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Igal Galili

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Weight versus gravitational force: historical and educational perspectives

Igal Galili, Science Teaching Department, The Hebrew University of Jerusalem, Jerusalem 91904, Israel; e-mail: igal@vms.huji.ac.il

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This paper discusses the existing dichotomy regarding the definition of weight and its implications in science education. The history and epistemology of the weight concept and its present status in instruction and students' knowledge about weight are reviewed. The rationale of the concept of gravitational weight, currently accepted in many textbooks, is critiqued. Two mutually related implications stem from this study in science teaching: a conceptual distinction between weight and gravitational force; and replacement of the gravitational definition of weight by the operational one. Both innovations may improve the quality of science education.

Introduction

After space (length, area, volume) and time, the concepts of weight, force and mass are among the most fundamental physical notions thus essentially affecting general physics knowledge. Here I chose to focus on weight, a concept with a long history, ubiquitous use and of considerable theoretical perplexity. Although some consider it to be solely a pedagogical topic, as Newton had already 'solved the problem', a review of developments within the 20th century does not support this assertion. Since the twenties, when the scientific correctness of the gravitational weight definition was first questioned (Reichenbach 1927), and in particular during the early sixties when the issue produced a serious pedagogical debate (King 1962, Sears 1963), a new operational definition of weight has appeared in physics textbooks (Orear 1967). The problem emerges simultaneously from the epistemology of physics and the theory of general relativity. Each approach to the problem reveals the dichotomy in the definition of weight: operational versus gravitational. Discussion of the subject is repeatedly revived in education periodicals (Taylor 1974, Iona 1975, 1976, 1987, 1988, Morrison 1999). Recently the issue was investigated in studies of students' knowledge (e.g. Galili 1993, Galili and Kaplan 1996), and this approach is gaining increasing recognition. However, empirical educational study presents only one facet of the integral treatment required for a reliable analysis of a problem in physics education. Such analysis should include a variety of other perspectives; the subject matter, history and philosophy, cognitive science, and so on. The issue of weight concept presents a subject to be satisfactorily resolved only within such an integral approach.

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A brief history of the weight concept

Before Newton

The conceptual evolution of the weight concept in science started from the notions of heaviness (weight) and lightness (levity) which both appeared very early as fundamental intrinsic properties of objects themselves. Greek philosophers were first to account for the origin of weight/levity qualities. Atomists explained the appearance of weight by a centrifugal effect within cosmic vortexes, and lightness as resulting from the squeezing out of smaller atoms (Brumbauch 1964). The concept of levity lost its independence only in renaissance physics (Galilei 1638). As to weight, two theoretical conceptions prevailed in Greek science. The first was attributed to Plato, who interpreted weight as a tendency or inclination of bodies towards their kin (Plato 1952). The second approach was originated by Aristotle, who rejected both the Platonic and atomistic explanations (Aristotle 1952) and introduced weight within his cosmology. Weight manifested a tendency of objects to restore the violated order in which fundamental elements (earth, water, air and fire) were spatially organized along a line from the centre of the Universe. He stated that the permanent seeking of the appropriate state of rest constituted the formal cause of the natural motion of any object, while its weight designated the efficient cause of such motion. Although different, Platonic and Aristotelian perspectives both provided weight with a nominal definition (Margenau 1950).[1] Aristotle ascribed absolute weight to the earth (an element) and absolute levity to fire, while the weight of other elements was relative. A compound object possessed weight in accordance with the ratio of its light to heavy components (e.g. Grant 1990). Although distinguished from force, weight could interact with it, determining the natural motion of the object and its swiftness. In violent unnatural motion, weight resisted the moving force. Archimedes, soon after Aristotle, saw weight as a quality opposing the buoyant force that pushed objects immersed in water (Clagett 1961, Archimedes 1978). This conflict determines whether the body sinks or floats (e.g. Archimedes 1978).[2]

Two manifestations linked the nominal definition of weight with the empirical domain: the falling of non-supported objects, and the downward pressure exerted on a support, when available. Thus, as non-supported, but apparently not falling, heavenly bodies were inferred by Aristotle to be weightless. An alternative approach to the definition of weight appeared soon after Aristotle. It was Euclid who took the measure of the pressure on the support, a subject of practical experience and measurement, to define weight. He thus provided its first operational definition:

> Weight is a measure of the heaviness and lightness of one thing, compared to another, by means of a balance.
>
> (Euclid 1959)

A balance scale served as the instrument of weighing throughout the documented history of mankind (e.g. Taton 1963). The question of relationship between the nominal and operational definitions of weight never arose in classical science.

