AQUADEMIA
2024, 8(2), ep24006
ISSN 2542-4874 (Online)
https://www.aquademia-journal.com/

Research Article

OPEN ACCESS

Thought experiments in science education: The case of water movement in tracheophyte plants in the gravity conditions of moon

Kyriacos Athanasiou [1*], Sotirios Douros [2]

[1] Department of Early Childhood Education, National and Kapodistrian University of Athens, Athens, GREECE
[2] Head Master, Public Lyceum of Koropi, Attica, GREECE
***Corresponding Author:** kathanas@ecd.uoa.gr

Citation: Athanasiou, K., & Douros, S. (2024). Thought experiments in science education: The case of water movement in tracheophyte plants in the gravity conditions of moon. *Aquademia, 8*(2), ep24006. https://doi.org/10.29333/aquademia/14991

ARTICLE INFO

Received: 07 Jun. 2024

Accepted: 20 Jul. 2024

ABSTRACT

The work is part of a larger project of teaching interdisciplinary teaching of physics concepts in biology within the science education class. It concerns the application of a thought experiment (ThE) about the movement of water in tracheophytes under different gravity conditions, i.e., the behavior of plants on another planet, for example the Moon or Mars. The ThE was designed and implemented in a science class of 25 students who were instructed to perform it in a simulation environment using a software file that we created with the help of Interactive Physics software. The evaluation of the ThE carried out with a written questionnaire showed that the use of such educational procedures can significantly help students to better understand the concepts related to capillary phenomena, the way water is transported to plants from roots to leaves and, generally, to contribute to the interdisciplinary teaching of physics concepts in modules related to the teaching of biological phenomena and functions.

Keywords: thought experiments, water movement, plants, Moon, science teaching

INTRODUCTION

Theoretical Framework

Thought experiments (ThEs) or mental experiments played an important role in the development of science, especially during the scientific revolutions of the 17th and 20th centuries. ThEs have been used by leading scientists, such as Galileo, Newton, and Einstein, whose works were milestones in the evolution and development of science.

The term *gedankenexperiment* was used at the end of the 19th century by Mach (1886/1897) to describe a special research method used by scientists as a mental analogue of the common experiment. In the following century, ThEs appear sporadically in the literature of the philosophy of science with important representatives being Kuhn (1962, 1977) and Popper (1968). From the 1980s, in the 20th century onwards, ThEs were recognized as a technique in analytic philosophy, and it is characteristic of Mach's (1886/1897) statement that "ThEs are important not only in physics but in every field". From then until nowadays, despite the existence of negative criticisms against ThEs, they are considered a common method of confirmation and research.

According to Brown (1991, 2006), ThEs are recognized when we encounter them, we can describe them, but it is difficult to say exactly what they are. We can say metaphorically that ThEs are experiments conducted "in the laboratory of the thought" because they are impossible for various reasons to be performed. They are experiments designed by scientists in such a way that it is not necessary to carry them out (Sorensen, 1992). According to Kuhn (1962), ThEs have played a crucial role in the development of theories of physics as they are dynamic tools for humans in their attempt to understand nature.

In most ThEs the influence of some factor or factors on the evolution of the state of a physical system can be eliminated. For example, Mach (1896/1976) states that ThE and continuous abstraction led Galileo to the law of inertia. This abstraction is required to mathematically approximate nature, and this approximation is a process that takes place only in the thought.

Mental experiments can be divided into those that are destructive to already accepted conceptual schemes or theories and those that are constructive or supportive of new or old theories. Brown and Fehige (2010) proposed a classification system for cognitive experiments that includes a third category and classifies them into the following three categories:

1. destructive mental experiments,
2. constructive mental experiments, and
3. platonic mental experiments.

