greater distance to cover ! How can both beams reach Jim at the same moment if they are going at the same speed???
   - The solution: the beam from the left has left *earlier* than the beam from the right. That is, the flashes *were not simultaneous.*

   $\longrightarrow$ *Whether or not two distant events are simultaneous depend on whether or not you are moving*

Figures 11.14, 11.15 : Simultaneity in Spacetime

How do I measure when a distant event occurs?

- Send a light beam, receive it back: the event occurred in the middle

- Seeing in spacetime, you see that whether you move or not influence the time at which a distant event occurs.

11.4 General Relativity

Basic Principles – two basic principles

1. **The principle of covariance** :

   - generalized version of the principle of relativity (= the laws of physics are the same in all inertial frames)

   - i.e.: the laws of physics are the same in all reference frames *even accelerated ones*

2. **The principle of equivalence** : equivalence between gravity and acceleration, that is:

   - The effects of gravity vs. acceleration are indistinguishable

   - Thought Experiment: elevator – See Figures 11.16, 11.17

   - Another way to say it: inertial mass and gravitational masses are of the same kind

$$F = ma$$

$$P = mg$$

$$a = g$$

   You have never wondered whether m was referring to the same thing in both equation??

   Einstein puts it as a postulate

Accurate Predictions :

1. Recession of Mercury's perihelion : See Figure 11.18

2. Red Shift: light moving away from strong gravitational fields (like a star, the Sun for example) is shifted to red

A new view of spacetime : curvature of spacetime – See Figures in the book p. 229

- magnet: the notion of field lines

- Gravity: curvature of spacetime

Geodesics : the shortest way to go is not a straight line in the sense we understand it

- Billiard ball or golf experiment

- same thing in space ! Light around the sun

Consequence for gravity – gravity is not real : the curvature of spacetime is.!

11.5 Conclusion

The STR teaches us that there are:
- no absolute facts about what is moving (inertial movement) and what is at rest
- no absolute facts about length and duration (rods and clocks)
- no absolute fact about simultaneity and synchronization

What remains invariant?
- Speed of light
- Spacetime interval – "distance" in spacetime

The GTR:
- Curvature of spacetime
- Gravity is not real

Alright then, we have to change many of our favored beliefs. This means that, even within modern physics, we have shifts in worldviews. We have talked a lot of the impact of the existence of such shifts regarding the possible *truth* of scientific theories. Next chapter is about how this impacts the notion of scientific progress.

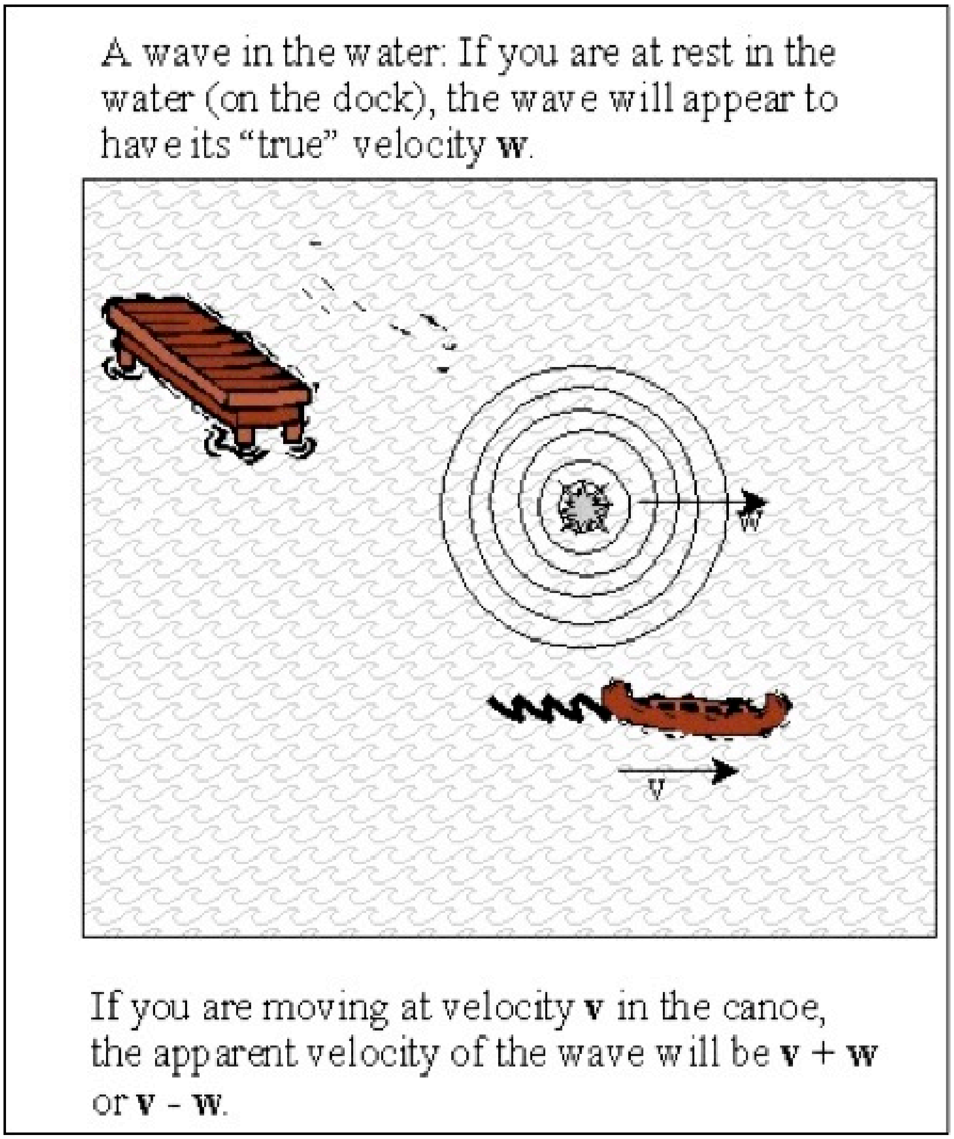

Figure 11.3: Chasing waves: the addition of velocity in water(from Prof. DiSalle)

