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ARTICLE

The Observer Concept in Science as a Basis for Its Further Curricular Application Within the Discipline-Culture Paradigm

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Abstract
This study considers the concept of observer-the fundamental concept axial for fundamental physical theories. The history of the observer concept in physics is reviewed and summarized. In the following, the observer concept is considered with regard to science education where scientific concepts should reflect their status in science. This parallelism between science and education is epistemological and dynamic. The examination of the school curriculum reveals invalid correspondence in the case of the observer. The curriculum often presents the observer when addressing the Galileo principle of relativity, while frequently missing relativity of motion in presenting natural phenomena. Multiple observers are avoided in dynamics where the modern epistemology—drawing on a "local observer"—introduces non-inertial observers (inertial forces) currently banned in school physics. The article refines the possible curricular changes with respect to dynamics and kinematics which emphasize multiple observers. The suggested curricular changes could provide science learners with a new perspective on physics knowledge within the paradigm of multiple observers—cultural content knowledge of the subject matter.

1 Introduction

The *observer* is a pivotal concept in physical science. This role follows from the understanding of science as a *theory* replacing actual reality[1] and the fact that this replacement is performed by an observer in a general sense of continuous interpretation, the nature of science. Given the major feature of scientific knowledge, its objectivity, we face a complexity represented by asking the following: how can a human investigator, the observer, naturally not immune from subjective views, perception, and worldview, possibly produce objective knowledge about nature? The answer is provided by a very specific method of knowledge construction continuously developing throughout the history of science, its epistemology.

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[1] Heidegger in Kockelmans (1985, p. 162).

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One path of this history immerges to our appreciation when we follow the changes to our understanding of the role of the observer in physics.

The question regarding the observer usually remains in the background of science teaching, only occasionally appearing above the water, such as in the debate on the nature of science.[2] Here, it appears in different claims, for example, the need for a student of science to distinguish between observation and inference,[3] whereas further refinement reveals their being deeply interwoven.[4] In any case, the history of physics testifies to the concept of observer being developed from its scarcely recognized role of watching, analyzing, and making inferences in a cyclic manner by a *single* individual observing the world, to the emphasized validity of the accounts by *multiple* observers investigating nature each in his/her local laboratory.

This history, long in time but rather compact in the number of ideas, has a specific relevance for science education. Among the pragmatic reasons for this interest is the claim of recapitulation, a certain similarity between the development of collective scientific knowledge (its phylogeny) and the individually constructed knowledge (its ontogenesis) on behalf of each student of science. Indeed, each child starts with the extreme egocentrism of a single observer and more or less quickly progresses towards recognition of other points of view and socially accepted knowledge.[5]

In this study, we have reviewed the progress of understanding the role of observer in creating physics knowledge including its understanding in modern science, and the shortcomings of the present situation in education. Revealing the shortcomings, the gap between the scientific understanding and pertinent school teaching, the subject guided us to consider possible implications for school curricula. In this, we can draw on the recently developed perspective of cultural content knowledge[6] and the performed experiment in middle school teaching, which report was separately published, and only briefly depicted here.[7]

2 History of the Observer in Physics

2.1 The Greek Start

Greek science is often considered to be a natural philosophy, rather than science, to a large extent due to its understanding of the role of observer. Pythagoras wrote:[8]

> In life, there are three kinds of men, just as there are three sorts of people who come to the Olympic Games. The lowest class is made up of those *who come to buy and sell*, and next above them are those who come to compete. Best of all, however, are those *who come to look on* (θεωρεῖν). The greatest purification of all is, therefore, science, and it is the man who devotes himself to that, the true philosopher who has most effectually released himself from the "wheel of birth."

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[2] Galili (2019a).

[3] e.g., Lederman et al., 2002; McComas 1998, p. 55.

[4] Galili (2019a).

[5] Piaget, 1970, Vygotsky 1934/1986.

[6] Galili (2012).

[7] Stein et al., 2023.

[8] Burnet (1920, p.70).

Though the translator from Greek used “look” instead of “observe,” he was kind enough to mention the original term used, “theory” (θεωρεῖν), which is all about making science, that is, the replacement of reality with a theory of reality, which is at the disposal of an observer. Such knowledge construction presumed pure philosophical analysis, drawing on *contemplation,* interweaving observation with induction, the inference of explanatory principles through the art of induction and deduction together establishing a cycle as refined in detail by Aristotle (Fig. 1).[9] This was a major invention of the scientific method. Another important fact was the continuity of this process. The established cycle remained open, that is, in case of an unsatisfactory explanation, it was upon the observer to produce new explanatory principles and continue with a new deduction. Furthermore, as we can see it now, this process creates a double spiral of development: observation vis-a-vis the theory construction (the method) both developing in time in reciprocal connection. This great process continued throughout the history of science.

Naturally, the contemplation-based methodology was especially effective in astronomy. For example, only by analyzing appearances, was Aristotle able to make inferences regarding the opaque nature of the Moon’s surface only reflecting the light of the Sun, and the proofs for the spherical shape of the Earth.[10] Yet, these significant achievements by Hellenic science demanded the inclusion of mathematical modelling with calculations in order to reach quantitative results, and subsequent measurements were mainly introduced in the following Hellenistic science. Such achievements brought the discovery of relative distances and sizes of the Moon and Sun by Aristarchus and Earth’s diameter by Eratosthenes.[11] In fact, the results Aristarchus created were a good reason for bringing the geocentric system into dispute and the alternative option implied a clear contradiction with the observed motion of the Sun by the terrestrial observer. Yet, this fact was not developed to the claim of observer dependence of reality Aristarchus did not expand on this amazing aspect: the observed picture could be a subject for interpretation by different observers on the way to “true” understanding. No awareness was shown as to the apparent relativity of motion beyond revealing the correct numerical details of the natural setting, distances between the celestial objects, and their true magnitudes.

An important tool of contemplation introduced by the Greeks was *thought experiment*,[12] such as that by which Aristotle proved that the Earth’s center coincided with the center of the universe, the attractor of all heavy objects with prevailing earth-water elements.[13] Yet, the highly important progress of Hellenistic science was in upgrading the observer’s contemplation with complementing experimentation, such as Ptolemy’s experiment of the measurement of light (visual rays) refraction[14] and Archimedes’ findings of the secrets of buoyancy, the lever, and center of gravity.[15]

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[9] Losee (2001, pp. 5–10).

[10] Losee (2001, p. 6), Rogers (1960, pp. 230–234).

[11] Heath (2004, pp. 556–570), Rogers (1960, pp. 24–236).

[12] Facing certain vagueness with regard to the concept of thought experiment (TE), we reproduce here its definition as provided in (Galili 2009): “Thought experiment is a set of hypothetico-deductive considerations regarding phenomena in the world of real objects, drawing on a certain theory (principle or view) that is used as a reference of validity.” The major implication is that, given the valid argumentation, TE does not testify to the true or false status of the produced claim regarding reality, but the true or false status of the claim under certain theoretical assumptions. That is why TE cannot replace a real experiment.

[13] Aristotle (1952, pp. 388–389).

[14] Cohen & Drabkin (1948, pp. 271–281), Hogben (1938, pp. 130–132).

[15] Moody & Clagett (1952), Stein (1999, pp. 7–25, 63–68), Assis & Magnaghi, 2012, pp. 9–13).

2.2 The Medieval Doubt

However, it was medieval science which introduced doubt regarding the reliability of the observer's perception in the context of motion regardless of mastering the skill of observation. Several scholars, Buridan, Oresme, and Nicolas of Cusa, among them, used the allegory/thought experiment of a moving ship, inferring the unavoidable uncertainty in establishing the fact of motion which is relative in our perception.[16]

> The ancients [continues Nicholas of Cusa] did not arrive at the things that we have brought forth, because they were deficient in learned ignorance. But for us it is clear that this earth really moves, though it does not appear to us to do so, because we do not apprehend motion except by a certain comparison with something fixed. Thus if a man in a boat, in the middle of a stream, did not know that the water was flowing and did not see the bank, how would he apprehend that the boat was moving? Accordingly, as it will always seem to the observer, whether he be on the earth, or on the sun or on another star, that he is in the quasi-motionless center and that all the other [things] are in motion…

This uncertainty was extrapolated to the doubt regarding the Earth being at rest.[17] There was a vivid argument around this uncertainty, weighing pro and contra the motion of the Earth, diurnal and annual, containing new claims surpassing the defense raised by Ptolemy in his *Almagest* (such was the motion of the air as shared with the motion of the Earth, the role of the center of gravity). Altogether, however, the old Aristotelian view survived, though it was seriously shaken by doubt. As Clagett wrote: "We must conclude, however, that Buridan and Oresme certainly argued most persuasively for the rotation before finally rejecting it." Not to forget, the researchers, were all high-ranking clerics, who could sincerely try to avoid the straightforward confrontation with the Church canon and reason by authority.[18] The discussion of a moving observer was further developed by Bruno and Galileo. The original *kinematic* claim was generalized to the claim of indifference to motion of any phenomenon inside a closed cabin moving uniformly—*dynamic* relativity. It was the renowned principle of relativity—the Galileo principle. In 1632, it was stated in a descriptive form without any formalism. The theory of classical mechanics was yet to arrive.

2.3 Copernican Debate

One may see the debate around the helio- versus the geocentric system, which had already begun in the era of Greek science, as a continued battle between the directly observed and conceived. The relative nature of motion instigated this clash. The last model which ardently tried to leave the Earth at rest, as the "observed" reality testified, while adopting the advantages of heliocentric arrangement, was the Tycho Brahe model (the stationary Earth and planets rotating around the Sun) revolving around the Earth. This compromise actually drew on the relativity of motion perception as being rather close to the inversion between Earth and the Sun in the Copernicus scenario. For Galileo, the protagonist of

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[16] Koyré (1957, p. 17) and the references to the original texts there.

[17] Buridan, Oresme (Clagett, 1961, pp. 585, 588, 594–599).

[18] One may see the echo of this defensive position—"it is only a hypothesis"—in the introduction to Copernicus' (1501/1952) *On the Revolutions* provided by Osiander (Copernicus, 1978, p. XVI): "So far as hypotheses are concerned, let no one expect anything certain from astronomy, which cannot furnish it...".

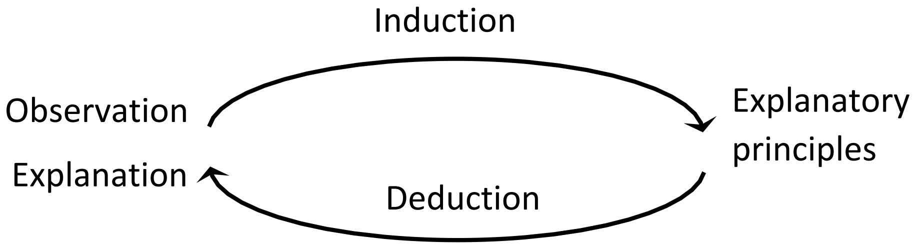

Fig. 1 Aristotelian induction-deduction cycle performed by the observer

relativity, rotational inertia, the natural non-stop motion of any object moving along the Earth's surface, it was too difficult for him to falsify Tycho's model, and he retreated. Galileo's debate was only with Aristotle and the model of Ptolemy. The situation was far from clear. The doubts of the medieval scholars were impelling, but there was no big *physics theory* to crush the Tychonian alternative, *the relativity of motion was not enough*. At the time of Galileo, there was no such theory. Riccioli scrupulously collected the available evidence to prove Tycho Brahe correct, rather than Copernicus (Fig. 2).