ThEs as a Teaching Tool

The pedagogical effectiveness of ThEs derives from the fact that ThEs contain the element of narrative, as Klassen (2006) argues. They include arguments and narrative. The narrative, whether in story form or not, is the seed of the human element, while the argument includes the scientific element. These two aspects can be separated for the sake of analysis but in effective pedagogical use of ThE the scientific element is embedded within the story and both are necessary. According to Klassen (2006), when ThEs are presented to students, they should be rewritten by teachers in a narrative form that activates students and leads them to those situations and processes that will help them to understand to a significant extent what is intended by the teaching. In this direction, the science teacher could draw important educational material from texts by scientists drawn from science popularization books. For example, Einstein (1917/1961), invented some ThEs not only for the development of his theories but also for their popularization. Also, eminent scientists, such as Gamow (1966, 1990) or Landau (1959), wrote books trying to popularize theories of physics.

In education, ThEs are considered by educators as irreplaceable tools to teach laws involving relations with significant abstraction. Teachers feel that ThEs bridge the gap between new concepts to be taught to students with their everyday experience and pre-existing knowledge (Helm at al., 1985). The use of ThEs in the classroom requires students to use their imagination, develop their critical thinking, make assumptions, draw conclusions, and share their opinions with their peers. Such features, however, as the use of imagination, hypothesis making, and creative thinking are aspirations of contemporary ThEs teaching (Matthews, 1994). Furthermore, they can help students to approach ThEs through their history and become familiarized with practices used by scientists in the past (Gilbert & Reiner, 2000; Moue, et al., 2006).

Despite the foregoing, science teaching still falls short of recognizing the pedagogical advantages of ThEs. Their use in the science teaching textbooks used in the Greek secondary education system ranges at about 20-25% of the total number of described experiments (real and mental). Meanwhile, some historical ThEs are mentioned, or others are composed by the writing team to serve specific educational objectives, without any effort to highlight them as an educational tool aiming to motivate the teacher or the student to use them systematically. But also in educational systems of other European countries, such as that of the UK, the emphasis is placed on actual experiments carried out in an organized school laboratory and the advantages of these experiments as pedagogical ways of approaching pupils in the specific field of knowledge are highlighted, without a corresponding or similar emphasis being placed on the ThEs (Velentzas, 2009; Velentzas et al., 2007; Velentzas & Halkia, 2013).

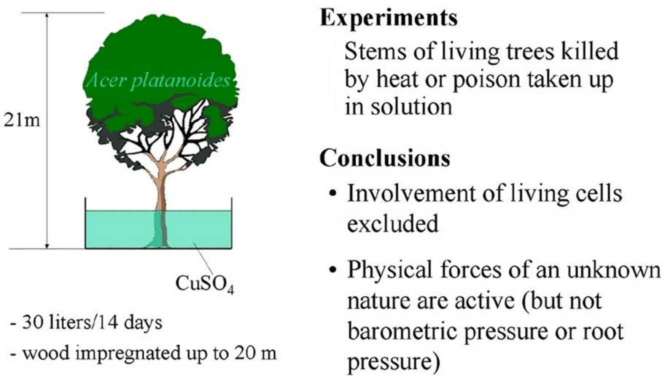

Figure 1. Strasburger's experiment (1890)

About the Capillary Phenomena: A Theoretical Framework

This mental experiment is about the movement of water in plants. There are two ways to propel water towards the leaves: either something pulls it from above or something pushes it from below. Coherence-surface tension theory supports the first way, while root pressure theory supports the second.

Most biologists and physicists support the THET and the corresponding teaching units that accompany it are:

- photosynthesis from biology,
- the properties of water from chemistry,
- the capillary phenomena, which is the basic theory on which this mental experiment is based, as shown by Strasburger's experiment (1890), and
- according to the THET, the pressure in the scraping of the tallest trees can reach -20 atm, a value that can explain trees 115 m high.

Strasburger's experiment (1890)

Figure 1 describes Strasburger's experiment (1890).