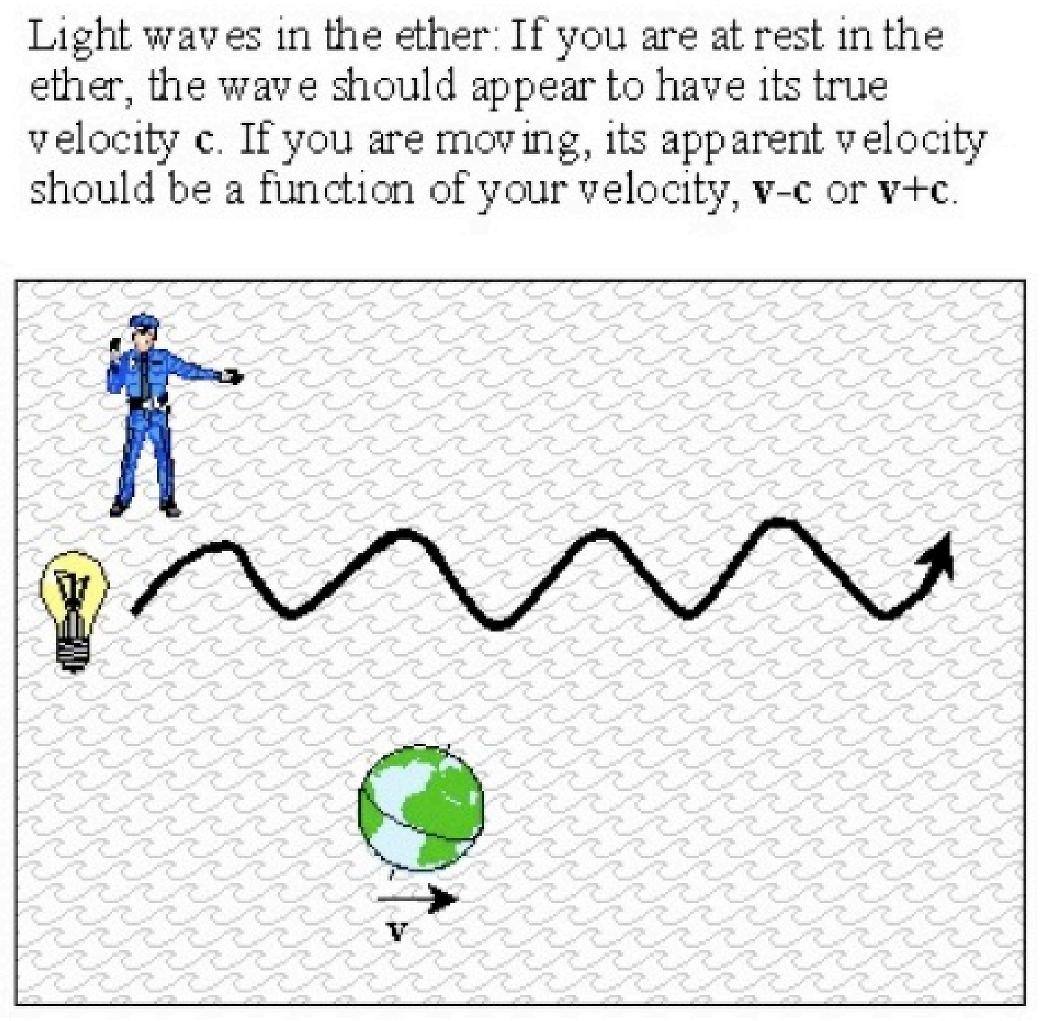

Figure 11.4: Chasing waves: the addition of velocity in ether (from Prof. DiSalle)