2.4 Newton's Change

Newton established the new theory of motion—classical mechanics. Though it happened after Galileo, the relativity principle in its full scale was left aside. In a way, it did not sit well and challenged the basic Newtonian paradigm—absolute space and time, the absolute motion relative to space as a container of the universe. Addressing the Galilean ship, Newton added his clarification:[19]

> But true rest is the continuance of a body in the same part of that unmoving space in which the ship itself, along with its interior and all its contents, is moving. Therefore, if the earth is truly at rest, a body that is relatively at rest on a ship will move truly and absolutely with the velocity with which the ship is moving on the earth.

The presence of absolute space questioned and rejected the relativity of motion in its totality. As with other concepts, Newton distinguished between *true* and *apparent* motions. Newton wrote:[20]

> Although time, space, place, and motion are very familiar to everyone, it must be noted that these quantities are popularly conceived solely with reference to the objects of sense perception. And this is the source of certain preconceptions; to eliminate them it is useful to distinguish these quantities into absolute and relative, true and apparent, mathematical and common. … Absolute space, of its own nature without reference to anything external, always remains homogeneous and immovable.

Indeed, the motion of an object presents the change of its location with respect to other objects, and it is that which is observed and what we mean by motion. Newton meticulously looked for physical evidence of the difference between true and apparent motions.

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[19] Newton (1687/1999, Definitions, Scholium, p. 409).

[20] Newton (ibid, p. 408).

With regard to the *rectilinear uniform* motion, he could not find anything indicating *true* motion (not a surprise as it was the natural implication of the Galilean relativity). But that did not change Newton's mind, whereas for the *curved* motion, Newton thought he could point to such evidence. He referred to the surface of water in a spinning bucket (Fig. 3).[21] His reasoning was, however, falsified soon after by Berkeley in 1721 and later by Mach in 1883.[22]

In particular, Newton considered a bucket half filled with water suspended by a cord that could be twisted. After being liberated, the bucket starts to rotate and after some time is stopped. Through considering four different moments of this scenario, Newton pointed to the fact that whether the surface of the water is curved or flat does not depend on whether the walls of the bucket rotate with the water or are at rest. He implied that what determines the curved surface of the water is its motion with respect to absolute space. Berkeley and Mach pointed to the fact that the variation of the conditions of the experiment ignored the Earth and other celestial bodies, whether the results depend on the motion with respect to them (that is, when the experiment is performed on a stationary, non-rotating Earth) or not, and that falsified the inference regarding absolute space as an entity of reference.[23]

The Newtonian absolute space-container was postulated and firmly remained in the foundation of science until Einstein. One may see Newtonian vision not as an invention even, but as an articulation of the intuitive perspective, deeply rooted in us all, vis-a-vis the world around us. Natural philosophers, en masse, adopted this phenomenological concept. Against this background, the Galilean principle of relativity appeared as a curious feature of the limited ability of an observer to make any implication regarding motion, rather than as a practical tool.

2.5 Huygens' Revolt

The first break in this conceptual stance took place due to Huygens. He was the first who applied the principle of relativity to the account of the collision of elastic bodies (Fig. 4). He succeeded in replacing Descartes' incorrect laws and derived a new conservation law—of the quantity termed by Leibniz *vis viva* (mv^2)—in this kind of collision.[24]

However, the highest achievement of Huygens was the introduction of a new kind of observer—the one who moves at acceleration.[25] Huygens considered an observer on a spinning disc and inferred that to describe the dynamics of motion from his point of view, the observer needs a new force—centrifugal force, acting radially outwards from the axis of rotation (Fig. 5a). He did not elaborate on the new kind of observer but discovered an exact formula for his *vis centrifuga* (F_{cf}), which in common notations is:

$$F_{\mathrm{cf}} = m\omega^2 r \tag{1}$$

m designates the mass of the revolving body, ω is the angular velocity, and r is the radius of revolving.

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[21] Newton (ibid, p. 413).

[22] Born (1922/1962, pp. 69–70).

[23] Mach (1919, p. 232).

[24] Huygens (1977), Smith (2006).

[25] Huygens (1659/1703).

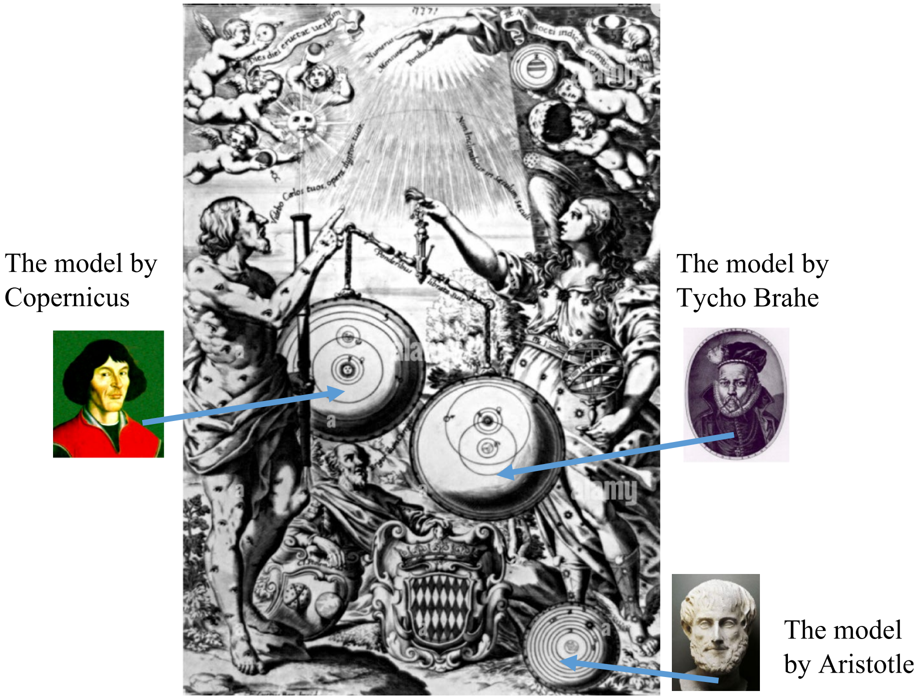

Fig. 2 Tycho Brahe overtakes the model by Copernicus in the competition of the worldviews as documented on the front page of the popular book *Almagestum Novum* by Riccioli in 1651, in Bologna. The abandoned geocentric model is placed below, out of the competition

Moreover, through a virtuous quantitative analysis (Fig. 5b), he arrived at the inference: the centrifugal force acts exactly as the force of gravitation does.[26] In fact, however, this inference already qualitatively follows on from Eq. 1. Indeed, replacing $\omega^2 r = g^*$ provides the well-known $F_{\mathrm{cf}} = mg^*$, which, nevertheless, was not known to Huygens in 1659 as he achieved his result prior to *the Principia*, published in 1687. Equation 1 served as a theoretical definition of the force. No operational definition (through measurement) was considered important at that time.

The centrifugal force was an important epistemological invention. Yet, the new dynamic account of reality was left without being adequately elaborated and understood. The new observer was non-existent for Newton, as well as for Galileo. This realization only took place in the twentieth century. Specifically, what remained in oblivion was the idea of a different *observer*—the accelerated observer. The inertial forces (e.g., *vis centrifuga*) emerge only in the account by such observers whom we call non-inertial. Yet, the notion of centrifugal force did not die. What happened was more sophisticated and was related to the very idea of an observer.

Newton knew about this result of Huygens and reacted to it in his *Principia*. Within the Newtonian vision of the world, there was no place for any other observer but the unique

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[26] e.g., Galili (2021a, Ch.4).

Fig. 3 Newton experiment with a spinning bucket (Born, 1922/1962, p. 69)

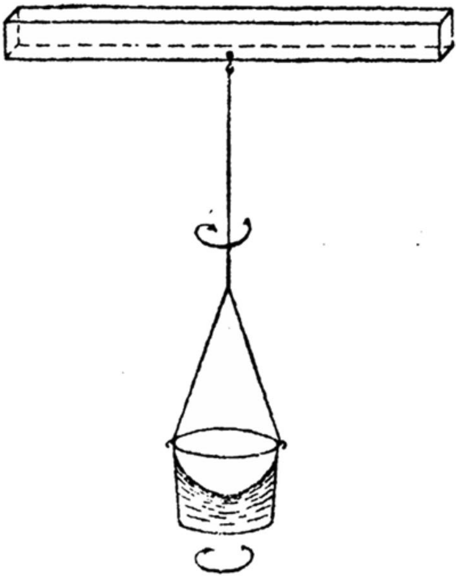

FIG. 42.

observer at rest in *absolute space*. Newton falsified the idea of the Huygens' centrifugal force in a rather smart way. Indeed, he stated, there was a centrifugal outward force but it was applied to another body, the one which was responsible for exerting *centripetal* force on the rotating body, on the constraint (rope, curb, the partner of interaction). In other words, centrifugal force presents the action-reaction partner of the centripetal force. Newton declared:[27]

> This is the centrifugal force with which the body urges the circle; and the opposite force, with which the circle continually repels the body toward the center, is equal to this centrifugal force.

In this way, the discovery of Huygens was pushed by Newton into oblivion as a simple "confusion of agent and victim."[28] There was no place for Huygens' centrifugal force (as exerted on the revolving body itself) in the framework of one observer, the only framework held by Newton. Huygens' discovery of a new *dynamic* account of reality was left without being adequately understood, since the latter required the new kind of observer, nonexistent for Newton as well as for Galileo. Galilean relativity and the associated multiple inertial observers did not pose any conceptual problem for the Newtonian observer and his account of reality beyond the variation of kinematic appearance of the form and velocity, a trivial modification.

A certain revival of the original centrifugal force in classical mechanics was when d'Alembert suggested considering $\boldsymbol{F} = -\mathrm{m}\mathbf{a}$ as a special force acting *on* the body (or a system)—d'Alembert force—which causes an imaginary equilibrium of the otherwise accelerating body. Yet, without the idea of a different *observer*, it was considered by physicists rather as a trick/principle allowing the treatment of static system being at equilibrium.

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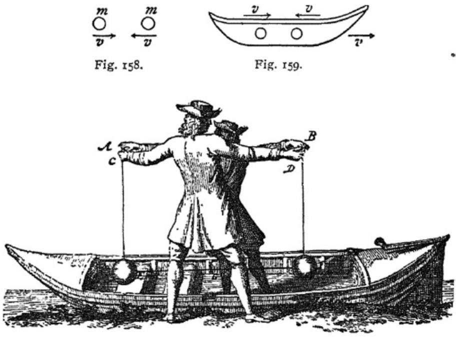
[27] Newton (1687/1999, Book I, Sect. 2, Scholium).

[28] Rogers (1960, p. 305).



An Illustration from *De Percussione* (Huygens).

Fig. 4 A sketch from Huygens' study illustrating the use of multiple observers and the relativity principle in the account of a collision between two balls by two observers, one on a river bank, and the other on the boat passing by (Mach (1919, p. 314))

This was confusing, especially in the case of a body moving in a rotating system (Coriolis forces). In effect, the transformation of d'Alembert does present the account by the observer who moves at the acceleration **a**, for example, in a stopping vehicle. Yet, the idea of a different observer did *not* arise, presumably suppressed by a so "obvious" absolute space that was beyond any doubt and was considered the a priori form of intuition.[29] Quite ironically, the widely accepted physics literature continued to use centrifugal force as it applied to the rotating body while ignoring the relation to the observer, that is to say, "illegally."[30]

Leibnitz, a distinguished philosopher of science, criticized Newtonian absolute space at the same time. His critique however drew on the principle of sufficient reason, to which he supplied highly speculative theological reasoning which, unlike Huygens, had no implication for physics formalism.[31] Leibnitz did not introduce an alternative theory of mechanics which could compete with the Newtonian theory. In contrast, Newton's arguments for the absolute space were of a physical nature and were disproved in physics much later by Mach and Einstein. This critique looked more convincing due to another philosopher, Berkeley, who was both concrete and suggestive:[32]

> … for determining true motion and true rest, by which means ambiguity is eliminated and the mechanics of those philosophers who contemplate a wider system of things is furthered, it would suffice to take the relative space enclosed by the fixed stars, regarded as at rest, instead of absolute space. Indeed, motion and rest defined by such a relative space can conveniently be applied in place of the absolutes, which cannot be discerned by any mark.