Capillary phenomena

- Because of capillary effects, a substance can attract water when the cohesive forces between the molecules of the liquid and the substance are greater than the cohesive forces between the molecules of the liquid.
- The weight of the column of liquid is proportional to the square of the radius of the tube W = r-p-r2-h-g, but the contact length (wall perimeter) between the liquid and the tube, where the cohesive forces that attract water upwards occur, is proportional only to the radius of the tube.
- This results in a narrow tube attracting a column of liquid higher than a wide tube because, when the mass of the liquid decreases, the volume decreases faster than the surface area (**Figure 2**).
- If we place a small tube into a liquid, the liquid will be drawn upwards into the tube until the forces of gravity and friction overcome the capillary force (**Figure 3**).
- The sum of the cohesive forces along the surface of the liquid is called the surface tension, which is a force per unit length.

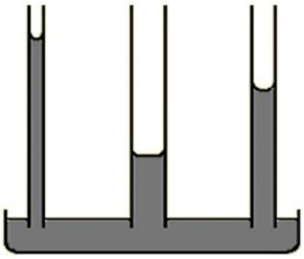

Figure 2. Narrow tube (ESA, 2009)

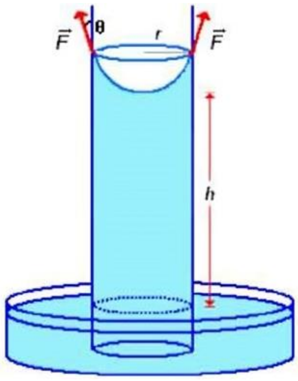

Figure 3. Small tube in liquid (ESA, 2009)

- The direction of the surface tension is tangential to the surface of the liquid and the angle θ it makes with the vertical line upwards is called the contact angle.

The vertical component of the surface tension *σ* is **σ • cosθ**, where θ is the contact angle.

- The total upward force is obtained by multiplying the vertical component by the contact length between the liquid and the wall, so that σ • cosθ • 2πr.
- In the equilibrium position, this force is equal to the weight of the liquid: W = σ • cosθ • 2πr or p • π • r2 • h • g = σ • cosθ • 2πr.
- Or for a given liquid and container, the height of the column of liquid is inversely proportional to the diameter of the tube and gravity.

For water and glass, it is h = 1.4 - 10^{-5} m^2/r, where *r* is the radius in meters. Therefore, for a pipe with a radius of 1m the water can rise by 0.014 mm, while for a pipe with a radius of 0.0001 m, the water will rise by 140 mm. For trees 115 m high, the radius is of the order of 10^{-4} m because the surface is not smooth like glass but porous, so other forces contribute to the rise of water.

Purpose of the study

Of course, the main aim of the present ThE was to prove that when the acceleration of gravity changes, the height of water in a capillary tube change, as well, while the rise of the water in the inner tubes (tracheas) of a plant, is a physical phenomenon of capillary tubes that does not need very much the involvement of biological procedures.

Other aims of the study were, as follows:

- To see if through a ThE the students can learn how to distinguish between scientific and non/scientific ideas, while learning how to defend the correct ones.
- To stimulate the interest of science teachers in the use of mental experiments in everyday teaching practice.
- The search for more attractive procedures for students in the science education class.
- To introduce and familiarize students with abstract thinking as a fundamental feature of scientific methodology.
- To provide the science teacher with an innovative low-cost teaching method that stimulates better student participation and enables the use of computers.

MATERIAL AND METHODS

Prediction or Question for the ThE

Students in grade 1 (that corresponds to grade 9 of the Anglo-Saxon system of education) of the 1st Lyceum of Rafina, a Greek town near the ancient area of the historic Marathon, were given the following written assignment, within the physics class:

> "In case man in the future attempts to settle on Mars, it is necessary for his survival to cultivate plants. What do you think would happen to the height of plants on Mars, if we have solved the problem with the supply of nutrients that plants need"?

Together with the assignment, they were supported by a questionnaire that they had to complete before and after the class session. The 25 students were randomly selected from a total of 77 students. The students were divided into two-member groups and carried out the experiment in the computer room. Each group shared one computer and through the ***file ip-capillary_1,*** that we had created from the Interactive Physics software, and they were led to a capillary phenomena simulation environment. The drawing of conclusions and the pedagogical evaluation was based on the method "prediction, experimentation, confirmation, conclusions".

