Teaching the Equivalence Principle through a combination of real life experiments and computer simulations

Efstratios Kapotis [1] and Panagiotis Tsakonas [2]

[1] National and Kapodistrian University of Athens, dept. of Phyiscs; ekapotis@phys.uoa.gr

[2] University of Pireaus, dept. of Informatics; ptsakon@unipi.gr

1.1. Necessity

- The Equivalence Principle was of major importance in the formulation of the General Theory of Relativity [1].
- Its role is equally significant in teaching Relativity [2].
- Authors present the EP early, emphasizing that a free fall is equivalent to inertial motion.
- Used also as a means of interpreting
  - light bending,
  - time dilation in gravitational fields
  - gravitational redshift

1.2. Literature review

- Researchers suggest that the EP, its consequences and the thought experiment of the elevator suffice to familiarize students with the scientific and cultural value of the GR [4].
- They also propose the introduction of thought experiments [5].
- The PE is the subject of real-life or thought experiments proposed.
- To ease the connection with "great ideas" of Relativity experimentation is combined with computer simulation software [6].
- Students face difficulties due to pre- and misconceptions [8][9][10].

2. Methods

- We present and evaluate the combination of traditional experimentation in the classroom with educational simulations used to teach the EP.
- The evaluation of an improvised experimental device used for experimentation in the classroom [11] showed positive impact on learning, but students still face a number of limitations.
- Appropriate simulation software was developed and combined with experimentation.

2.1. Research question

Does the use of original demonstrative experimentation using simple means paired with interactive computer simulations, incorporating control of variables that, according to research, pose difficulties to students in reference to the EP, promote positive learning outcomes of a higher level compared to those accomplished by usual ways of teaching?

2.2. Objectives

Our educational proposal and intervention aims at:

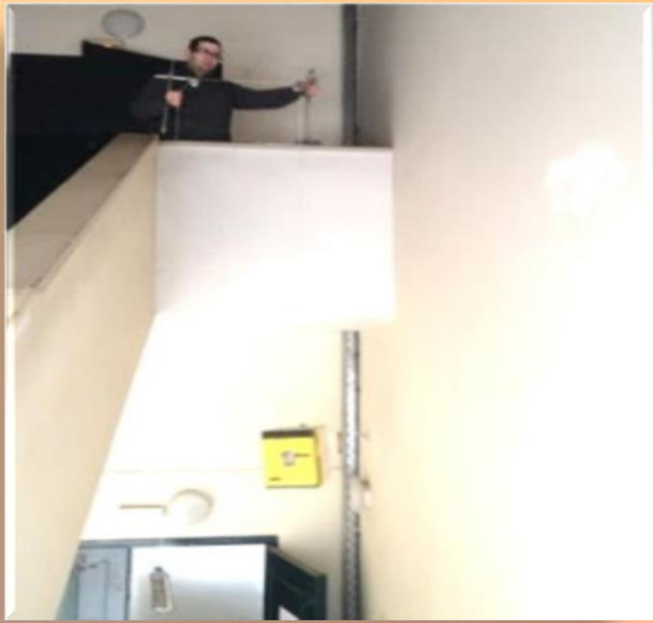
- creating digital simulations which complement traditional experimentation, in order to facilitate students' understanding, while being suitable for use in every modern device,
- composing an educational sequence – worksheet which utilize digital teaching tools (video, images, sounds, text open for concurrent processing, hyperlinks, digital evaluation tools),
- conducting and evaluating a teaching intervention based on the proposed experimentation.

2.3. Creating experiments

Original improvised elevator using a cardboard box.

Materials needed to assemble the device

Elevator in free fall.