This argument was fully adopted by Mach in his critique of absolute space in the nineteenth century.[33]

2.6 The Revolutionary Change

The true eruption of the observer concept took place within the special theory of relativity by Einstein. For the first time, considering the observer was raised to the status

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[29] Kant (1781/1952, Part I, Sec. 2).

[30] Thomson & Tait 1883/2009).

[31] Leibniz (1715/1989, pp. 324–327), Agassi (1969).

[32] Berkeley (1721/1992, pp. 102–103).

[33] Mach (1919, p. 543), Galili (2019b).

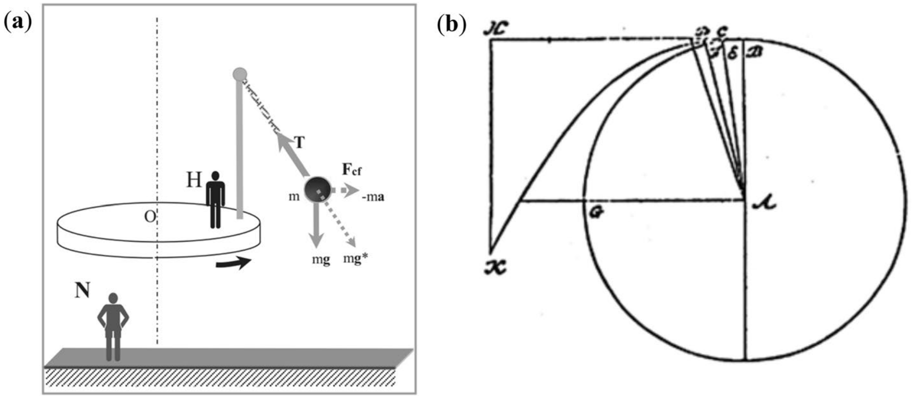

Fig. 5 (**a**) A sketch illustrating the dynamic account of motion by two observers. Observer H is the observer addressed by Huygens (non-inertial, accelerated observer) whereas observer N is the observer addressed by Newton (inertial observer at rest). **b** The sketch used by Huygens to derive the action of the centrifugal force. After escaping the connection to the radius of rotation, the body proceeds at the tangential path DH. Huygens calculated the rate of increased distance to the center A and obtained the increase similar to that in free falling

of a principle in the fundamental physics theory from which the Newtonian absolute space was removed. The new concept of space was in apparent contradiction to the naive perception as well as to the claims of philosophers who faced the need to reconsider the commonplace Kantian a priori form of intuition, transcendental and ubiquitous, not a concept one can consider from the side.[34] The Kantian conception of space prevented it from any physical probe but allowed learning about its features through geometry. Einstein removed this concept which, by that time, had transformed into the *luminiferous aether* filling the Newtonian space container. This was a great relief for the physicists who struggled to imagine the medium with the highly problematic controversial properties (frictionless but elastic as a solid, etc.) necessarily ascribed to the aether.

In the event, the breakthrough emerged in Mach's approach of logical empiricism which moved to the fore the *operational* definition of physical concepts. It was a rebellion against the Newtonian preference for theoretical definitions undermining operational definitions. Mach redefined mass and force but did not touch on space, time, and weight.[35] The progress was still within the Newtonian mechanics, and the latter preserved the hegemony of an inertial observer.

The spatial length and time interval were addressed by Einstein within his *special* theory of relativity. The postulated invariance of the speed of light for all inertial observers essentially changed the appearance of space and time extensions for different observers. Importantly, spatial observations of motion in modern physics cannot be imagined as one thing in the absolute flat space being looked at from several positions. The new vision presumes multiple local observers, each using a closed laboratory, applying instruments, performing measurements of some physical quantities, and inferring others, such as the electrical and

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[34] Kant (1781/1952, pp. 24–25).

[35] Mach (1919 p. 243).

magnetic fields, through using and constructing physical theories which account for the local perspective of any observer. This activity essentially expanded the area of "directly perceived" (visual), *kinematic* perspective. Yet, the kind of observers involved in this initially introduced relativity theory, however, remained inertial; a dynamical account and gravitation were left outside the theory.

In the next phase, the *general* theory of relativity expanded to the accelerated observers and included gravitation. Multiple observers, regardless of their kind, could perform an empirical account of all phenomena, including gravitation and acceleration, which happened to be impossible to distinguish as long as the *local* observer performed measurements in a closed laboratory.[36]

Einstein's relativity replaced Galilean *kinematics and dynamics* accounts which vary between different observers. Mach's "We may interpret the one case that is given us, in different ways. … The principles of mechanics can, indeed, be so conceived, that even for relative rotations centrifugal forces arise"[37] obtained a much more sophisticated meaning beyond mere relativeness. Indeed, Newtonian physics treated relative rotation without any problem. The issue of multiple observers of different kinds, as Einstein (and Huygens before him) suggested, produced new kinds of non-interactive inertial forces, which had not existed for non-accelerating observers. This violated the Newtonian definition of interactive forces.

Among other innovations, the concept of weight was redefined, based on the principle of equivalence which excluded the univocal identity of weight/gravity as gravitational force. It became possible to fully realize the meaning of the discovery made by Christian Huygens much before. The operational concept definition came to the fore and complemented theoretical definitions.[38] The operational definition of weight removed the strange situation in which the magnitude of weight (if defined as the gravitational force—the Newtonian definition) did not match the weighing result (as used in commerce, for instance). In geodesy, theoreticians recognized the contribution of the centrifugal force in the results of weighing and distinguished between the *true* weight (gravitation force or "attraction") and actually perceived and measured heaviness/gravity. This was much before the theory of general relativity. In 1873, before Mach, Todhunter wrote in his study that for practical reasons, he distinguished between attraction and weight:[39]

> By gravity [heaviness] I denote the force which arises from the combination of the attraction [gravitation] and the so-called centrifugal force; and weight may be considered as an effect produced by gravity as the cause.

Yet, without the new *theoretical* framework of multiple observers, the new role of the *observer* in its Einsteinian version, such "practical strategies" such as those stated by Todhunter were undermined by Newtonian epistemology as merely auxiliary assumptions fixing "local inconsistencies." Within the new vision, however, the fact that both gravitation and inertial forces cause exactly the same effect—heaviness, tension of the suspending rope, and the gradient of stress within a physical body—was finally taken as

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[36] e.g., Einstein (1920, p. 55), Born (1922/1962, p. 213), Reichenbach (1927/1958, p. 230).

[37] Mach (1919, p. 232).

[38] Margenau (1950) formulated the requirement of compound concept definitions—theoretical, together with operational, as equally fundamental.

[39] Todhunter (1873/2023, p.16).

fundamental. Reichenbach in 1927 recognized these aspects causing weight to be distinguished from gravitation by multiple observers. He wrote:[40]

> What is the basis of this indistinguishability? According to Einstein, its empirical basis is the equality of gravitational and inertial mass. This new distinction must be added to the usual distinction between mass and weight. There are therefore three concepts: inertial mass. gravitational mass, and weight. The concept of weight will also be subject to certain changes. In Newtonian mechanics, weight results from the single gravitational force which pulls the body down at all points. In Einstein's mechanics, on the other hand, the body is in a "state of stress" due to the gravitational field; it is subject to tension and compression in all directions. These may now be combined in a resultant which we call 'weight'. Newtonian mechanics knows only this resultant.

In particular, the force, perceived while supporting/suspending an object and measured in the procedure of weighing (T force equal to mg* in Fig. 5a), was taken as indicating weight. Weight, as the perceived heaviness, or, in its archaic synonym, gravity, is split from gravitational force.

2.7 The Quantum Refinement

The final refinement of the role of observer and observer dependence was introduced by the quantum theory of mechanics. This time, the role of an observer in reference to the considered system was upgraded. Within the new vision, the observer, while investigating the reality in his laboratory, deals with specific features in the *micro* world (atoms and subatomic objects). Several new features of this reality emerge.

Firstly, each elementary particle (quantum object) exists in states (eigenstates) specific to each observable quantity describing the particle. These states can be discrete or continuous in the magnitude of the observable.

Secondly, the state of a particle can be pure or a superposition of several eigenstates with weight coefficients. The set of these coefficients establishes a wave function—a full description of the particle.

Thirdly, the coefficients of the superposition determine the value of the observable to emerge in the act of specific measurement predicted statistically.

Fourthly, in the depiction of a quantum object, observables split into two mutually exclusive groups. Only the observables within each group can be determined simultaneously and can coexist in exact values. An attempt to measure observables from two groups produces unavoidable uncertainty, limited by a minimal value.

Of course, these rules make the role of observer more sophisticated and demanding in planning measurements and their interpretation. However, it is important to emphasize that despite the new features, and especially the statistical type of measurement prediction by the observer, this does not change the objective nature of the scientific knowledge. In exact similarity with classical mechanics, the observer plans and constructs the experiment while its results are determined by nature. Given the experimental setting, the observer may not determine the exact results of the measurement but can provide their distribution. "Statistical" does not mean chaotic or unpredicted. Scientific knowledge remains objective. The aspect of objectivity emerged due to the connotation with the term "observer" and was discussed by physicists, science educators, and philosophers.[41]

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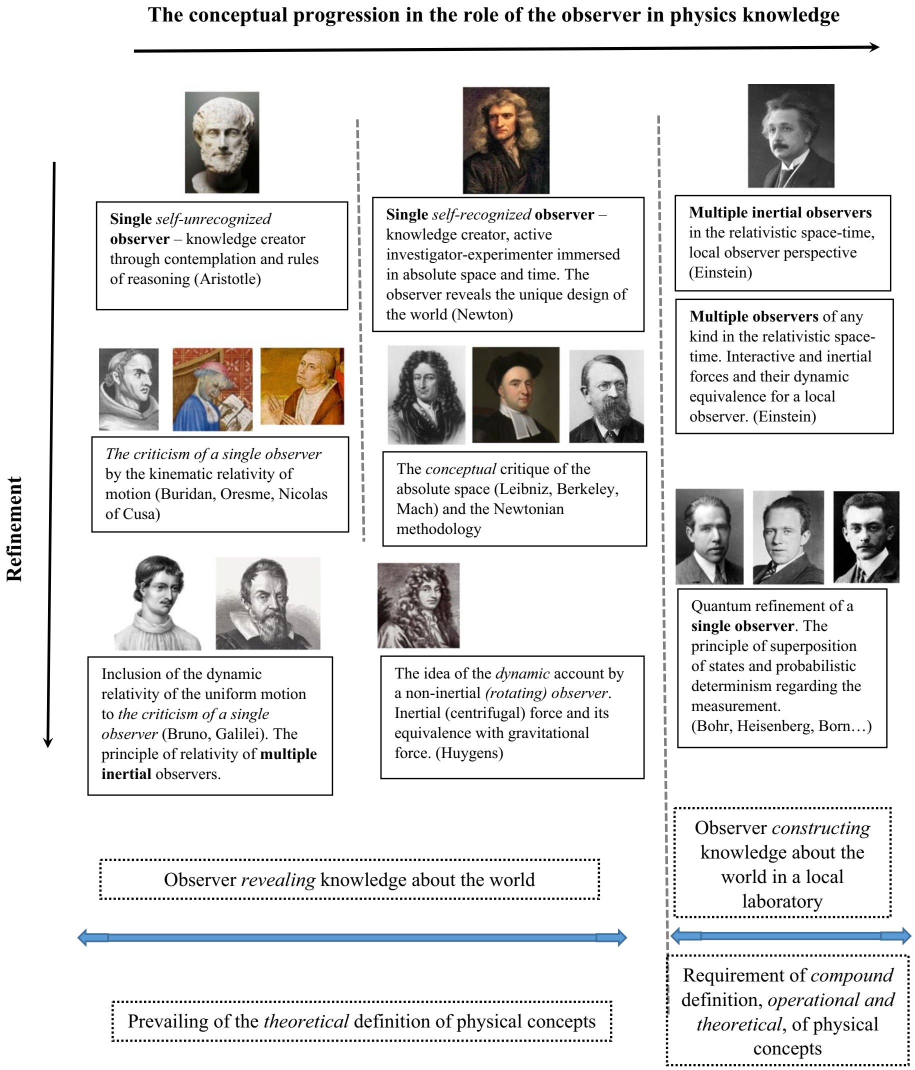
[40] Reichenbach (1927/1958, pp. 223, 235).