Experimental Procedure

Each group opened the ***file ip-capillary_1*** file which leads to a simulated capillary environment. For its development, the software "Interactive Physics" was used for the needs of the ThE, which we adapted with parameters

- the acceleration of gravity (g) and
- the height of plants.

In the opened file they could experiment and study capillary phenomena. In particular, the dependence of the height *h* of the capillary tube water on the variation of the acceleration of gravity *g*. For this purpose, the software has been provided with a tank-container, which contains water and a capillary tube with a diameter of 10^{-4} m, some iThEut boxes for the values of the height h of the capillary tube, the acceleration of gravity *g*, and the reset box for entering new values.

Because of capillary effects, a substance can attract water into its interior when the forces between the liquid and the substance (cohesive forces) are greater than the forces within the liquid (affinity forces). The weight of the column of liquid is proportional to the square of the diameter of the tube W = r – p - r2 – h - g, but the contact length (wall perimeter) between the liquid and the tube, where the forces between the liquid and the tube that attract water upwards occur, is proportional only to the diameter of the tube. This results in a narrow pipe attracting a column of liquid higher than a wide pipe because, when the mass of the liquid decreases, the volume decreases faster than the surface area. If we place a small tube into a liquid, the liquid will be drawn upward into the tube until the forces of gravity and friction overcome the capillary force. This is a key feature of the capillary effect, meaning that in the ground the surface tension forces become significant when the pipe is small because of the strong effect of gravity. Therefore, the capillary effect is particularly evident in porous materials that have tiny empty spaces. The sum of the cohesive forces along the surface of the fluid is called the surface tension.

Surface tension is a force per unit length and is the reason the surface area of the liquid is minimized because it keeps its molecules together. The curve on the upper surface of the liquid is called a meniscus and can be curved or concave. It is convex when the molecules of the liquid have a stronger attraction to each other than to the walls of the container, and it is concave when the opposite is true. The direction of the surface tension is tangential to the liquid surface and the angle θ it forms with vertical line upwards is called the contact angle.

We can calculate the height h where the liquid reaches in the capillary effect. The vertical upward component of the surface tension σ is $\sigma \bullet \cos\theta$, where θ is the contact angle. The total upward force is obtained by multiplying the vertical component by the contact length between the liquid and the wall, so it is $\sigma \bullet \cos\theta \bullet 2\pi r$, where *r* is radius of capillary tube.

At the equilibrium position, this force is equal to the weight of the liquid, which is equal to $W = \rho \bullet \pi \bullet r \bullet h \bullet g$, where *p* is the density of water, *h* is the height, and *g* are the acceleration of gravity. Then $\sigma \bullet \cos\theta \bullet 2\pi r = \rho \bullet \pi \bullet r \bullet h \bullet g$, or else, $h = (2 \bullet s \bullet \cos\theta)/(p \bullet g \bullet r)$.

For a given liquid and container, the height of the column of liquid is inversely proportional to the diameter of the tube and gravity $h \sim 1/(g \bullet r)$.

For water and glass, $h = 1.4 - 10^{-5}\ m^2/r$, where *r* is the radius in meters. Therefore, for a pipe with a diameter of 1 meter radius, the water can rise by 0.014 millimeters, but for a pipe with a diameter of 0.0001 meter radius, the water will rise by 140 millimeters. For trees 115 meters high the diameter is in the order of 10^{-4} meters because the surface is not smooth like glass but porous, so other forces contribute to the rise of water (NASA Science, n.d.; Noesis Science Center & Technology Museum of Thessaloniki, 2024).

- Theories involved with water rise in plants were also developed from biology the photosynthesis and from chemistry the properties of water.

Figure 4 and **Figure 5** show the mental experiment device of capillary phenomena.