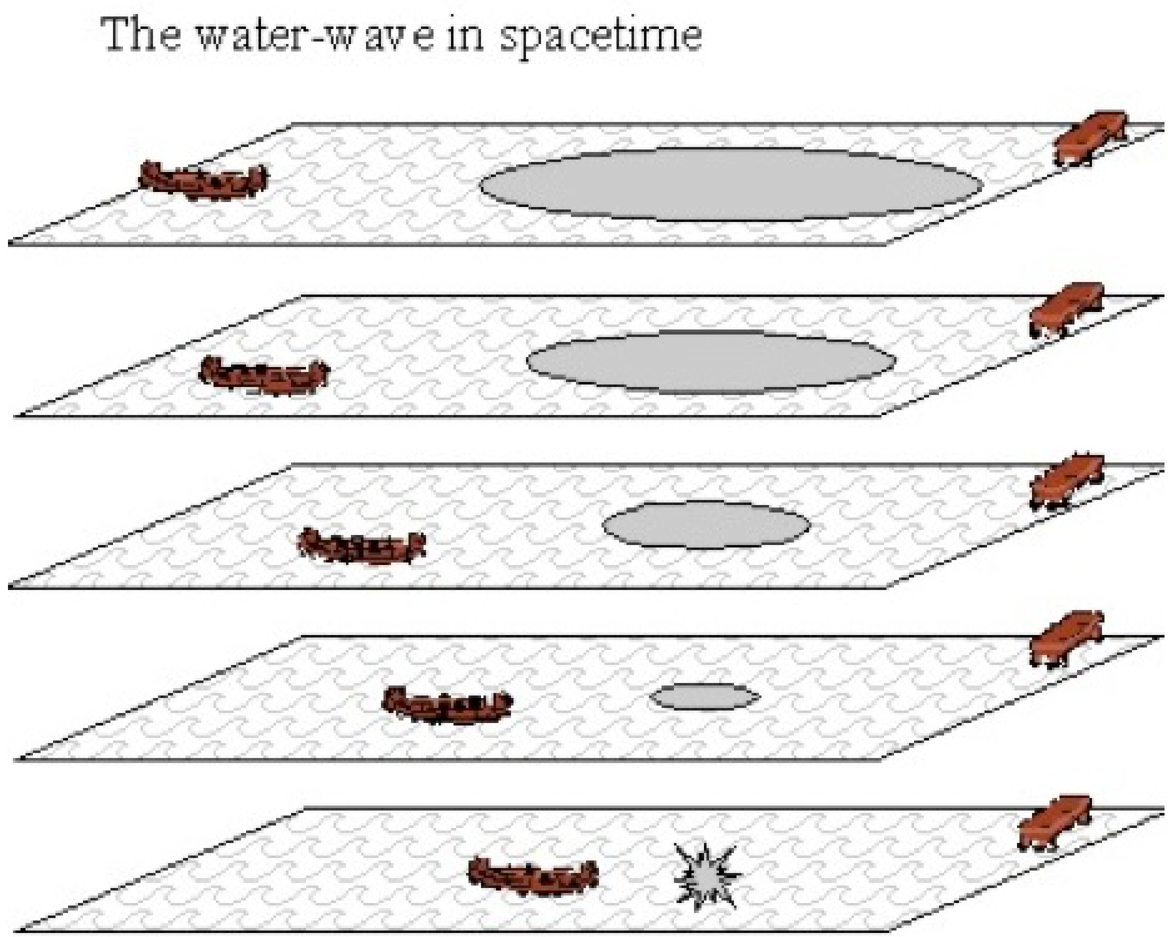

Figure 11.5: Chasing waves: the addition of velocity in water – in spacetime (from Prof. DiSalle)