[41] Galili (2019a).

2.8 Summary of the History

We have thus reviewed the evolution of the role of observer in physics. The complexity of the concept has essentially grown both ontologically and epistemologically throughout the whole history of science. This fact places a significant challenge in representing scientific knowledge, particularly in education. We will consider this aspect in the following.

To summarize, we present here the flowchart of the evolution of the observer concept in the history of science (Fig. 6). The flowchart emphasizes major changes regarding the observer concept in physics. Of them, one may identify two major periods. The *first* period unites the classical Greek, medieval, and Newtonian classical physics. The idea of a single observer revealing the all-inclusive, the universal in the form of knowledge,



Single *self-unrecognized* **observer** – knowledge creator through contemplation and rules of reasoning (Aristotle)

The criticism of a single observer by the kinematic relativity of motion (Buridan, Oresme, Nicolas of Cusa)

Inclusion of the dynamic relativity of the uniform motion to *the criticism of a single observer* (Bruno, Galilei). The principle of relativity of **multiple inertial** observers.

Single *self-recognized* **observer** – knowledge creator, active investigator-experimenter immersed in absolute space and time. The observer reveals the unique design of the world (Newton)

The *conceptual* critique of the absolute space (Leibniz, Berkeley, Mach) and the Newtonian methodology

The idea of the *dynamic* account by a non-inertial *(rotating) observer*. Inertial (centrifugal) force and its equivalence with gravitational force. (Huygens)

Multiple inertial observers in the relativistic space-time, local observer perspective (Einstein)

Multiple observers of any kind in the relativistic space-time. Interactive and inertial forces and their dynamic equivalence for a local observer. (Einstein)

Quantum refinement of a **single observer**. The principle of superposition of states and probabilistic determinism regarding the measurement. (Bohr, Heisenberg, Born…)

Observer *revealing* knowledge about the world

Observer *constructing* knowledge about the world in a local laboratory

Prevailing of the *theoretical* definition of physical concepts

Requirement of *compound* definition, *operational and theoretical*, of physical concepts

Fig. 6 The flowchart of the conceptual evolution of the role of observer through the history of physics valid everywhere in the universe, prevailed. This period spreads from Aristotle to Newton. Though multiple observers were included in the medieval and entered classical mechanics, this extension had a limited significance being limited to inertial observers. The latter allowed the relativity of views rather as a simple variation of kinematic appearances while preserving dynamic (interactive forces) accounts by inertial observers, easily permitted by classical physics operating in the all-inclusive space and time, absolute and shared by all.

The *second* period signified the revolutionary transition to *multiple observers* of any type, inertial and non-inertial observers, each a local laboratory. As its first step, it changed the kinematic, space, and time accounts thus removing a simplified image of perspectives in exchange for moving an observer from place to place. The great change took place in dynamics, the force accounts, of course.

Another feature mentioned in the flowchart addressed knowledge construction, in particular, concept definitions. The first period could be perceived rather through the allegory of knowledge *discovery*, the discovery of the fundamental design of the universe in the form of a theory. This vision may justify the prevalence given to the theoretical definition of concepts simply illustrated by operational ones. Moving to the observer in a local laboratory, however, moderated the ambition of the researcher who *invented* and constructed the new theory. This vision made the operational concept definitions and theoretical definitions equally important in the complementary relationship within a compound concept definition.

3 Representation of the Role of Observer in Physics Education

The historical evolution of the observer concept was projected onto the image of physics constructed in education. Naturally, there was a certain time lag after the appearance of new ideas in science. Ascribing importance to the role of the observer characterizes, in particular, modern physics, relativity, and quantum. Seemingly, for this reason, the concept of observer is often neglected and optional in teaching other parts of modern science, classical mechanics among them. The emphasis of school teaching is often on the application of physics knowledge, rather than on its foundation. Moreover, in teaching classical mechanics, the idea of observer is often impoverished by replacing it with the *frame of reference*, a formal tool for problem-solving, lacking the act of making sense of observables, seeking explanation within a chosen theory, or constructing a new theory. To illustrate the situation, we will consider a number of representative examples related directly to the concept of observer.

3.1 Season Change

The phenomenon of season change was originally explained by Greek science from the view of a terrestrial observer.[42] Copernicus suggested another explanation as viewed by an imaginary observer at rest, relative to the Sun.[43] Galileo corrected the Copernican explanation and provided a more adequate explanation of the phenomenon using the concept of light flux.[44]

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[42] Kuhn (1995, p. 10).

[43] Copernicus (1978, p. 24).

[44] Galilei (1632/1953, p. 80).

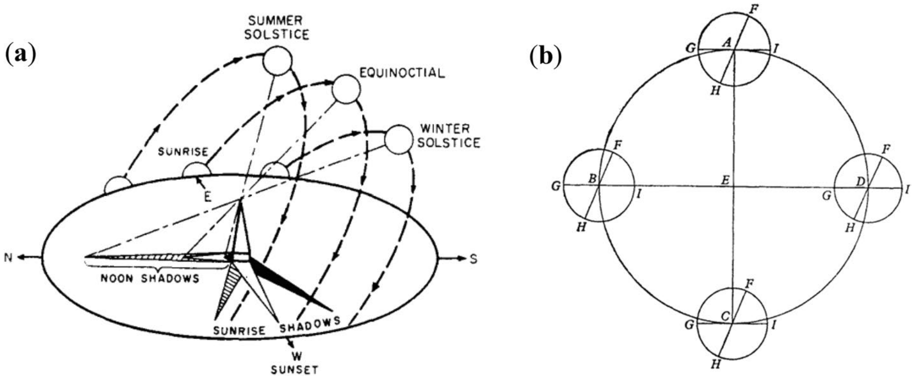

Fig. 7 (**a**) The sketch explaining seasons' annual change within the geocentric framework. **b** The sketch from the Copernicus treatise which explained seasons' annual change within the heliocentric framework. The imaginary observer is presumed outside of the Earth, at rest relative to the Sun in the center of the Earth's orbit

Importantly, while both sketches present a correct explanation of the seasonal change, it is the observer of Fig. 7a which corresponds to the actually observed phenomena, whereas the observer of Fig. 7b has to be imagined. Textbooks today use a much more artistic version, often an animated illustration, but of the same heliocentric model, not specifying the observer at all—a "pure" truth.

In education, the interest in students' knowledge started with the scandalous report on the failure of Harvard PhD students of theoretical physics who showed an amazing ignorance in their understanding of seasons.[45] That study, under the title "Private Universe," heralded a burst of interest in students' misconceptions, often called alternative knowledge. Its publication caused a wave of reports regarding similar failures of teachers and students in colleges and schools.[46] As to the reason which could cause the particular failure of students, researchers mentioned the everyday experience with heaters (the closer to the stove—the warmer it is). Others pointed to the deficient school curriculum lacking the concept of flux.[47]

However, here we may point to another striking feature of the curriculum. Very often, teaching addresses the seasons' change only once, in elementary school. Moreover, it is explained solely within the heliocentric framework, ignoring the geocentric. This is at the time when many young students still incline to the egocentric interpretation of reality directly related to their actual perception.[48] This is in exact parallel with the geocentric understanding of the world by the early science. Doesn't it look like a recapitulation?[49] In any case, despite the widely agreed need for the spiral curriculum, promoting hermeneutic conceptual refinement, seasons are addressed once and from the perspective of a cosmic observer, forgetting about the light flux account. This leads the way to the ignorance of a wide public regarding the causes of seasons.[50]

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[45] Atwood & Atwood (1996).

[46] Schnepps & Sadler (1989).

[47] Galili & Lavrik (1998).

[48] Piaget (1930).

[49] Piaget (1970).

[50] Galili & Lavrik (1998).

3.2 Earth Motion and the Foucault Pendulum

The issue of the Earth's motion is considered to be a simple fact nowadays and is often declared without any discussion. The Earth moves. It is "obvious" and there is nothing to talk about. At the same time, the stationary Earth is our everyday context. The dropped contradiction is about observer dependence. The univocal perspective of a cosmic observer is often the only one considered in class. Bridging between the *two observers* as legitimate could be the alternative. These two observers are often linked to the struggle of science against religion: Bruno and Galileo against the inquisition, "Eppur si muove" ["And yet it moves"].[51] Whether the Earth moves or not was a highly passionate debate until the seventeenth century, when people believed in motion in its Newtonian meaning in absolute space. The observer at rest in the absolute, all-inclusive space prevailed in physics until the twentieth century. In 1893, Mach reminded his readers about the relativity of motion:[52]

> …the motions of the universe are the same whether we adopt the Ptolemaic[53] or the Copernican mode of view. Both views are indeed equally correct; only the latter is more simple and more practical. The universe is not twice given, with an earth at rest and an earth in motion but only once with relative motions, alone determinable.

In fact, however, this critique was still not sufficiently mature as it did not use the *dynamic* account of different observers, as Huygens did. Also saying that the Copernican mode of view is more "practical," is rather confusing given any on-ground navigation… In any case, school curricula usually do not offer any relativism of the claim regarding the Earth's motion, even at the level of kinematics. Since the twentieth century, there could, and should, be more appropriate phrasing avoiding addressing the Earth's motion in absolute terms.

Furthermore, for the broader public, the Foucault pendulum is the commonplace demonstration of the Earth's rotation (Fig. 8a), while what was directly observed was the rotation of the plane of pendulum oscillations (Fig. 8b). Again, the explanation of the experiment commonly appeals to the same imagined cosmic observer,[54] missing the essential feature of motion, its relativity with respect to other bodies, as argued by so many since Galileo. The pendulum experiment in Paris was arranged in 1851. At that time, physics held only one view—the Newtonian absolute space. What was observed was considered then the Earth's rotation with respect to that space by a cosmic observer. The interpretation (erroneous, within the modern epistemology) was provided by Newton regarding the abovementioned water surface in a swirling bucket where the water recedes from the axis of rotation.[55] The alternative terrestrial non-inertial observer has to apply the Coriolis inertial force, illegitimate in the Newtonian framework of interactive forces.

The possible change to the school curriculum expected in the future would address two observers and bridge between their accounts, excluding considering motion in absolute terms as inappropriate context today.[56] Clearly, public discussion and popular literature have no such limits, e.g.,[57]

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[51] Ascribed to Galileo after being investigated by the inquisition in Rome, in 1633.