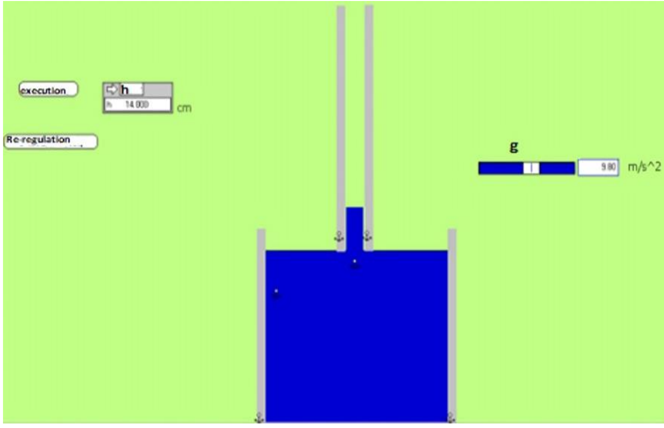

Figure 4. The mental experiment device of capillary phenomena: The tube has a diameter of 10- 4 m and at the surface of the Earth the height of the water is 14 cm (to enter values, we click on the box of interest and change the value of the acceleration of gravity *g* or the height *h* of the capillary tube & to enter new values, we click on the reset box) (ESA, 2009)

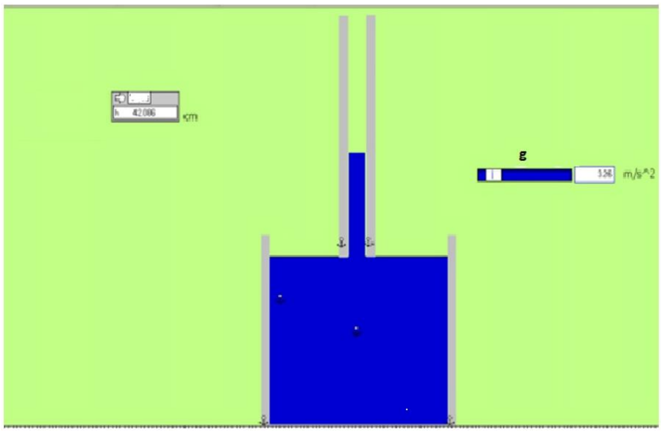

Figure 5. The mental experiment device of capillary phenomena on the surface of Mars, where $g = 3.26\ m/s^2$ (ESA, 2009)

RESULTS

The software was evaluated on 25 first grade students. As can be seen from the prediction and confirmation samples, there was a large improvement rate from 52% correct answers before the ThE application to 80% correct answers, post application. **Table 1** shows the responses to the evaluation questions of the educational process. In the t-test of the dependent samples of Excel from the data analysis option, **Table 1** shows that the difference observed between prediction and confirmation is statistically significant and not random (the probabilities are < 0.05), so the ThE seems that really helped the students to improve their understandings on water movement in plants through their capillaries.

DISCUSSION

The concept of capillary phenomena is a difficult concept for students to grasp because it combines knowledge from biology, physics, and chemistry. It is known that the biggest weakness of students is an interdisciplinary approach. It has been suggested that mental experiments using new technologies can help in understanding these concepts. As the

Table 1. Improvement in students' knowledge on water movement in plants at the 0.05 level (2-tailed) through the application of a ThE

Student	Pre-lesson score (M ± SD) (true/false)	Post-lesson score (M ± SD) (true/false)	t	Pearson's coefficient
N = 25	52 ± 0.26	80 ± 0.16	-2.064	-0.80

Note. M: Mean & SD: Standard deviaton

results of the study show that the improvement in knowledge was significant and the students were able to overcome the difficulties.

In one of our previous works, we investigated the perceptions of primary school teachers related to the intake and transport of water in plants and the function of transpiration (Athanasiou & Papadopoulou, 2005). The research was done through written proposition creation papers and a recording questionnaire that recorded a limited knowledge of the existence and action of molecular forces as well as the occurrence of osmotic and capillary phenomena during the uptake and transport of water by plants. In further investigation of perceptions through individual interviews with some of the teachers, animal-type models were recorded that were reproduced to describe plant functions. At the same time, there was no possibility of applying the corresponding models of physics to the description of biological functions related to purely phenomena of physics and chemistry. We thought that the findings raised some interesting points for enriching teachers' and students' education and further education in physics concepts as applied and displayed in biological phenomena and functions.