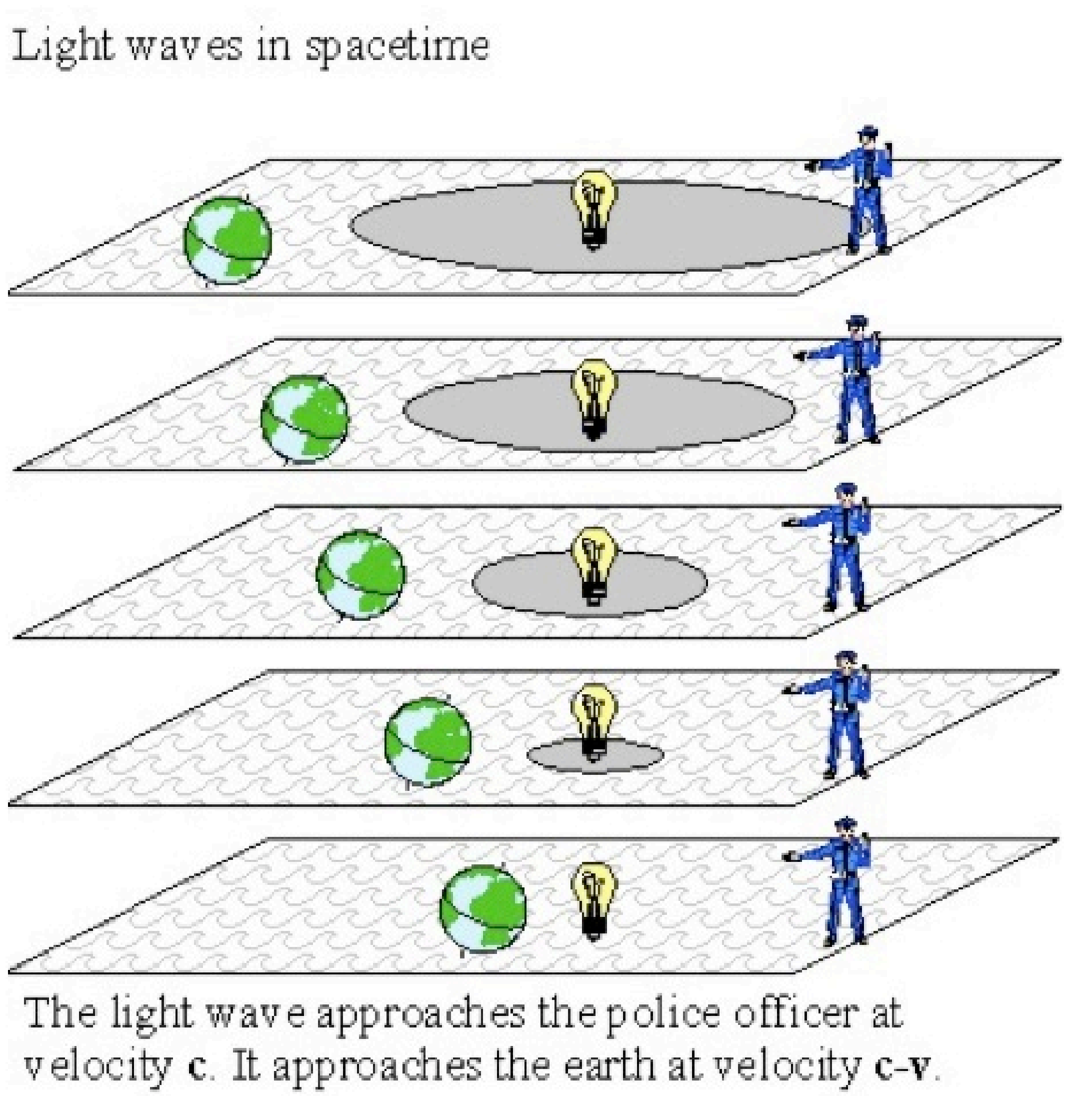

Figure 11.6: Chasing waves: the addition of velocity in ether – in spacetime (from Prof. DiSalle)

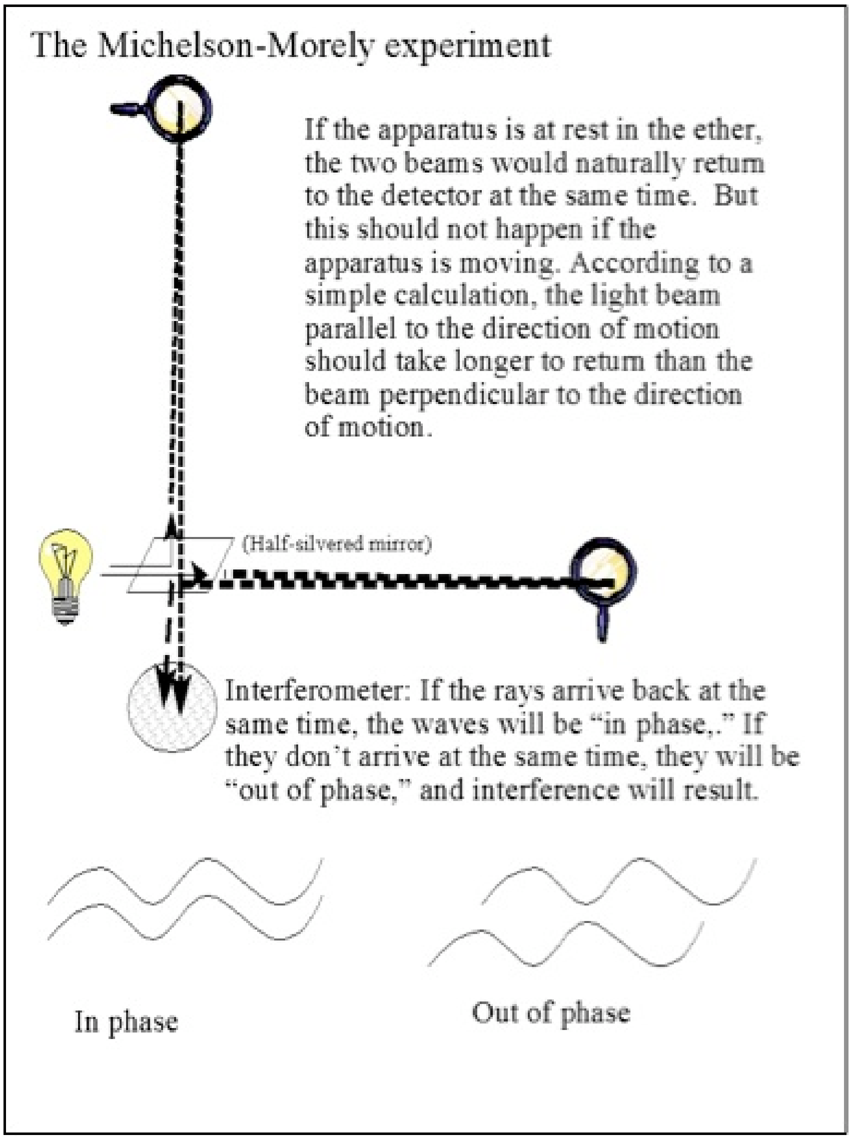

Figure 11.7: Measuring the ether wind – Michelson and Morley (from Prof. DiSalle)