Medieval science preserved the interpretation of weight as an inclination of the body and not as a force. Thomas Aquinas elaborated on this distinction:

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> A thing moved by another is forced if moved against its own inclination; but if it is moved by another giving to it its *own inclination*, it is *not forced*. For example, when a heavy body is made to move downwards by that which produced it, it is not forced. In like manner God, while moving the will, does not force it, because He gives the will its own inclination (emphasis added).
>
> (Aquinas 1267)

According to Aristotle, the speed of natural falling was directly proportional to the weight. When medieval scholars discovered that objects accelerate while falling, the original concept 'had' to be modified. Weight was split into two components, the natural (habitual) *still-weight* (or pondus) which remained unchanged, and *actual gravity accidental weight* (gravitas), reflecting the apparent rise in the speed of falling (Brown 1978). In the view of some, the new concepts represented potential and actual gravity (Albert of Saxony 1961), thus preserving the logical bond between weight (cause) and speed (effect), the increase of both occurring during natural falling. With time, *impetus* replaced the actual gravity and served Buridan to describe the accelerating nature of falling (Clagett 1961, Grant 1990).

As the Earth lost its central position in the new Copernican picture of the world, the old Platonic idea of 'attraction of likes' was revived to justify the natural downward pull, this time towards every heaven body, instead of the centre of the universe in Aristotle's world. Galileo followed the same path. Although starting from the medieval conception, in 1608 he suggested a way to measure the difference between 'dead weight', the weight at rest, and the one in motion (Drake 1978). Galileo eventually arrived at a conception akin to that of Archimedes (Sharratt 1994). Galileo's contribution was noticeable, since weight no longer was regarded as being related to speed, and the proportionality between the strength of the downward pull and the amount of matter in the object was alleged (closely approaching Newton's understanding). Some of Galileo's thoughts were new:

> ... as has been often remarked, the medium diminishes the weight of any substance immersed in it ...
>
> (Galilei 1638)

apparently reflecting an operational perception of weight itself, as a subject of influence by the medium. One may have difficulty in consistently relating the understanding of weight, a setting-dependent quality, with the idea of the *universal* downwards pull (a setting-independent quality) initially claimed to be weight. One however, may see here two complementary facets of science, though not well developed. The first, pointed at the phenomenological origin of weight (its nominal definition), while the second dealt with the epistemic aspect of perception (operational definition). The lack of commitment to a distinction between the two, brought into use the terms 'pondus-gravity-weight' as very close synonyms with subtle nuances of difference. As such they were used by Galileo, all conveying the same idea of burden, heaviness measured by weighing (e.g. Moody and Clagett 1952, Jammer 1957).

Although Descartes (1647), essentially changed the ontology of weight (its nominal definition), ascribing weight to the residual centripetal push exerted on a body in a vortex of fine matter ('matiere subtile'), the difference between the cause (push) and its effect (heaviness) was still not discussed. Descartes' mechanism of gravitation was reminiscent of the old idea of the atomists. Fine matter particles, which pervades the pores of objects, are in a constant very fast whirl

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which the particles of the body itself cannot copy. The *centrifugal* tendency pushes the spinning fine matter outwards, thus creating the *centripetal* push on the bodies, making them heavy. In such approach weight does not correspond to the quantity of matter (Aiton 1959).