The intake and transport of water to plants, in combination with the function of transpiration, is one of the difficult phenomena of science teaching. Indicatively, the limited effectiveness of experimental teaching with the use of experimental devices such as the potometer is recorded, and the development of other teaching sequences is proposed (Yip, 2003). Apart from the teaching interest, the negotiation of the intake and transport of water to terrestrial plants in combination with the function of transpiration, is an interesting case of application of the laws of physics to biological functions and could make an important contribution to the release from vitalistic beliefs that students and teachers often have. We refer to those beliefs that distinguish biological functions from the processes of physics and chemistry. As we noticed in our previous survey, most teachers did not have sufficient knowledge about capillary phenomena and molecular forces of coherence and affinity as causes of water rise in woody pipes. So, it seems that the use of the specific ThE, seems that helped students to overcome to a satisfactory degree the difficulties that these functions seem to present in the teaching of biology and botany.

Another contribution to the teaching of natural sciences that the teaching of such ThEs can have is the dismantling of zoomorphic concepts that we often find in the teaching of science, especially biological phenomena, with functions to which laws and functions of physics and chemistry are applied. One such case is the view that the plant feeds on its roots that play the role that mouths play in animals, and that plants are nothing more than "inverted animals", a view that has appeared repeatedly in the history of biology (Barker, 1995). The first to formulate such views was Aristotle, while in modern history we find the case of *analogists*, one of whom was C. Darwin's grandfather, namely Erasmus Darwin. As for the latter, we can comment on two things:

- The ideas of the *analogists* were characterized by zoomorphic conceptions, which are essentially the attribution of animal properties to plants and the construction of analogies, where the starting point is the functions of animals, and the goal is the functions of plants.
- The second point to comment on is the fact that students and teachers often repeat these ideas, and analogies can be barriers to learning related to plant functions (Athanasiou & Papadopoulou, 2006; Barker, 1995). As shown by the present results, the use of ThEs, such as the present ones, can be a useful tool for students to overcome such perceptions and detach themselves from the transfer of zoomorphic perceptions to the interpretation of phenomena concerning plant life and functions.

Finally, the other element of education that emerges from the application of these ThEs in the classroom is the usefulness of the interdisciplinary approach in science education. As mentioned above, it is quite difficult to transfer knowledge from the field of physics to the field of biology. Thus, an interdisciplinary approach seems necessary for all levels of education, as proposed by STEM in science education programs. The use of such ThEs seems to be a useful tool in the application of STEM education in the classroom, especially in teaching units where concepts of physics and chemistry need to be transferred to the teaching of biological phenomena and functions (Choudhary, 2024; Popova, 2011).

Author contributions: Both authors were actively involved in all stages of this study while preparing the final version. They both agree with the results and conclusions.

Funding: No external funding is received for this article.

Ethical statement: The authors stated that the study was approved by the National and Kapodestrian University of Athens, through the head of department.

Declaration of interest: The authors declare that they have no competing interests.

Availability of data and materials: All data generated or analyzed during this study are available for sharing when appropriate request is directed to corresponding author.

REFERENCES

Athanasiou, K., & Papadopoulou, P. (2005). Perceptions of primary education teachers on the transfer of water in plants: An example of the application of physics concepts to the teaching of biology. In D. Coliopoulos, & A. Vavouraki (Eds.), *Proceedings of the 2nd International Organization for Science Education* (pp. 157-167). IOSTE. https://doi.org/10.13140/2.1.4506.3207

Barker, M. (1995). A plant is an animal standing on its head. *Journal of Biological Education, 29*(3), 201-208. https://doi.org/10.1080/00219266.1995.9655446

Brown, J. R. (1991). *The laboratory of the mind: Thought experiments in the natural sciences (1st ed.)*. Routledge. https://doi.org/10.4324/9780203979150