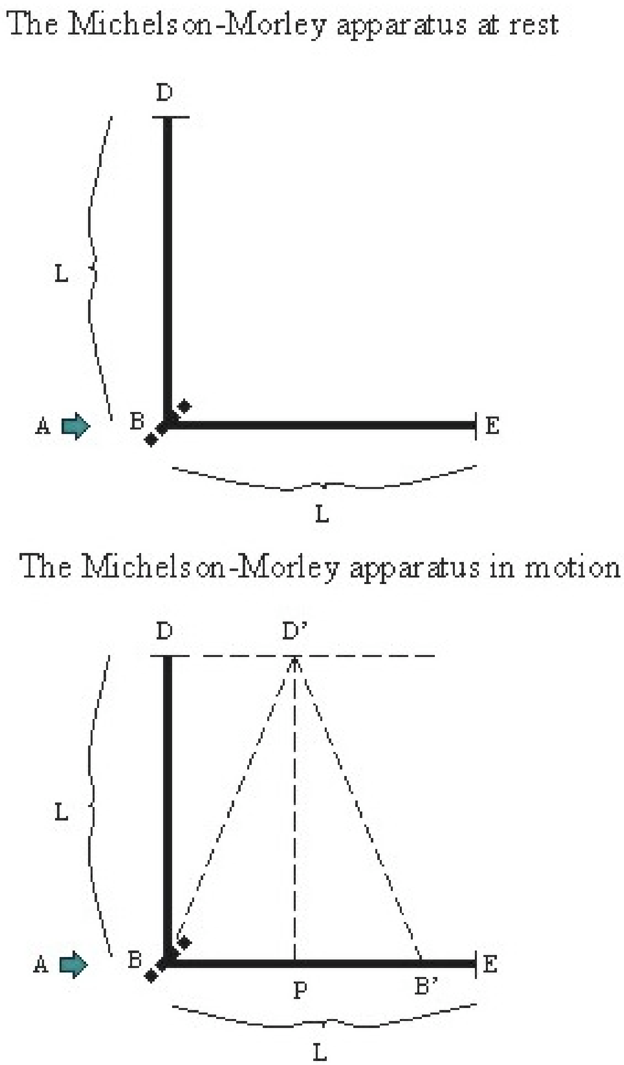

Figure 11.8: Measuring the ether wind – Difference in speed (from Prof. DiSalle)

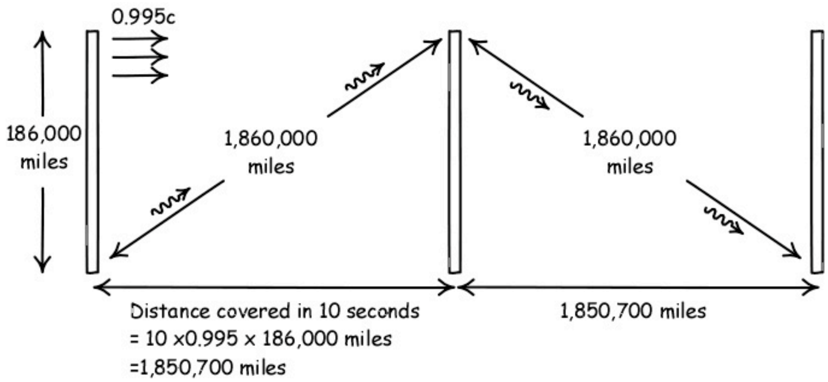

Figure 11.9: A light clock (From John Norton)

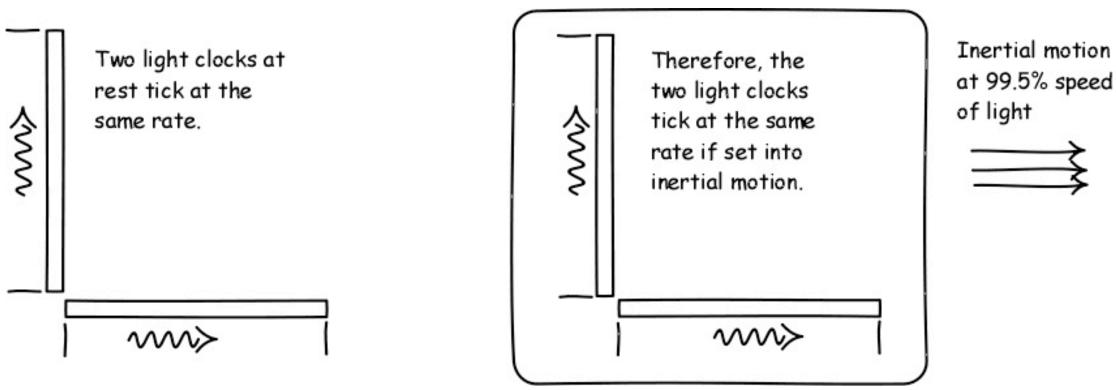

Figure 11.10: Two clocks (From John Norton)

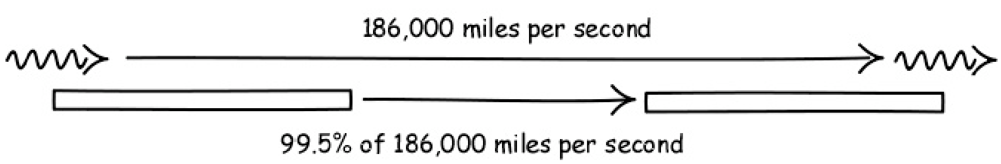

Figure 11.11: horizontal clock (From John Norton)

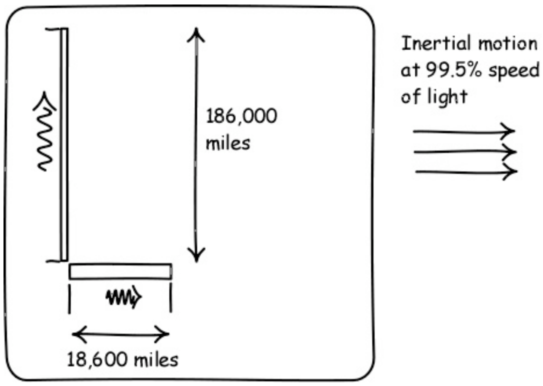

Figure 11.12: Two clocks contracted (From John Norton)