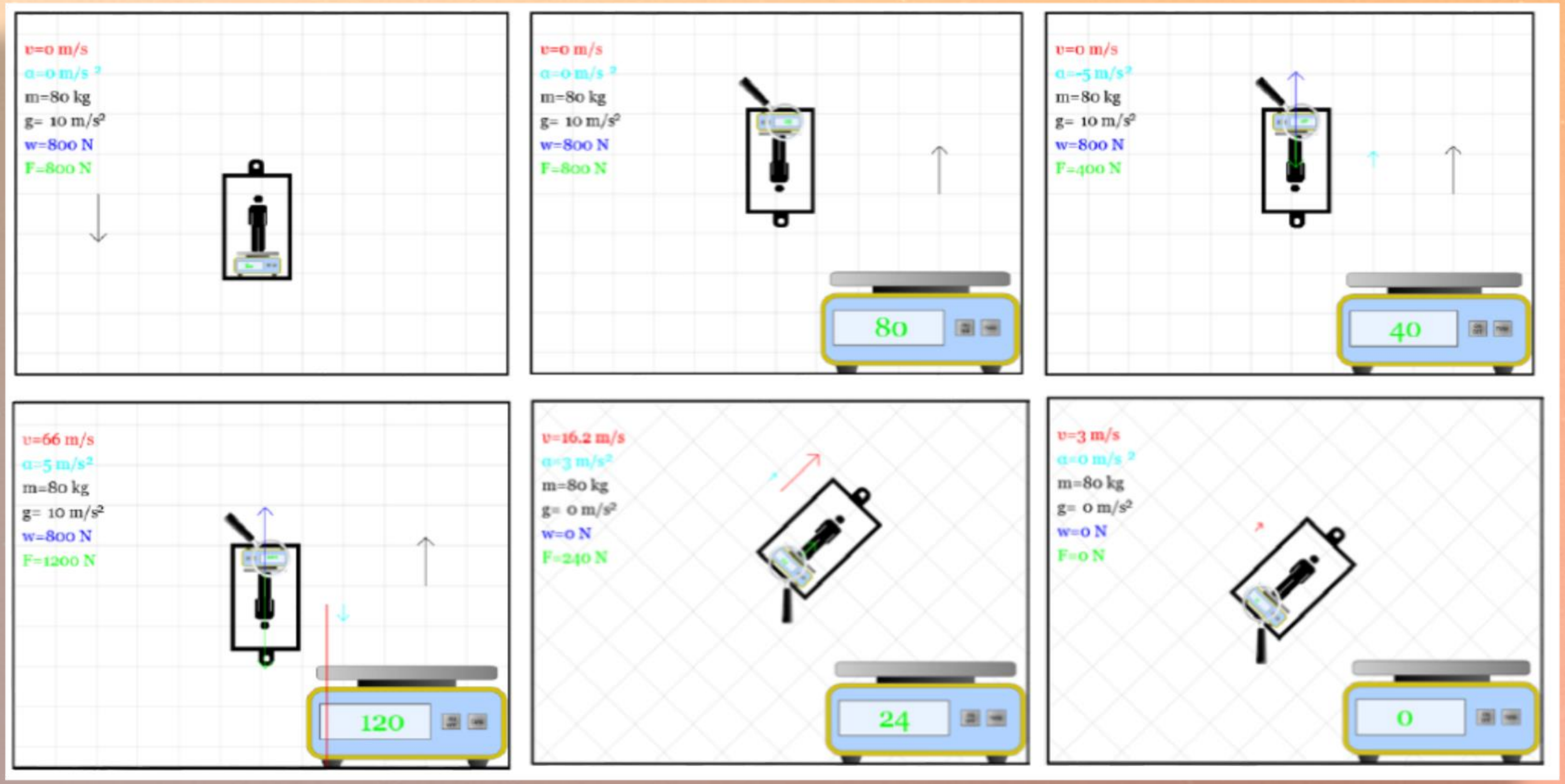
Elevator moving upwards at constant acceleration

Spring scale measurement during free fall equaling 0N, 0g, while a 100g body is suspended from the spring’s free endpoint.

DEVICE LIMITATIONS: Inability to perform measurements for various directions of movement and/or outside gravitational fields

2.3. Creating experiments – Overcoming limitations

Extend experimentation situations through the use of appropriate interactive simulation software.