[52] Mach (1919, p. 232).

[53] Tychonian, instead of Ptolemaic, would be more appropriate here.

[54] e.g., Flammarion (1964, pp. 60–61).

[55] Newton (1999, pp. 412–413).

[56] Born (1922/1962, pp. 71–72).

[57] e.g., Tauber (1979, p. 161), What keeps the Focault pendulum at the Pantheon in Paris going?—Quora.

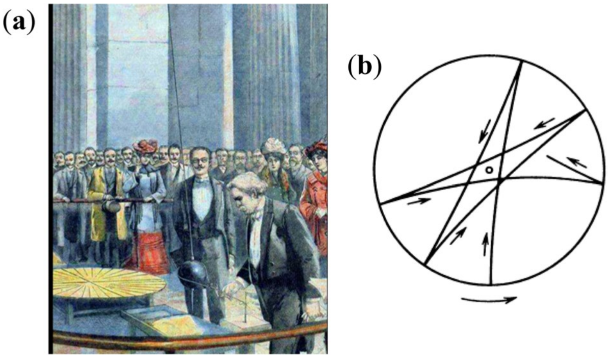

Fig. 8 (**a**) The pendulum experiment by Foucault in 1851 in the illustration from *Le Petit Parisien* in 1902. **b** The sketch of the track change of the pendulum bob is from the school physics textbook Landsberg in 1944

> This was not because the pendulum itself was rotating, but because the **Earth was rotating underneath it.** [that is to say, do not believe to your eyes… I.G.] The pendulum was acting like a gyroscope, preserving its orientation in space while the Earth moved around it. (emphasized in the original)

Poincare addressed the situation not in this way. He, much more maturely, stated another view, but who cared?[58]

> …these two contradictory propositions: ‘The earth turns round’ and ‘The earth does not turn round’ are, therefore, neither of them more true than the other. To affirm one while denying the other, in the kinematic sense, would be to admit the existence of absolute space

Poincare concluded:

> The truth for which Galileo suffered remains, therefore, the truth, although it has not altogether the same meaning as for the vulgar, and its true meaning is much more subtle, more profound and more rich.

Sounds like a challenge? It definitely is, but it is about teaching physics after the nineteenth century, and science philosophy may be helpful in this, making the new teaching feasible and more interesting. We succeeded in locating a school physics textbook with an appropriate passage addressing the Foucault pendulum:[59]

> If these forces explain the observed motions of the bodies, i.e. the forces and accelerations obey Newton’s second law in all cases, the system is inertial. If, however, it turns out that there are accelerations that cannot be explained by the action of other bodies, this means that the system is non-inertial, and accelerations are due to corresponding inertial forces. An experiment proving in this way the fact that the Earth is a non-inertial system (namely, its rotation relative to inertial reference systems).

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[58] Poincare (1913/2015, pp. 353–354).

[59] Landsberg (1944/1988, pp. 250–251).

3.3 Weight and Gravitation

As was mentioned, the concept of observer projects onto the definition of weight. The latter had three periods of understanding—(1) body heaviness (weight, gravity) is its feature (coincides with the quantity of matter), (2) body heaviness (weight, gravity) is determined by the gravitational force exerted on the object (and is different from its mass, the quantity of matter), and finally, (3) body heaviness is defined in standard weighing (by a calibrated spring or pendulum) regardless of the cause.[60] The first two periods coincided with the idea of a unique universal observer and a prevailing theoretical definition of concepts, while the third period brought to the fore the operational definition.

The transfer to the third historical stage of weight understanding in the era of modern physics followed the transfer to multiple local observers, the sensitivity to operational definition of concepts, and the full recognition of the equivalence principle (the shared identity of gravitational and inertial forces:[61]

> The same quality of a body manifests itself according to circumstances as "inertia" or as "weight" (lit. "heaviness").

Physics education embraced the new approach which distinguished weight from gravitation in teaching mechanics, firstly, at the university level.[62] Soon after, Landsberg published a school physics textbook[63] with the same weight account. However, due to the highly uniform curriculum in the USSR, the transfer to the operational definition of weight was fast and all-inclusive. Millions of students heralded the new era of the public understanding of weight.

The previous understandings of weight were ignored by the authors, and they explicitly referred to the *observer* in a local lab, copying the approach of Einstein's observer in an elevator (Fig. 9).[64] Newtonian weight was as if it never existed… Later, the new approach to weight and the related observer emerged in the US.[65] Yet, there, and in many other countries, the apparent majority of the textbooks retained the Newtonian approach, though modified, by splitting weight into the *true* (gravitational force) and the *apparent* (weighing result).[66] A slow transfer of the authors to the new approach can be observed.

In fact, however, with regard to the definition of weight, physics education is currently split between the second and third historical stages. To represent the plethora of weight definitions, we list the following examples:

> The *weight* of the body is the total gravitational force exerted on the body by all other bodies in the universe Young & Freedman, 2012, p. 406)
> So each observer thinks that tension F must be opposed by an equal and opposite force W which we call the *apparent weight*.[67]

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[60] Galili (2001), Moody & Clagett (1952, pp. 123, 124, 147, 161…).

[61] Einstein (1920, p. 53), Reichenbach (1927/1958, p. 235).

[62] Chaikin (1940/1971).

[63] Landsberg (1944/1988).

[64] Einstein & Infeld (1938, p. 33).

[65] Orear (1961, p. 59), King (1962), Marion and Hornyack, 1982, p. 129), Keller et al., (1993, pp. 99–100), Knight (2013, p. 146).

[66] Orear (1979, pp. 86–87), Young & Freedman (2012, pp. 421-422).

[67] Young & Freedman, 2012, p. 422).

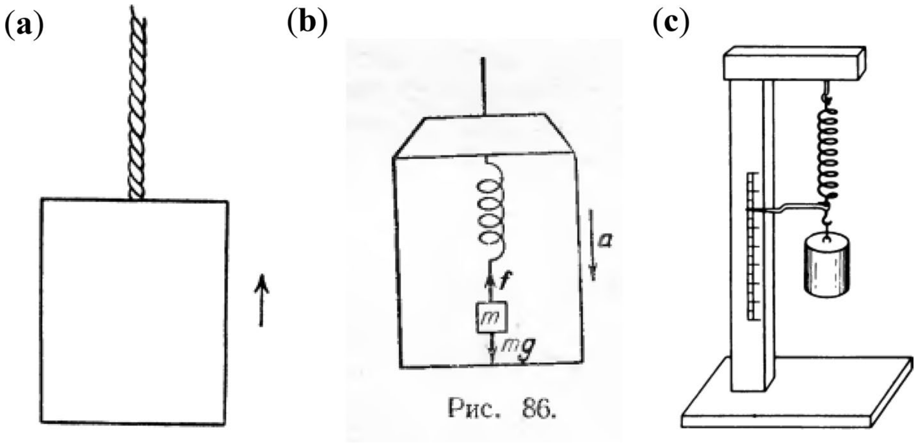

Fig. 9 (**a**) Einstein's sketch of an elevator in 1938. **b** Chaikin's sketch of an elevator in 1940. **c** Landsberg's illustration of the weight definition in 1944

> The weight of a body in a specified reference system is that force which, when applied to the body, would give it an acceleration equal to the local acceleration of free fall in that reference system.[68]
>
> The contact force that an object exerts on whatever is supporting it is called the *weight* of the object.[69]
>
> The *weight* of an object will be defined as the magnitude W, of the upward force that must be applied to the object to hold it at rest relative to the earth.[70]

Of these cases, the first represents the gravitational definition of weight, while the following three reproduce the variations of the operational definitions (to which one may add [1b]). It can be shown that all three operational definitions are physically equivalent in magnitude while only definition 3 addresses the force applied to the support, unlike the others which are exerted on the object itself.

In parallel, educational research revealed the negative potential of the gravitational weight definition with respect to students' learning, especially protruded in the account of free gravitational motion (free falling), the state of weightlessness.[71] In this context, the educational preference for the operational definition of weight is apparent.[72] It was revealed that students' conceptions of weightlessness distinguish between the observer inside the space station and outside it, on the Earth's surface.[73] The split in science education with regard to the weight concept remains; the debate continues, but the role of observer in this dichotomy, though essential, is not well appreciated. Is it a necessity? In fact, it is.

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[68] ISO (1992), Keller et al., (1993, pp. 99–100).

[69] Marion & Hornyack, 1982, p. 129).

[70] French (1971, p. 130).

[71] Galili & Kaplan (1996), Galili (2021b).

[72] Galili et al. (2017).

[73] Stein & Galili (2015).

This is because, in common practice, people do not fully adopt weight as mere gravitation. In commerce, for instance, people always knew that the measured weight of a quantity of matter varied at different latitudes. That led people to refrain from the simple identity of weight and the attraction to the Earth (correction tables were introduced). Practice and theory were viewed differently by the wider public outside of the physics classes.

3.4 Tabu on Inertial Forces

Many physical situations can be explained in a significantly simpler way by the non-inertial observer using inertial forces. Yet, as with the concept of weight, the curricular situation is complex, more complex than it is in science. As was described above, inertial force, in its modern meaning, was introduced by Huygens as centrifugal force, and it was immediately suppressed by Newton. Revived by d'Alembert as a trick without reference to any observer, it remained such until the scientific revolution of the twentieth century, when Einstein revived it together with the concept of observer. In physics textbooks, however, inertial forces remain under the title "not real," "imaginary," and "pseudo-force." Seemingly, their great "sin" is that they are observer-dependent: non-inertial observers "have" them, inertial do not, and those forces are not interactive."Clearly, they merely present an illusion…"—a common statement in many schools and even some university physics textbooks:[74]

> In an inertial frame of reference there is no such thing as "centrifugal force." We won't mention this term again, and we strongly advise you to avoid using it as well.

Inertial forces are usually excluded from school mechanics curricula, but are normally present in university courses. Given the simpler account for dynamic reality through using inertial forces, we observe the following shortcomings in the present situation in classes:

> *1. Ignoring well-known natural phenomena.* The curricular decision to ignore inertial forces implies a practical inability to address such natural phenomena as the flattened Earth globe at its poles, for instance. The account for this phenomenon, without inertial forces, is rather difficult. Newton himself used Huygens' centrifugal force in his explanation,[75] forgetting its previous rejection in Part I of the same *Principia* (Fig. 10a).[76] Among other phenomena usually explained using inertial forces are the Coriolis force, eddies (cyclonic and anti-cyclonic) motions of the atmosphere (Fig. 10b) and the unequal erosion of banks where the river flows along the meridian. When water moves to the south, it washes away the right bank making it steeper than the left one (in the Northern Hemisphere). Similarly, the right rail of the railroad is worn out more quickly when the train runs to the south.

The phenomenon of tides is usually addressed in university textbooks and often (not always[77]) using inertial forces.[78] We found a rare case where the school textbook mentioned the rotating terrestrial observer stipulating the employment of inertial forces (Fig. 10c).[79]

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[74] Young & Freedman (2012, p. 155).

[75] Newton (1687/1999, Book III, Proposition XIX).

[76] Newton (1687/1999, Book I, Sect. 2, Scholium, pp. 452–453).

[77] e.g., Benson (1996, pp. 277–278).

[78] e.g., Benson (1996, pp. 277–278).

[79] Landsberg (1944/1988, Fig. 211, p. 253).