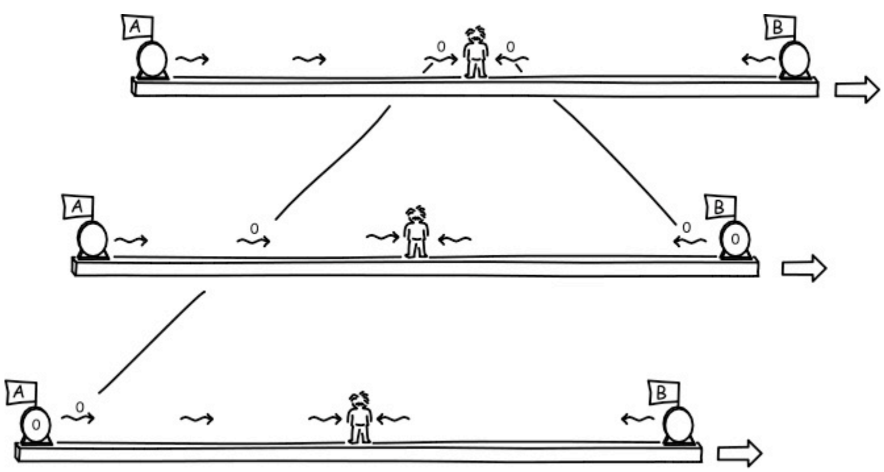

Figure 11.13: Relativity of simultaneity (From John Norton)

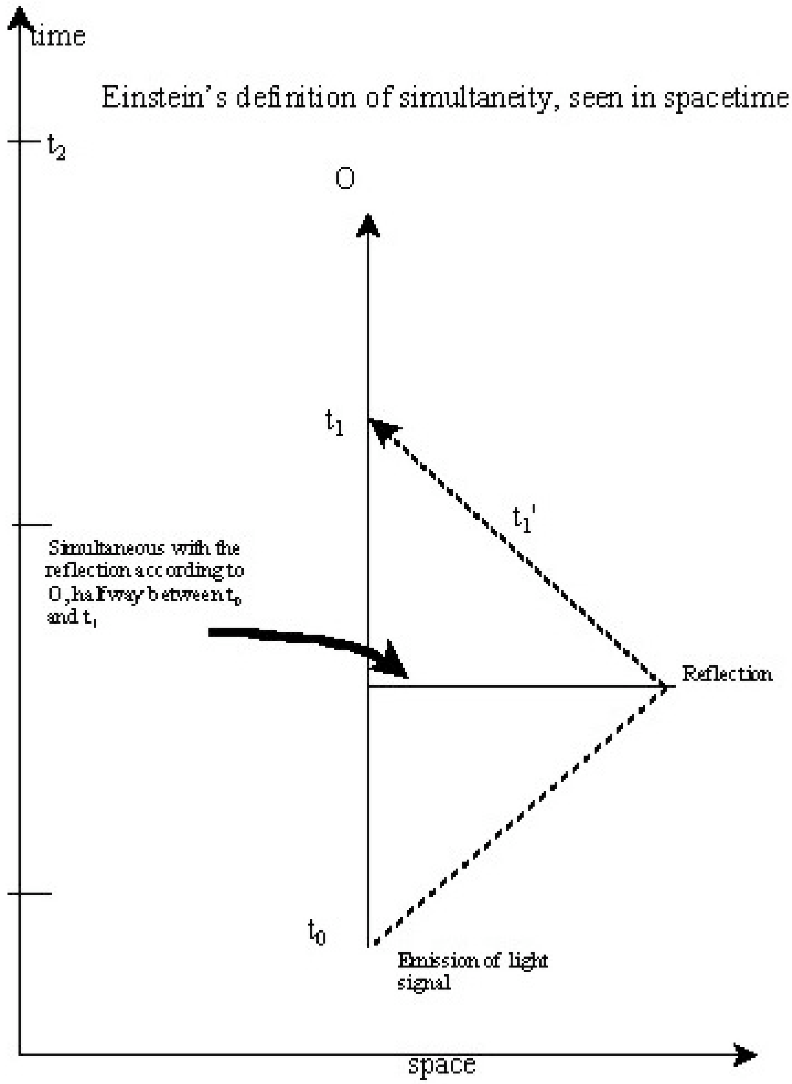

Figure 11.14: Simulaneity in spacetime (From Robert DiSalle)