2.4. Digital environment and worksheet

Interactive web page, embedding:

- experimentation
- simulations,
- images and videos, used to trigger students’ interest,
- interactive co-authoring documents used to record assumptions, measurements, conclusions and generalizations

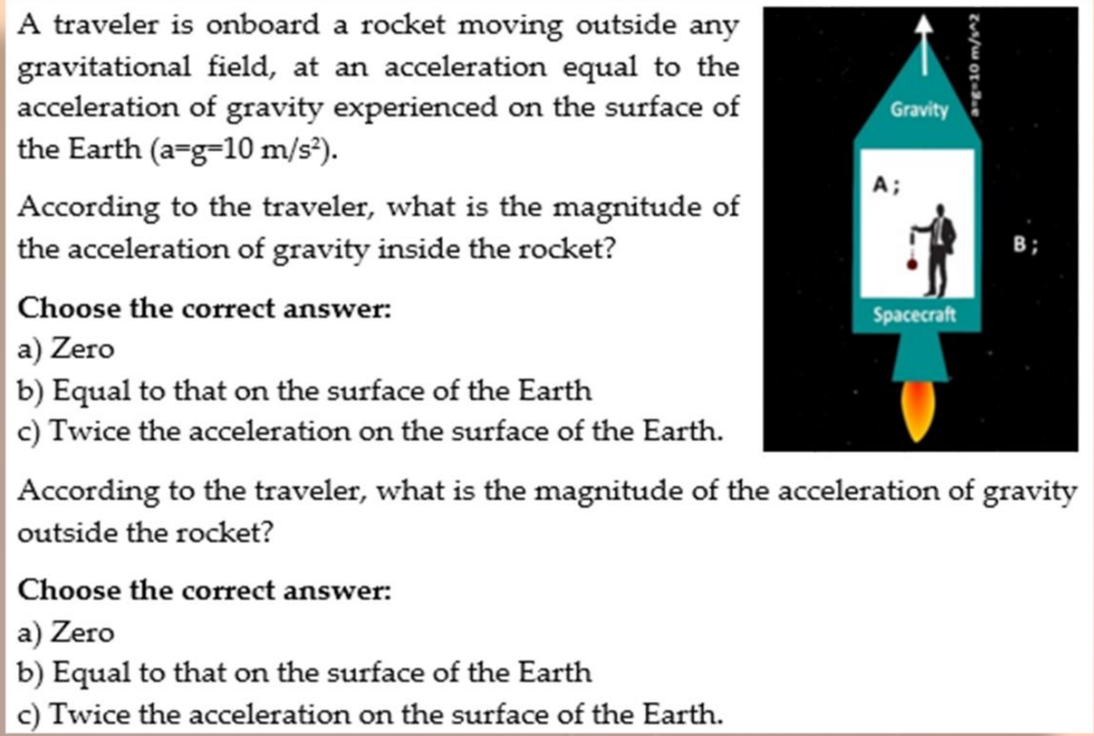
Weightlessness in free fall flight, designs for future space stations recreating gravity through acceleration

Instructions on constructing an improvised “Einstein elevator - box”

The educational stages of the worksheet are the ones proposed in the Scientific / Educational Method by Inquiry [12].

2.5. Research Sample and Evaluation tool

- 120 (19 male and 101 female) undergraduate students of the Department of Primary Education of the University of Athens (not majoring in Physics).
- Questionnaire consisting of five multiple choice questions



A traveler is onboard a rocket moving outside any gravitational field, at an acceleration equal to the acceleration of gravity experienced on the surface of the Earth ($a=g=10\ m/s^2$).

According to the traveler, what is the magnitude of the acceleration of gravity inside the rocket?

Choose the correct answer:

a) Zero

b) Equal to that on the surface of the Earth

c) Twice the acceleration on the surface of the Earth.