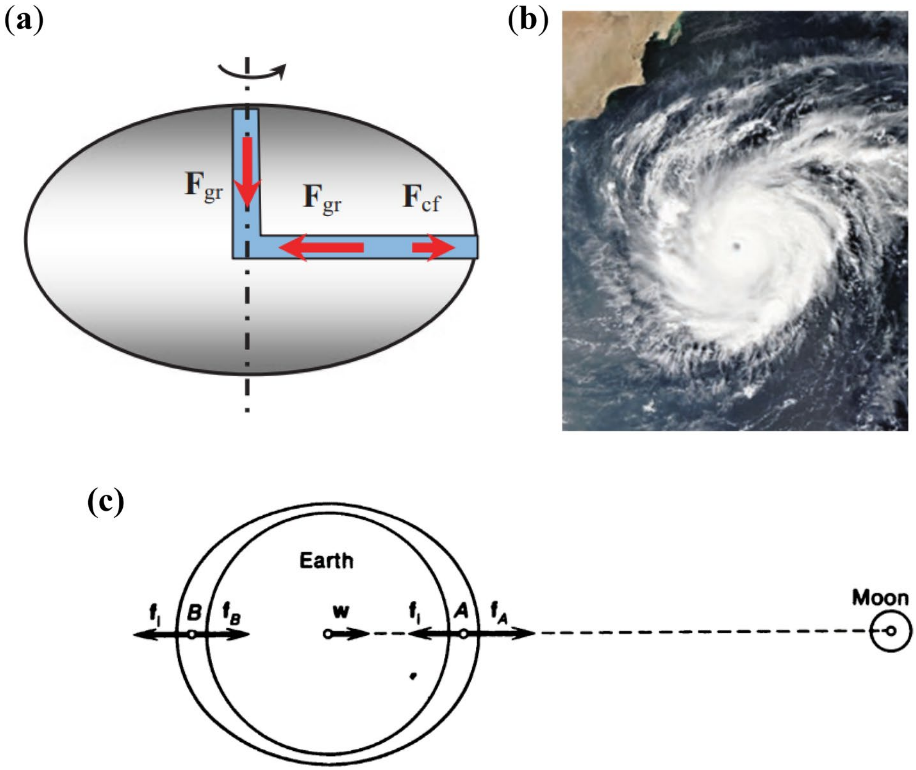

Fig. 10 (**a**) Reconstructed sketch by Newton in his proof of the Earth flattened at the poles. F_{cf}—the non-Newtonian centrifugal force—was used; thus, the rotating observer was tacitly presumed. **b** Cyclonic motion of atmosphere: its description by the terrestrial observer requires Coriolis force (photo credit: NASA). **c** Explanation of tides by the observer on the rotating Earth in school physics textbooks. f_i, inertial force, f_A, and f_B ($f_A > f_B$) are the attraction of water by the Moon and w is the acceleration of the Earth towards the Moon

2. Rebellion in engineering and astronomy. An interesting situation is observed in engineering and astronomy textbooks. There, the centrifugal force is widely used as a *regular* force playing the central role together with gravitational force. Thus, in engineering, the centrifugal force emerges as the factor causing the breaking apart of wheels and flywheels at high spinning rates, in Watt's speed governors in steam engines (Fig. 11a), in the account of the appropriate inclination of rails to cause the tilt of trains in turning, to calculate the periodic change of train direction to prevent asymmetrical burnout of rails for the Coriolis force, etc. In astronomy, the centrifugal and Coriolis forces are among the major factors determining the structure of galaxies and black holes' environments, planetary structure in the solar system, the inner structure of planets, etc. The amazing fact is, however, that the great multitude of textbooks in these science domains numerously apply inertial forces without any mention of the required, in this case, non-inertial observers (Fig. 11b). This lack of matching in generic mechanics courses is striking.[80]

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[80] e.g., Boyd (1921), Bansal (2016), Harrison (2000, p. 129), Rudaus & de Vaucouleurs (1959, pp. 78–79).

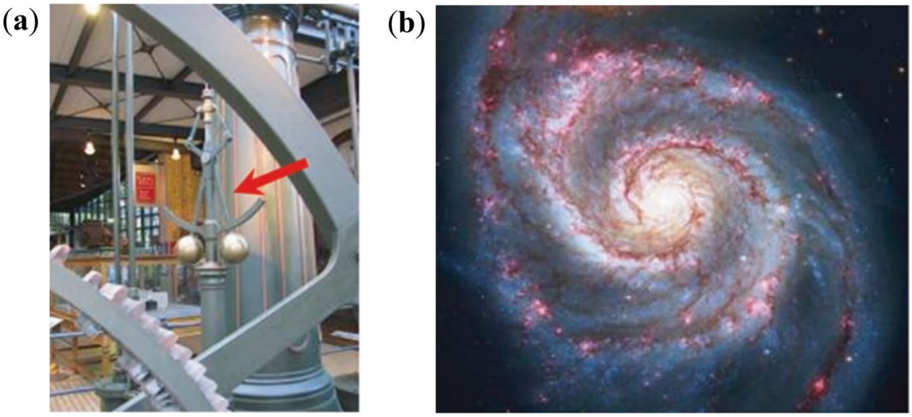

Fig. 11 (**a**) Steam machine in a museum of technology. Watt's centrifugal governor of two balls receding under spinning (marked by an arrow). It is explained by a centrifugal force which requires a rotating observer—never mentioned in engineering texts. **b** A spiral galaxy (photo credit: NASA). Explanation of its structure normally uses centrifugal and Coriolis forces which presume a specific observer—usually not mentioned

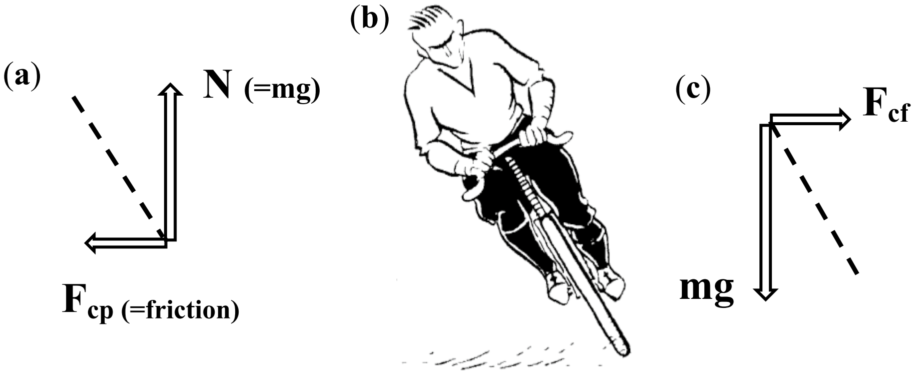

Fig. 12 (**a**) Free body force diagram for the bicycle rider on the turn as learned at school (Newtonian). F_{cp} centripetal force produced by friction. **b** Bicycle rider on passing the turn (Hogben, 1938, p. 268). **c** Free body force diagram for the bicycle rider on the turn in accordance with Huygens. F_{cf} centrifugal force acting on the rider. F_{cf} and F_{cp} (centripetal force) are equal in magnitude but must be used by different observers

3. Public understanding and the hidden observer. Though only a minority of the wider public had physics in their educational background, the term "centrifugal force" is a colloquial commonplace when discussing riding a bicycle—the necessity of the bicycle tilting towards the turn (Fig. 12), with a car—the necessary reduction of speed on turns, tilting while riding a horse, skiing, and skating, and so on and so forth. All these are used by laymen as intuitive behavior, without any reference to the observer, while stipulating stability in such activities. Yet, the explanation of centrifugal force may puzzle our students in advanced placement courses in school physics where they were indisputably

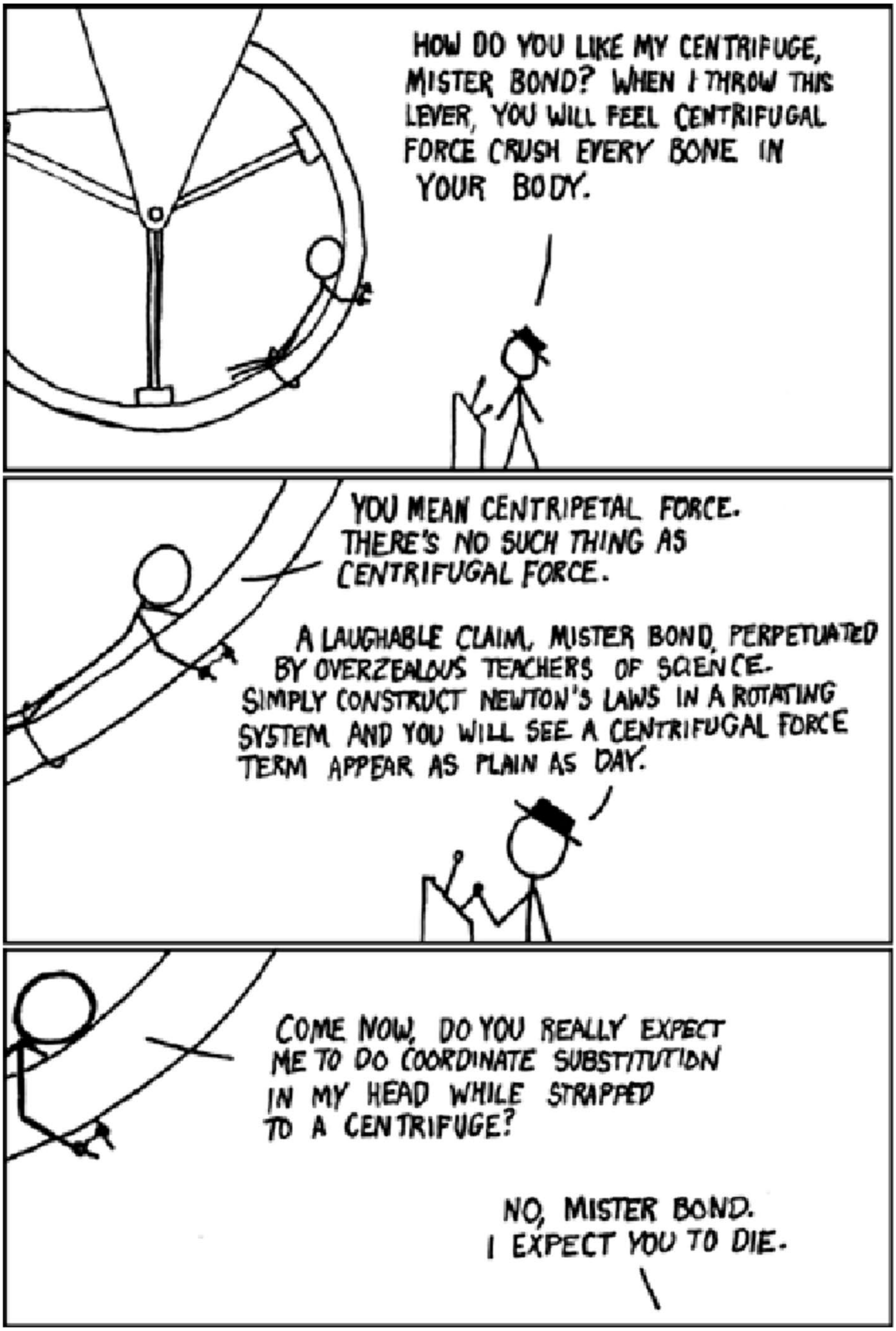

Fig. 13 Comics used to joke about the reality of the centrifugal force based on Adam Grim's comment in the discussion on how to resolve the centrifugal force misconception (see footnote for the reference)

> informed of the purely imaginary, illusionary nature of fictitious inertial forces that actually “do not exist…”.