Newton

After Galileo, the search for the cause of gravity left the terrestrial realm. The context became astrophysical—the search for a theory which would explain the mechanism of the universe. Progress was swift, and molded the scientific revolution of the 17th century. In the newly introduced force-paradigm of the universe's organization, the conception of an attractive central force between the heavenly objects eventually produced the *gravitational force* described by Newton's Law of Universal Gravitation. Having been invented with regard to the heavenly bodies, the gravitational force was transferred to a terrestrial context. It became the *force of gravity*, and identified with *weight*, thus establishing its new nominal definition. The identity of a cosmic attraction with the weight of objects on the earth seemed natural to Gilbert, Descartes, Huygens, and of course, Newton (1687: Book III, Proposition 6, Theorem 6). Only after more than two centuries, this same identity of cause (gravitational force) and its effect (weight) was recognized as peculiar and subject of further inquiry.[3]

Within this development, identified with the gravitational force, weight ceased to be a universal characteristic of objects, while mass (quantity of matter) and inertia (vis insita) remained so (*ibid.*: Book III, Rule III). An often forgotten important feature of the gravitational force-weight reunion was that weight became *relative*, characteristic of a pair of material bodies rather than of a single one, as was previously considered. Newton wrote: 'the weights of the planets *towards the sun* must be as their quantities of matter' (*ibid.:* Book III, Proposition 6, Theorem 6) (emphasis in the original).

Newton did not forget to also define weight operationally: 'it (weight) is always known by the quantity of an equal and contrary force just sufficient to hinder the descent of the body.' (*ibid.*: Definition VIII). There was no doubt, and hence no discussion, about whether his gravitational (nominal) and operational (epistemic) definitions always provide the same weight. In fact, the limited correctness of the equation, 'weighing results = gravitational force', follows from Newtonian mechanics itself: the result of a weighing is not necessarily equal to the magnitude of gravitational attraction. Nevertheless, the misconception that gravitational force is directly perceived by the human organism and is the subject of an easy measurement, became popular perhaps for reasons external to physics itself. Contemporaries of Newton, much excited with the discovery of *universal* gravitation, overlooked the obscurity of the weight-gravitational force identification, although a subtle asymmetry in the use of the two terms can be found in Newton's writings. 'Gravitational force' and 'gravitating towards' are commonly used by Newton with regard to celestial objects. In a few cases when a 'weight' is applied to astrophysical objects, it was normally followed with 'towards...' (e.g. *ibid.*: Book III, Proposition 6, Theorem 6).[4] In the terrestrial context however, and especially when discussing contact forces, Newton switched to 'weight', aiming at the *pressing force*, and referring to weight as *sustained* by the support (e.g. *ibid.*: Book II, Proposition 20, Theorem 15).[5]

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Newton never considered multiple observers and moving elevators. His world view satisfied the rationalists' canon. He conceived the Universe as a single system governed by universal laws, occupying an absolute space and running in absolute time. The concepts of space and time were self-evident, and beyond the need to define (*ibid*.: Definitions, Scholium). As we today, he distinguished between true and relative rest; but in contrast, he also distinguished between *true* and *relative movement*. Newton suggested a way to discriminate between the latter, by means of forces (*ibid*.: Definitions, Scholium). His example addressed solely the case of rotation, where he believed he found evidence for the true movement. However, even there Newton never considered anything which would remind us of inertial and/or accelerated frames of reference.

Although employing *relative quantities*, Newton charged these concepts with more than kinematic relativity. He instituted the pair of opposites, absolute-relative, as true-apparent, mathematical-vulgar. He applied them to reflect unavoidable errors of measurements due to human limitations:

> I must observe that the common people conceive those quantities under no other notions but from the relation they bear to sensible objects. And from these arise certain prejudices, for the removing of which it will be convenient to distinguish them into absolute and relative, true and apparent, mathematical and common.
>
> (*ibid*.: Definitions, Scholium)

Newton's example was *absolute* and *relative* time. He wrote:

> Absolute time, in astronomy is distinguished from relative, by equation or correction of the apparent time.
>
> (*ibid*.: Definitions, Scholium)

Newton proceeded to explain that in measuring time, humans use unreliable tools and so they can only attain relative time. With regard to the measure of true quantities, it is agreed that: 'In the Newtonian world and in Newtonian science, it is not man, but God, who is the measurer of things' (Koyre 1956: 183).