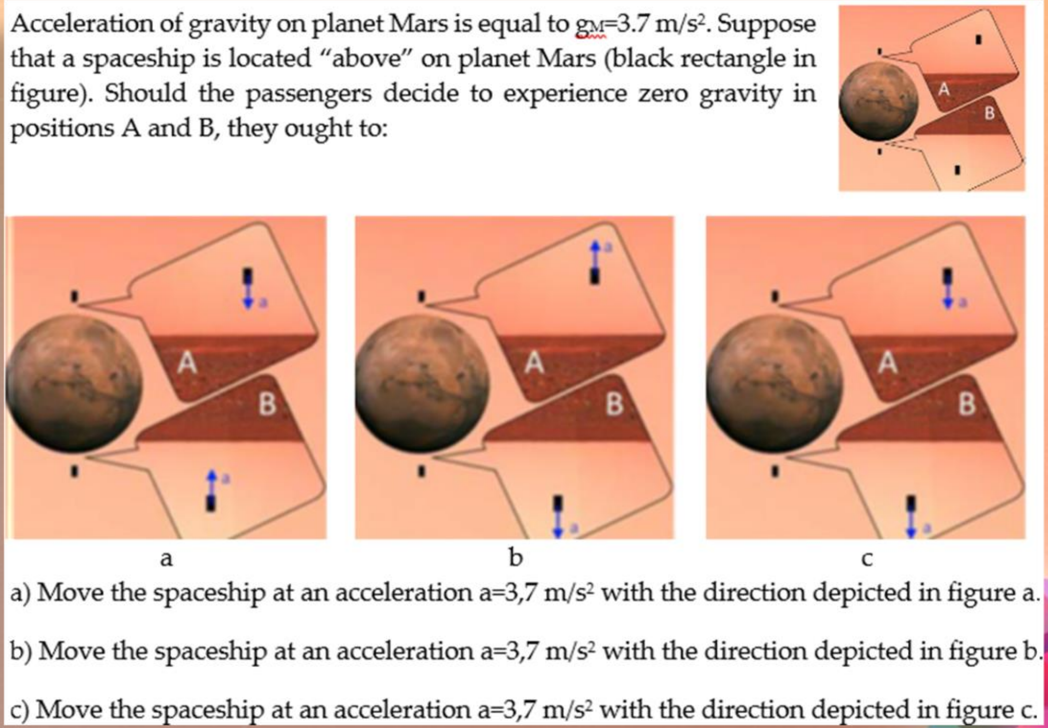
According to the traveler, what is the magnitude of the acceleration of gravity outside the rocket?

Choose the correct answer:

a) Zero

b) Equal to that on the surface of the Earth

c) Twice the acceleration on the surface of the Earth.



Acceleration of gravity on planet Mars is equal to $g_M=3.7\ m/s^2$. Suppose that a spaceship is located "above" on planet Mars (black rectangle in figure). Should the passengers decide to experience zero gravity in positions A and B, they ought to:

a) Move the spaceship at an acceleration $a=3{,}7\ m/s^2$ with the direction depicted in figure a.

b) Move the spaceship at an acceleration $a=3{,}7\ m/s^2$ with the direction depicted in figure b.

c) Move the spaceship at an acceleration $a=3{,}7\ m/s^2$ with the direction depicted in figure c.

2.6. Research process

- Two physics majors with a postgraduate title on teaching science and a PhD specialized on the General Theory, were called upon to to check the validity of the educational and evaluation material.
- A formative – pilot research with 10 students of the Department was conducted.
- Only then were the educational material and the questionnaire given their definitive form.
- Students formed two sets of 60 individuals. (control group – test group)
- Members of test group formed 20 teams of three students each.
- Both groups were handed questionnaires before (pre-tests) and after (post-test) the intervention. We used the x^2 test in order to perform the statistical analysis of the collected data and reach conclusions, since our research variables are measured on a tactical scale and include two nominal independent groups.

3. Results and Discussion (1/2)

- The x^2 test was used for statistical analysis, since our research variables are measured on a tactical scale and include two nominal independent groups.
- Groups were initially equivalent on their knowledge of the EP and its consequences.
- After the intervention, a statistically significant difference was observed with the test group improving the level of comprehension of the EP.

Question #	Pre – test (x^2 test)	Post – test (x^2 test)
1	Pearson Chi-Square 0.409, p =0.522	Pearson Chi-Square 7.566, p =0.006
2	Pearson Chi-Square 0.240, p =0.624	Pearson Chi-Square 24.422, p =0.000
3	Pearson Chi-Square 0.136, p =0.713	Pearson Chi-Square 0.891, p =0.345
4	Pearson Chi-Square 0.657, p =0.418	Pearson Chi-Square 0.874, p =0.350
5	Pearson Chi-Square 0.376, p =0.540	Pearson Chi-Square 32.475, p =0.000

3. Results and Discussion (2/2)

- Although in absolute numbers the test group appears to prevail, in two of the question no statistically significant difference was observed.
- We included these questions (3 and 4) intending to address and inspect the findings of other researches who state “students limit the area of the gravitational field inside the lab” [8], although the size of their sample and their general approach allows for preliminary results and approximations, rather than generalizations.
- At this stage but also in previous research concerning students’ difficulties we were unable to validate this report [9,11].