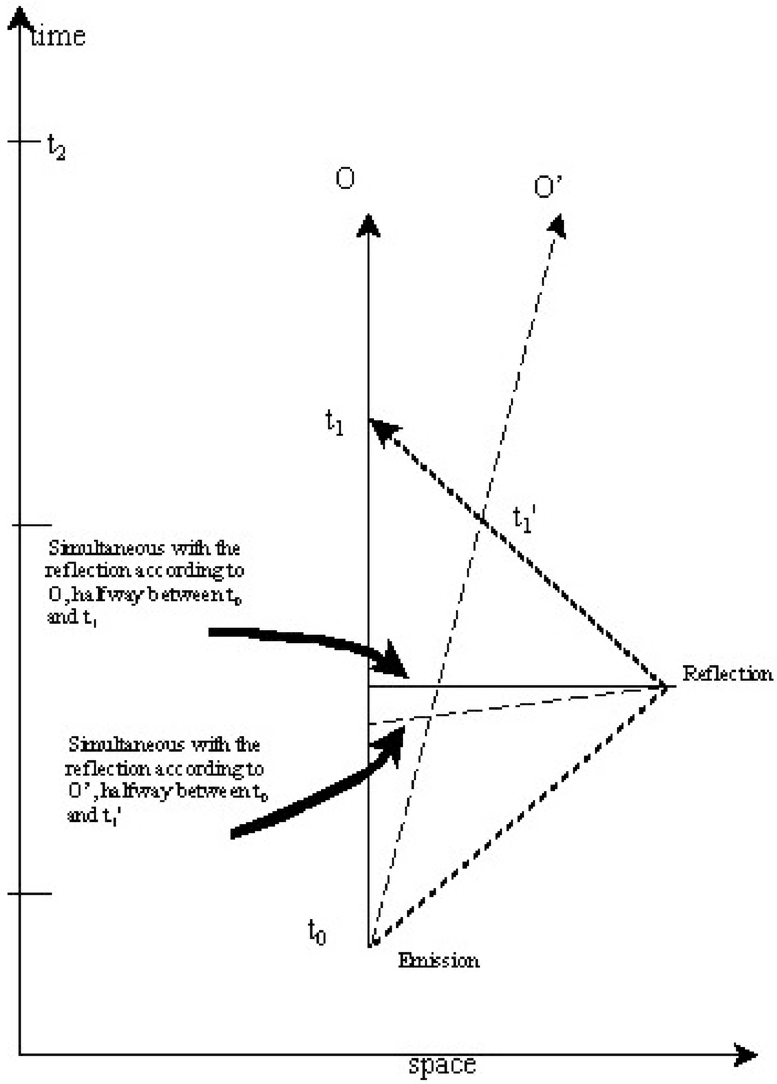

Figure 11.15: Relativity of simulaneity in spacetime (From Robert DiSalle)

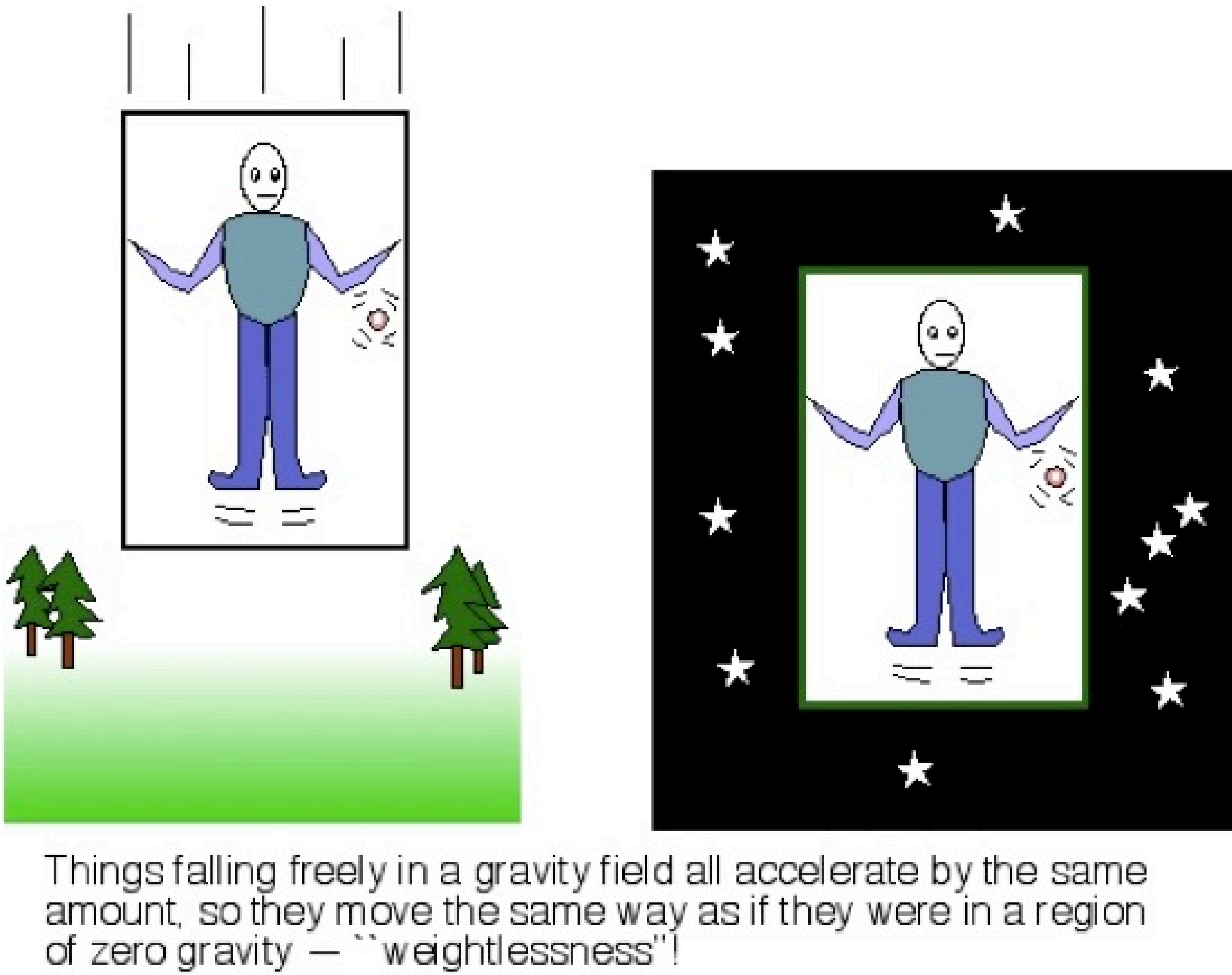

Figure 11.16: The elevator experiment: Free Fall (From Robert DiSalle)