With regard to weight, we find the same approach. The notion of *true-weight* was reserved for the gravitational force, and *apparent-weight*, was coined by Newton to represent results of weight measurement in the presence of impediment factors which might deceive laymen (but not the philosopher). Newton considered only one such misleading factor: the buoyant force. For him, apparent-weight is similar to relative time, and may cause a misunderstanding:

> But those things (immersed in water) which neither by preponderating descend, nor, by yielding to the preponderating fluid, ascend, although by their *true* weight they do increase the weight of the whole, yet comparatively, and as *commonly understood*, they do not gravitate in water (emphasis added).
>
> (Newton 1687: Book II, Proposition 20, Theorem 15, Cor. VI)

Here, the theoretical framework of gravitational weight was established:

> . . . bodies placed in fluids have a two-fold gravity: the one *true* and *absolute*, the other *apparent, common, and comparative*. . . . Those things which are in air, and do not preponderate are commonly looked upon as not heavy. Those which do preponderate are commonly considered to be heavy, inasmuch as they are not sustained by the weight of the air. The *common* weight is nothing but the excess of the *true* weights above the weight of the air (emphasis added).
>
> (*ibid*.: Book II, Proposition 20, Theorem 15, Cor. VI)

The apparent-weight, presently in use in the modern classroom, does not coincide with that in Newton's perception. The currently used apparent-weight may incorporate inertial forces, for example the centrifugal force, in explaining the dependence of the apparent-weight on the geographical latitude.

Newton's entanglement with the inertial force was far from simple (e.g. Steinberg *et al*. 1990). Although it is considered one of his achievements, to have gotten rid of the annoying concept of impetus as an internal moving force (a medieval replacement of Aristotelian 'external mover'), his 'vis insita', preserving the state of motion, was still a force. Inertial forces in their modern understanding (non-interactive forces in the non-inertial frames of reference), had no room in Newton's theory.[6] It was his great competitor Huygens, who introduced inertial (centrifugal) force, to denote a radial outward tendency (conatus) of revolving bodies in a rotating frame of reference, yet never mentioned its contribution to weight (Dugas 1955).

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After Newton

Although Newton's mechanics was subsequently highly developed, its space-time conceptual foundation remained a priori an absolute canon. The absolute space framework, in its turn, deprived the later introduced idea of inertial forces from any practical value. When suggested,[7] they were considered artificial and no more than 'fictitious', a mathematical trick: one could, in principle, render explanations without them. The equality of inertial and gravitational masses was viewed as an accidental fact, creating no difficulty for weight determination. On the contrary, weight became even more important after Lavoisier's discovery of its conservation in chemical reactions. Atomic weights became essential in chemical knowledge, playing a central role in its new organization in accord with the atomic paradigm (Merz 1904).

The twentieth century brought a fundamental change, the concept of absolute space-time was reconsidered and eventually replaced. The role of the observer was introduced in a completely new sense,[8] and the Galilean principle of relativity was modified. In general relativity, Einstein's Principle of Equivalence (POE) provided multiple observers (frames of reference) with a true equality (Einstein 1916, Born 1924). With regard to weight, the question of a discrepancy between the true and apparent weights received a new perspective, in light of the inability to distinguish between contributions to weight, different in their nature. Soon after the introduction of the POE in 1927, Reichenbach wrote (Reichenbach 1927):

> 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 distinction between mass and gravitational force became insufficient, forcing further refinement—to distinguish between gravitational force and weight. After an alliance of hundreds of years, gravitational force was conceptually divorced from weight. This step can be seen as a terminating point in the formal history of the weight concept in science. In the subsequent path of progress, the areas of macrophysics (astrophysics, cosmology, etc.) as well as microphysics (elementary particles, atoms, molecules) do not require the weight concept.[9] It is in educational practice in introductory physics courses (and in everyday life) that weight remains a relevant and useful concept, although traditionally difficult for the learners.