4. Conclusions (1/3)

Taking into account:

a) the course of implementation and educational use of an original real life experimentation with simple materials,
b) the development of simulation software that, besides being scientifically accurate, is structured in order to contribute to the elimination of difficulties students face,
c) the synthesis of an integrated way for the educational approach of the EP
d) the comparative assessment of our proposal in view of similar work suggested in literature and used by teachers,

we believe that our work answers the research question proposed.

4. Conclusions (2/3)

In both educational and scientific research, a generalization of the findings is safe only to the extent that results are based on scientific methodology (repeatability and application from independent researchers).

The proposal and its application must be tested on a large scale, evaluated and published, actions necessary to ensure the successful adaptation of the scientific model of the GR to an educational model.

Extensive research of learning outcomes and an improvement of conceptual understanding are needed, to ensure that students comprehend the principles of relativity in depth rather than experiencing an illusion of understanding. To this end conducting interviews is of vital importance [7].

4. Conclusions (3/3)

We suggest that parts of the curriculum may serve a dual purpose:

- function as pre-existing knowledge and as a useful working process that leads seamlessly to the introduction of Relativity,
- make the material taught less fragmentary and emphasize and highlight its unifying character.

Examples:

1. Newton’s laws in Classical Mechanics, are suitable for introducing the interesting yet “mysterious” equivalence between inertial and gravitational mass and refer to phenomena that would be radically different if such an equivalence did not hold.
2. In the study of Earth’s gravity the effects of rotation in the determination of weight may be examined which may trigger a discussion about weightlessness in spaceships.

References

1. Pais, A., B. *Subtle is the Lord: The science and the life of Albert Einstein*, Oxford University Press: USA, 1982.
2. Di Casola, E.; Liberati, S.; Sonego, S. Nonequivalence of equivalence principles. *American Journal of Physics* **2015**, *83(1)*, 39-46, https://doi.org/10.1119/1.4895342.
3. Drake, S.P. The equivalence principle as a stepping stone from special to general relativity: A Socratic dialog. *American Journal of Physics* **2006**, 74*(1)*, 22-25, https://doi.org/10.1119/1.2135316.
4. Levrini, O. Reconstructing the Basic Concepts of General Relativity from an Educational and Cultural Point of View. *Science & Education* **2002**, 11, 263–278, https://doi.org/10.1023/A:1015297814508.
5. Zahn, C.; Kraus, U. Sector models—A toolkit for teaching general relativity: I. Curved spaces and spacetimes. *European Journal of Physics* **2014**, 35*(5)*, 39-46, https://doi.org/10.1088/0143-0807/35/5/055020.
6. Kersting, M.; Toellner, R.; Blair, D.; Burman, R. Gravity and warped time—clarifying conceptual confusions in general relativity. *European Journal of Physics* **2014**, 35*(5)*, 39-46, https://doi.org/10.1088/0143-0807/35/5/055020.
7. Pössel, M. Relatively complicated? Using models to teach general relativity at different levels. *arXiv.org* **2018**, arXiv:1812.11589.
8. Bandyopadhyay, A.; Kumar, A. Probing students' understanding of some conceptual themes in general relativity. *Physical Review Special Topics-Physics Education Research* **2010**, 6*(2)*, https://doi.org/10.1103/PhysRevSTPER.6.020104.
9. Gousopoulos, D.; Kapotis, E.; Kalkanis G. Students' difficulties in understanding the basic principles of Relativity after standard instruction. Proceedings of the ESERA Conference, University of Helsinki, Finland, 2015; Lavonen J., Juuti K., Lampiselkä J., Uitto A., Hahl K., Eds.; ESERA: Utrecht, The Netherlands.
10. Velentzas, A.; Halkia, K. The Use of Thought Experiments in Teaching Physics to Upper Secondary-Level Students: Two examples from the theory of relativity. *International Journal of Science Education* **2013**, 35*(18)*, 3026-3049, https://doi.org/10.1080/09500693.2012.682182.
11. Kapotis, E.; Kalkanis, G. Einstein's Elevator in Class: A Self-Construction by Students for the Study of the Equivalence Principle. *The Physics Teacher* **2016**, 54*(7)*, 404-407, https://doi.org/10.1119/1.4962774.
12. micro-kosmos. Available online: http://micro-kosmos.uoa.gr/en/ekp_protaseis/methodology.pdf (accessed on 30 01 2021).