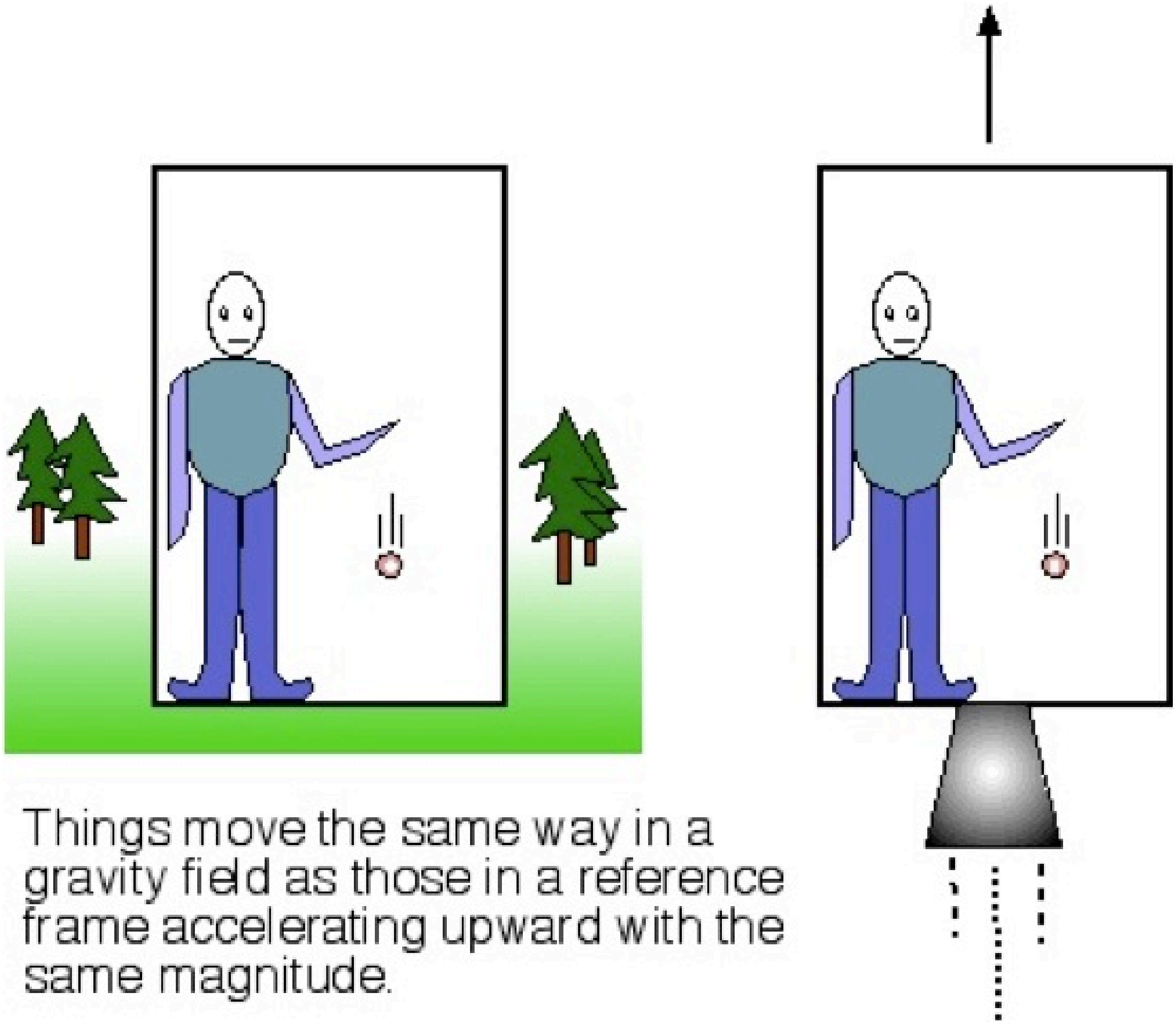

Figure 11.17: The elevator experiment: Gravity (From Robert DiSalle)

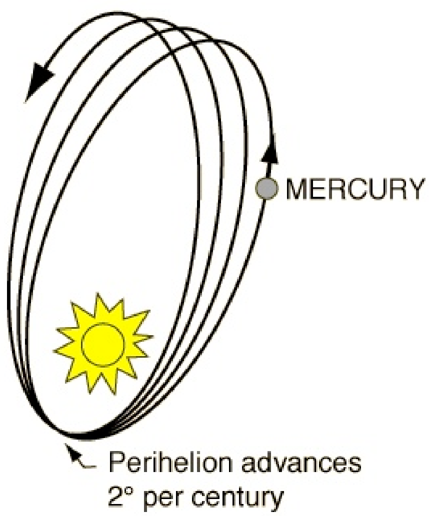

Figure 11.18: Recession of Mercury's perihelion (From hyperphysics website)