At the same time, moving in accelerated vehicles, wagons abruptly stopping or speeding up have plenty of moments when we rebuke the driver for careless driving causing unpleasant tilting and even passengers falling. The Luna park provides numerous activities which no young person wishes to miss and which are saturated with situations which make sense to people through referring to inertial force. In all these, students clash with what their physics teachers say in class.[81] The question arises as to whether the teachers should ignore such a mismatch. Should they ignore observer dependence in arguing by force? And if we do mention the observer, should we haphazardly mix different types of observers: the observer as introduced by Huygens, non-inertial, and that of Newton, the inertial observer, as so often has been done in relevant literature?

> *4. Spontaneous inertial forces in schools, unanimous “hostility” to the “the misconception.”* The common physics curriculum ignores inertial forces in school and considers them as a straightforward misconception, “the forces which do not exist in the real world”… Educators discuss this heresy and try to struggle with it by all possible means, using persuasion, animation (Fig. 13), comics,[82] computer technology, whatever, and a real crusade… (e.g., “The Forbidden World”).[83]

However, researchers in physics education probed students’ knowledge regarding a variety of accelerated motion situations and reported on spontaneously invented inertial forces by school students, including those from prestigious schools, who were never instructed in inertial forces.[84] The authors reported a spectrum of naïve views which recalled historical views regarding motion, forces, and inertial forces that had been held and expressed by Buridan, Kepler, Descartes, Borelli, Huygens, and Newton, views that were invented without any formal instruction in class.

3.5 The Attempt to Reconsider “the Misconception”

Facing this rather unsatisfactory situation with regard to addressing the concept of the observer as taught in school, and drawing on pertinent materials regarding inertial forces and the epistemological revolution of the twentieth century in physics, we carried out a teaching experiment.[85] To accomplish our depiction of the subject matter, the concept of the observer in education, we briefly present here the major points of our study and its inferences.

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[81] e.g., Mårtensson-Pendrill (2021), Pendrill (2023).

[82] Grim, A. (2003) in a long discussion—How to resolve centrifugal force misconceptions (centripetal force, centrifugal forces, physics)—Quora.

[83] The Forbidden F-Word (physicsclassroom.com); How to resolve centrifugal force misconceptions (centripetal force, centrifugal forces, physics)—Quora; Centrifugal Force—The Misconceptions by Jay Douglas (prezi.com).

[84] e.g., Galili & Bar (1992), Galili & Kaplan (2002), Volfson et al. (2020)

[85] Stein et al. (2023).

The experiment lasted for 2 years following a pilot year. The pilot included the construction of a new teaching unit for 12 meetings (double-period lessons of 90 min) with middle school students. The school was a regular urban school with an integrated social background population in central Israel. The major part of the experiment was conducted over 2 years involving 9th-grade students from two classes over two sequential years, 117 students in four groups. To increase the reliability of the results, our sample comprised whole classes. Each year, there was an experimental and a control group, approximately of the same size.

The teaching unit addressed observer-dependent concepts in physics. In the first half, six meetings included certain epistemological information regarding the observer (Plato's "Cave Parable," the debate on the geocentric and heliocentric models, observer dependence of motion perception, reliance on human senses) and addressed kinematic concepts depicting motion. Considering kinematic relativity of location, distances, velocities, and accelerations was not new in principle, but we certainly introduced it in a more intensive and richer way. The idea of an operational definition of physical concepts was introduced in this context.

The discussed observer dependence in kinematics paved the way for the observer dependence of the dynamic account in another six meetings. In particular, an observer on a rotating disc was addressed (the setting used by Huygens, Fig. 5a), and the centrifugal force was introduced to keep the force equilibrium in view of the rotating observer trying to act in accordance with Newton's second law of motion. The observer dependence on centrifugal force emerged in comparison with the outside inertial observer who did not need centrifugal force to account for the situation. The operational definition of force as the cause for deformation of the calibrated spring (Fig. 9) was established. The situations in the bus/car on the turn in the road, acceleration, and stopping were explained in view of inner (non-inertial) and outside (inertial) observers. Finally, the issue of gravitation and weight was considered another case of observer dependence on the dynamical account. The context of the orbiting space station was used to account for weightlessness inside the station by two observers, the terrestrial and a passenger in the station. The two accounts of the same situation illustrated the relativity of the dynamic account by two observers of different types, inertial and non-inertial.

The assessment of the results provided evidence for a positive impact on several aspects. In particular:

- There was significant success in the students' ability to describe situations from the perspectives of different observers, that is, to provide graphical dependence of the kinematic characteristics from such perspectives.
- Similarly, significant success was registered in producing free-body diagrams of the forces from the perspectives of inertial and non-inertial observers.
- Importantly, there was a positive correlation between students' success and their naïve knowledge regarding inertial forces, that is, the naïve knowledge served as a positive factor, rather than an obstacle to learning. This was in contrast to the similar evaluation in the control group of regular teaching. Moreover, the naïve knowledge of inertial forces had a higher impact than students' background knowledge in mathematics.
- Students showed greater interest in learning the new curriculum than in the regular curriculum. They mentioned that multiple accounts based on observer dependence made learning physics more interesting and attractive.

Summarizing, the quoted experiment indicated the absence of cognitive barriers which would prevent the considered innovative teaching and justify the suggested involvement of multiple observers already in middle school. By showing the benefits of the new approach to school students' knowledge, the experiment stimulated further studies considering the reconstruction of the current curricular content with respect to the subject of the observer, particularly at the more advanced levels of instruction.

4 Discussion

Considering the role of the *observer* is rare in educational research (not to be confused with *observation*). This fact determined the character of our study; the necessary reference to the history and philosophy of science in justifying learning about the attitude to this pivotal topic in science epistemology. Indeed, we have found that the latest change in the role of observer was practically missed in science/physics education in schools. To a great extent, physics education in schools has remained in the nineteenth century in this regard. In particular, the transfer from a single observer, with an all-inclusive perspective on the universe, a subject of investigation, to the observer, one of many, each active in a local laboratory receiving signals from outside, using his apparatus previously created and based on the evolutionary constructed theories. The latter vision has almost not reached science education in schools which touch little on modern physics. It is discovered by those few who proceed to specialized tracks in their university education involving relativity and quantum, whereas there are serious implications to the observer concept in classical mechanics as it (should be) taught today. We have discussed specific points where the school curricula, holding the old vision of observer, missed the representative character of physics knowledge today. The pressure for changes with respect to the observer does not come from the ambition to adjust the philosophical framework of thought to be provided by contemporary science education but by very practical needs—massive confusion and misconceptions by students rooted in the inadequate, impoverished, and sometimes obsolete subject matter content of the curriculum of school mechanics, astrophysics, and technology courses, as was illustrated in Part III.

Missing the true meaning of the observer in physics may start from considering the observer as a mere watcher, a lab assistant, that is, ignoring the observer's major role of making sense of the observed. This understanding is in contrast with the frequent identification of the *observer* as a *frame of reference*, depleting the very idea of the observer.

In this regard, we are reminded of the power of the Hellenic bare-hands *contemplation,* only later upgraded by Hellenistic experimenting. Medieval science led towards Galileo, F. Bacon, and others dealt with the observer who had to infer from the observed. Yet, even then, the observer remained alone, in the sense of constructing knowledge of a unique form, and that caused the observer not to be self-aware at all. Only recognizing the views of others could cause self-awareness and dependence on multiple observers. This trend was revealed vis-à-vis the relativity of motion and ultimately arrived at the Galilean principle of relativity. It, however, did not change much as it referred only to specific (uniform, rectilinear) motion, a curious insensitivity of reality which could not change the major scenery—the object sailing in the ocean of absolute space. Indeed, not any motion is non-distinguishingly relative. The ideas of rotational inertia (Galileo) appeared to be erroneous in classical mechanics (Descartes and Newton). Relativity of motion remained a rather fuzzy philosophical idea. Newton did not ascribe any complexity to the fundamentals:[86]

> time, space, place, and motion are very familiar to everyone…

In fact, Newton articulated the commonplace, the generally known, perception of absolute space, and the container of the universe. The conception was so strong that when a different dynamical account by Huygens (a new type of observer and a new type of force) did appear, it was not understood and simply rejected as mentioned above. Leibnitz and Berkeley's critiques of absolute space (that was equivalent to the unique observer), remained known to philosophers and unimportant to the physicists.

As we know, Einstein changed the game through the claim that (the Newtonian) mechanics laws are valid not for any observer; for the rotating observer, they are not.[87] Einstein aspired towards including any observer. That led to the epistemological revolution—the inclusion of multiple observers making sense of nature, each observing reality in an isolated room (laboratory)[88] and only then communicating this knowledge to other observers, in this way trying to produce a unifying theory. This was a revolutionary conceptual change in physics *epistemology*. It holds true in elementary classical mechanics pushing to the operationally defined forces (valid also in non-inertial frames of reference, inertial forces valid only in non-inertial frames) and in weight/gravity/measured heaviness (different from gravitation). This approach we replicated in our study of experimental teaching.

What could be the implication of a correspondent curricular change? Newton was a founder of classical mechanics. Yet, this knowledge continuously changed throughout history. Newton's laws, as taught in classes today, are very different from those he introduced and from other content, both new and old.[89] Within this perspective, inertial forces, the equivalence principle (the equality of the effect of gravitation and acceleration), and the choice of the observer are not reserved solely for the theory of relativity but present an integrative part of *classical mechanics*.[90] This is the change in school curricula that we argue for.

The other argument for the change is the requirement of *space of learning*, the need to present the scientific content in its conceptual variation.[91] One may refine this general claim through the new approach of the *discipline-culture*[92] as a structure representing

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[86] Newton (1687/1999, p. 408). "Observer" was for him only a synonym of spectator (p. 920).

[87] Einstein & Infeld (1938, p. 164).

[88] Einstein & Infeld (1938, pp. 226–235).

[89] Galili & Tseitlin (2003), Galili & Goren (2023). Even the tradition of teaching mechanics starting from Newton's laws was modified, e.g., Mazur (2021) suggested drawing on the conservation laws as the initial experience.

[90] French (1971, p. 507), Alonso & Finn (1992, pp. 112–114, 274), Goldstein et al., (2001, pp. 174–180).

[91] Marton et al. (2004).

[92] Supplement 1. The discipline-culture (DC) paradigm represents scientific knowledge while keeping with the explicitly identified hierarchical structure of the fundamental theory of the considered domain of knowledge. The paradigm uses triple cultural code. It comprises *nucleus* of the theory (the group of basic principles, concepts, and constitutional models) and *body* knowledge (laws, concepts, working models, experiments, explained phenomena and solved problems), the elements coherent with, drawing on the nucleus and those affiliated to the theory. In addition to the nucleus and body, DC includes the third group of elements, the concepts alternative to the nucleus, open problems, unexplained phenomena. This group constitutes the periphery of the DC and makes the construct nucleus-body-periphery cultural (e.g. Galili 2012, 2021a).

physical theory in general, and specifically in teaching mechanics. This approach will introduce the present understanding of the local observer as evolving through a debate with the older perspective of the observer of Aristotle and Newton, passing through Galileo on the way. This teaching is designed to encourage the construction of cultural content knowledge regarding the observer. The cultural knowledge of the subject includes more than a unique view, but a family of perspectives—a conceptual culture. To understand the meaning of an inertial frame of reference, one needs to see the non-inertial frame. Otherwise—confusion and uncertainty. To appreciate the local observer, one needs to compare it with the observer of Aristotle and that of Newton, and of Galileo. This approach establishes a new educational paradigm to be applied in the regular teaching of the subject matter.[93] Within it, the teaching of seasons should consider the points of view of both geocentric as well as heliocentric observers. The cultural approach to kinematics and dynamics emphasizes the relativity of certain concepts, inertial and non-inertial observers, inertial and interactive forces, and principle of equivalence implying gravitational and non-gravitational weight. This content creates the “space of learning” required for meaningful learning, the mature understanding of classical mechanics. At the same time, there is a place to distance the conceptual variation and cultural richness of knowledge from relativism or other forms of postmodernism. Teaching the disciple-culture of mechanics never forgets to specify the status of considered concepts, their affiliation to the specific theory from the past, classical, or modern.