Brown, J. R. (2006). The promise and perils of thought experiments. *Interchange, 37*, 63-75. https://doi.org/10.1007/s10780-006-8400-6

Brown, J. R., & Fehige, Y. (2010). Thought experiments. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy*. https://doi.org/10.4324/9780203744857

Choudhary, R. (2024). 260+ experimental research topics for STEM students. *All Programming Help*. https://allprogramminghelp.com/blog/experimental-research-topics-for-stem-students/

ESA (2009). Human spaceflight training group - European Space Agency. Take your Classroom into Space: Space for Life pamphlet. www.esa.int/esaHS/education.html

Einstein, A. (1917/1961). *Relativity: The special and the general theory*. Grown Publishers. https://doi.org/10.4324/9780203198711

Gamow, G. (1966). *Thirty years that shook physics*. Doubleday and Co.

Gamow, G. (1990). *Mr Tompkins in paperback*. Cambridge University Press. https://doi.org/10.1017/CBO9781139644143

Gilbert, J. K., & Reiner, M. (2000). Thought experiments in science education: Potential and current realization. *International Journal of Science Education, 22*(3), 265-283. https://doi.org/10.1080/095006900289877

Helm, H., Gilbert, J., & Watts, D. M. (1985). Thought experiments and physics education-Part 2. *Physics Education, 20*, 211-217. https://doi.org/10.1088/0031-9120/20/5/003

Klassen, S. (2006). The science thought experiment: How might it be used profitably in the classroom? *Interchange, 37*, 77-96. https://doi.org/10.1007/s10780-006-8401-5

Kuhn, T. (1962). *The structure of scientific revolutions*. The University of Chicago Press.

Kuhn, T. (1977). A function of thought experiments. In T. Kuhn (Ed.), *The essential tension: Selected studies in scientific tradition and change* (pp. 240-265). Chicago University Press. https://doi.org/10.7208/chicago/9780226217239.001.0001

Landau, L. (1959). *What is relativity?* Basic Books.

Mach, E. (1896/1976). On thought experiments. In E. Mach (Ed.), *Knowledge and error: Sketches on the psychology of enquiry* (pp. 134-147). Springer. https://doi.org/10.1007/978-94-010-1428-1_11

Matthews, M. (1994). Thought experiments. In M. Matthews (Ed.), *Science teaching: The role of history and philosophy of science* (pp. 99-105). Routledge.

Moue, A. S., Masavetas, K. A., & Karayianni, H. (2006). Tracing the development of thought experiments in the philosophy of natural sciences. *Journal for General Philosophy of Science, 37*, 61-75. https://doi.org/10.1007/s10838-006-8906-8

NASA Science. (n.d.). *NASA science*. http://science.nasa.gov/

Noesis Science Center & Technology Museum of Thessaloniki. (2024). *Noesis Science Center & Technology Museum of Thessaloniki*. http://www.tmth.edu.gr/

Popova, M. (2011). *Six famous thought experiments, animated in 60 seconds each*. http://www.braiThEickings.org/index.php/2011/10/19/open-university-thought-experiments/

Popper, K. (1968). *The logic of scientific discovery*. Rutledge.

Sorensen, R. (1992). *Thought experiments*. Oxford University Press.

Velentzas, A. (2009). *The contribution of mental experiments in the teaching of physics* [PhD thesis, National and Kapodistrian University of Athens]. https://doi.org/10.12681/eadd/20389

Velentzas, A., & Halkia, K. (2013). 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, 35*(18), 3026-3049. https://doi.org/10.1080/09500693.2012.682182

Velentzas, A., Halkia, K., & Skordoulis, C. (2007). Thought experiments in the theory of relativity and in quantum mechanics: Their presence in textbooks and in popular science books. *Science Education, 16*, 353-370. https://doi.org/10.1007/s11191-006-9030-1

Yip, D. Y. (2003). Developing a better understanding of the relationship between transpiration and water uptake in plants. *Journal of Science Education and Technology, 12*, 13-19. https://doi.org/10.1023/A:1022199325957