Finally, anticipating the critique of the high demands of the new teaching, we mention that teaching accounts by multiple observers draw on the ability of abstract thinking, on students’ ability to manipulate multiple perspectives. In accordance with cognitive psychology, the age of middle school students matches this requirement of abstract reasoning.[94] We may say that this was confirmed by the documented success of the experimental study described by us here.

5 Concluding Remark

This study pointed to the lacuna in science/physics education with regard to the concept of the observer, which is an axial epistemological concept of physics having evolved through the history of science to the present day. This study considered the problem of the observer in classical mechanics and the currently emerged discrepancy between science and education in this respect. Our findings call for changes in several fragments of the curriculum including the fundamental concepts such as inertial forces, non-inertial observers, and operationally defined force and weight concepts. Hitherto, the theoretical discussion draws on a single empirical study with middle school students. There is an apparent need for further investigation, both theoretical and empirical, expanding to a range of student populations and levels of science teaching.

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[93] Galili (2012, 2021a).

[94] Piaget (1930).

Declarations

Conflict of Interest The author declares no conflict of interest.

References

Agassi, J. (1969). Leibniz's place in the history of physics. *Journal of the History of Ideas, 30*(3), 331–344.

Alonso, M., & Finn, E. J. (1992). *Physics*. Addison-Wesley.

Aristotle. (1952). *On the heavens*. In the Works of Aristotle. Encyclopedia Britannica Great Books, Chicago.

Assis, A. K. T. & Magnaghi, C. P. (2012). The illustrated method of Archimedes: Utilizing the law of the lever to calculate areas, volumes, and centers of gravity. Apeiron, Montreal.

Atwood, R. K., & Atwood, V. A. (1996). Preservice elementary teachers' conceptions of the causes of the causes of seasons. *Journal of Research in Science Teaching, 33*, 553–563.

Bansal, R. K. (2016). *A textbook of engineering mechanics*. Laxmi, New Delhi.

Benson, H. (1996). *University physics*. John Wiley.

Berkeley, G. (1992). *De Motu and the Analyst*. North Carolina State University, Raleigh, U.S.A.

Born, M. (1922/1962). *Einstein's theory of relativity*. New York, Dover.

Boyd, J. E. (1921). *Mechanics. A textbook for engineers*. Mac-Graw Hill, New York

Burnet, J. (1920). *Early Greek philosophy*. The Meridian Library.

Chaikin, C. E. (1940/1971). *Basic mechanics*. Nauka, Moscow (Russian)

Cohen, R. M., & Drabkin, E. I. (1948). *A source book in Greek science*. McGraw-Hill.

Copernicus, N. (1978). *On the revolutions*. The Macmillan Press

Einstein, A., & Infeld, L. (1938). *The evolution of physics*. Cambridge University Press.

Flammarion, C. (1964). *The Flammarion book of astronomy*. Simon & Shuster.

French, A. P. (1971). Newtonian mechanics. The M.I.T. Introductory Physics Series. Norton, New York.

Galilei, G. (1632/1953). *Dialogue concerning the two chief world systems—Ptolemaic and Copernican*. University of California Press, Berkeley, CA.

Galili, I. (2001). Weight versus gravitational force: Historical and educational perspectives. *International Journal of Science Education, 23*(10), 1073–1093.

Galili, I. (2009). Thought experiment – Establishing conceptual meaning. *Science & Education, 18*(1), 1–23.

Galili, I. (2012). Promotion of content cultural knowledge through the use of the history and philosophy of science. *Science & Education, 21*(9), 1283–1316.

Galili, I. (2019a). Towards a refined depiction of nature of science. Applications to Physics Education. *Science & Education, 28*(3–5), 503–537.

Galili, I. (2019b). On the influence of Ernst Mach on contemporary physics curriculum at schools: The concept of weight. In *Ernst Mach – Life, work, influence.* Ch. 41, pp. 601–614. Springer, Nature, Switzerland AG 2019.

Galili, I., & Goren, E. (2023). Summary lecture as a delay organizer of cultural content knowledge – The case of classical mechanics. *Science & Education, 32*(3), 737–786.

Galili, I., & Kaplan, D. (1996). Students operation with the concept of weight. *Science Education, 80*(4), 457–487.

Galili, I., & Kaplan, D. (2002). Students interpretation of water surface orientation and inertial forces in physics curriculum. *Praxis Der Naturwissenschaften Physik in Der Schule, 51*(7), 2–11.

Galili, I., & Lavrik, V. (1998). Flux concept in learning about light. A critique of the present situation. *Science Education, 82*(5), 591–614.

Galili, I., & Tseitlin, M. (2003). Newton's first law: Text, translations, interpretations, and physics education. *Science and Education, 12*(1), 45–73.

Galili, I., Bar, V., & Brosh, Y. (2017). Teaching weight-gravity and gravitation in middle school—Testing a new instructional approach. *Science & Education, 25*(9–10), 977–1010.

Galili, I. & Bar, V. (1992). Motion implies force. Where to expect vestiges of the misconception? *International Journal of Science Education*, 14 (1), 63–81

Galili, I. (2021a). Scientific knowledge considered as a culture – The pleasure of understanding. Springer. ISBN 978–3–030–80200–4

Galili, I. (2021b). The impact of the equivalence principle on physics teaching—The ongoing opposition in teaching of weight-gravity. In B. Jarosievitz and C. Sükösd (eds.) *Teaching-learning contemporary physics. From Research to Practice,* pp. 109–124. Cham, Switzerland: Springer Nature

Goldstein, H., Poole, Ch., & Safko, J. (2001). *Classical mechanics* (3rd ed.). Addison Wesley, San Francisco.

Harrison, E. R. (2000). *Cosmology*. The science of the universe. Cambridge University Press.

Heath, T. (2004). *Aristarchus of Samos: The ancient Copernicus*. Dover.

Hogben, L. (1938). *Science for the citizen. A self-educator*. Alfred Knopf, New York.

Huygens, Ch. (1659/1703). On centrifugal force (De vi Centrifuga). In *Oeuvres Complètes* (Vol. XVI, pp. 255–301). Translated by M.S. Mahoney. On line: *Huygens – On centrifugal force (princeton.edu).*

Huygens, Ch. (1977). *The motion of colliding bodies*. Translated by R. J. Blackwell. *Isis*, 68(4), 574–597.

ISO. (1992). International Organization for Standardization, ISO-31-3, Quantities and units. Part 3, Mechanics. In Iona, M. (1999). Weight – An official definition, *The Physics Teacher*, 37, 238.

Kant, E. (1781/1952). *Critique of pure reason.* Cambridge University Press.

Keller, F. J., Gettys, W. E., & Skove, M. J. (1993). *Physics*. McGraw Hill.

King, A. L. (1962). Weight and weightlessness. *American Journal of Physics, 30*(4), 387.

Knight, R. D. (2013). *Physics for scientists and engineers* (3rd ed.). Pearson, Reading, MA.

Kockelmans, J. J. (1985). Heidegger and science. University Press of America

Koyre, A. (1957). *From the closed world to the infinite universe*. The Johns Hopkins Press, Baltimore.

Kuhn, T. (1995). *The Copernican revolution*. Harvard University Press, Cambridge, MA.

Landsberg, G. S. (1944/1988). *Elementary textbook on physics*. Vol. 1. Mir Publishers, Moscow.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Leibniz, G. W. (1715/1989). From the letters to clarke (1715-1718). In G.W. Leibniz (Ed.), *Philosophical Essays*. Hackett, Indianapolis & Cambridge, pp. 324–327, 340–341.

Losee, J. (2001). *A historical introduction to the philosophy of science*. Oxford University Press.

Mach, E. (1919). *The science of mechanics*. The Open Court Publishing, Chicago/London.

Margenau, H. (1950). The role of definitions in science. In *The nature of physical reality*, McGraw-Hill, New York.

Marion, J. B., & Hornyack, W. F. (1982). *Physics for science and engineering*. Saunders, New York.

Mårtensson-Pendrill, A.-M. (2021). *Physics for the whole body in playgrounds and amusement parks*. AIP Publishing Books.

Marton, F., Runesson, U., Tsui, A.B.M. (2004). The space of learning. In Marton, F., Tsui, A. (Eds.), *Classroom discourse and the space of learning*. Lawrence Erlbaum: Mahwah, NJ, pp. 3–40.

Mazur, E. (2021). *Physics. Principles & practice*. Pearson.

McComas, W. F. (1998). The principal elements of the nature of science: Dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 53–70). Kluwer.

Moody, E. A., & Clagett, M. (Eds.). (1952). *The medieval science of weights*. The University of Wisconsin Press.

Newton, I. (1687/1999). *The Principia. Mathematical principles of natural philosophy*. Translated by B. Cohen & A. Whitman. University of California Press, Berkeley, CA.

Orear, J. (1979). *Physics*. Macmillan.

Orear, J. (1961). *Fundamental physics*. John Willey, New York. Hathi Trust Digital Library

Pendrill, A.-M. (2023). Comment on 'Pendulum: The partial and global approach.' *Physics Education, 58*, 1–4.

Piaget, J. (1930). *The child's conception of physical causality*. Harcourt Brace.

Piaget, J. (1970). *Genetic epistemology*. Columbia University Press.

Poincare, H. (1913/2015). The value of science. In J. McKeen Cattell (Ed.) *The foundations of science* (Science and Education series). Cambridge University Press, London

Reichenbach, H. (1927/1958). *The philosophy of space and time*, Dover, New York.

Rogers, E. M. (1960). *Physics for the inquiring mind: The methods, nature, and philosophy of physical science*. Oxford University Press.

Rudaus, L., & de Vaucouleurs, G. (1959). *Larousse encyclopedia of astronomy*. Hamlyn.

Schnepps, M. H., & Sadler, P. M. (1989). *A private universe—Preconceptions that block learning*. Harvard University/Smithsonian Institution, Cambridge, MA.

Smith, G. E. (2006). The Vis Viva dispute: A controversy at the dawn of dynamics. *Physics Today, 59*(10), 31–36.

Stein, H., & Galili, I. (2015). The impact of operational definition of weight concept on students understanding of physical situations. *International Journal of Research in Science and Mathematical Education, 13*(6), 1487–1515.

Stein, B., Stein, Ch., & Galili, I. (2023). The concept of observer in science teaching in junior high school. Pre-instructional knowledge as a lever rather than an obstacle. *Education Sciences. Special issue: Innovative research based educational proposals, Physics Education, 13*(1), 95.

Stein, S. K. (1999). *Archimedes: What did he do beside cry eureka?* Jenson Books.

Tauber, G. E. (1979). *Man's view of the universe*. Crown, New York.

Thomson, W. & Tait, P.G. (1883/2009). *Treatise on natural philosophy,* 1. Cambridge University Press, London.

Todhunter, I. (1873/2023). *A history of the theories of attraction and the figure of the earth.* Macmillan, London.

Volfson, A., Eshach, H., & Ben-Abu, Yu. (2020). Identifying physics misconceptions at the circus: The case of circular motion. *Physical Review Physics Education Research, 16*(010134), 1–11.

Vygotsky, L. (1934/1986). *Thought and language*. The MIT Press, Cambridge, MA.

Young, H. D., & Freedman, R. A. (2012). *University physics*. Pearson, Addison Wesley.