Ontological aspect

Observing the weight concept as practiced after Newton, one finds his *true-weight* preserved in its identity with the gravitational force, and often modified in its being a reciprocal and relative concept, appearing in pairs of equal relative weights. This modification had the effect of reverting true-weight to the pre-Newtonian weight—a characteristic of the body itself.

Newton's concept of apparent-weight, originally reflecting the effect of a buoyant force on weighing, was extended to represent the scale reading, regardless of the factor perturbing the weighing. This approach, however, presumed that gravitational force could always be unambiguously inferred (as in the case of objects immersed in water). Newton's evidence of 'absolute' rotation (the curved surface of water) seemingly supported this perspective. Despite the lack of a similar procedure indicating uniform motion, the belief in absolute motion was retained in physics for a long time. Such an epistemological belief in the ability to elicit 'signal' out of 'noise', resembles the philosophical paradigm of the past, describing nature in terms of primary (essential) and secondary (derivative) qualities. The latter (e.g. apparent-weight) were the subject of a direct perception, whereas the former (e.g. true-weight) could be theoretically deduced (or revealed by intuition).[10]

Today we know that Einstein's Principle of Equivalence (Einstein 1916) prevents us from distinguishing between gravitational and inertial forces by simple weighing. Thus, when observer A, in an accelerated frame, experiences gravity and explains it by gravitational force; observer B, at the same time, regards this gravity as an inertial force due to the acceleration of A. This new Einsteinian understanding deprived the idea of true-weight from the meaning embedded in it by Newton.

Finally, since the POE claims only a local equivalence between gravitational and inertial forces, one may claim that in a sufficiently large area, it is possible to discriminate gravitational and inertial contributions to weighing results—the true gravitational field is always non-homogeneous. In principle, this is a valid argument for the preservation of true and apparent weights. We believe however, that this subtle theoretical point cannot refute the critique based on the wide practical context, where non-homogeneity presents only a tiny correction.

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Epistemological aspect

A pivotal contribution to understanding the nature of scientific concepts, known as operationalism, was made by Bridgman.[11] Discussing the epistemological lessons that had to be drawn from the genesis of the new physics (especially of the theory of relativity), he stated (Bridgman 1952):

> We do not know the meaning of the concept unless we can specify the operations which were used by us in applying the concept in any concrete situation. . .It is often supposed that the operational criterion of meaning demands that the operations which give meaning to physical concept must be instrumental operations.

Seemingly, a majority of the physics community accepted this philosophical dictum. Operationalism is so close to the intuitive strategy of practicing physicists, that often naive in philosophy, they perceive its tenets as self-evident truths, taking operationalism to be common sense itself rather than a 'philosophy'. As such, its tenets commonly appear in physics lectures. For instance, we read in physics textbook (Reif 1994: 5):[12]

> The definition of any scientific concept must be operational, i.e. it must specify what one must actually do to identify the concept or to decide whether any statement about the concept is true or false.

All too often, in lectures on relativity, teachers compete in their zeal by unanimously attacking the Newtonian concepts of time and space, and dismissing them regardless of their accuracy of measurement. The same criticism may and should be shown in the introductory course with respect to the Newtonian gravitational weight concept.

Operationalism implies the requirement of a measurement procedure which unambiguously defines a physical concept (e.g. Hempel 1969). It is this demand for uniqueness of interpretation that remains unmatched in considering the results of weighing. In post-POE physics, weighing cannot testify to the gravitational force; at best, weighing can provide the apparent-weight.[13] Then, what local measurement does provide the true-weight? There is none.[14] The only way left for the student to know about the true-weight is to calculate Newton's formula of gravitation. Isn't that an obsolete epistemology? Quite unintentionally, students and teachers find themselves bogged down in a dispute over the 'real evidence' of weighing results, a dispute so rich in metaphysics.

One should not however misinterpret the statement of this study, taking it for unrestrained support of the operationalist claim. Soon after the latter was launched, philosophers of science pointed at its limited validity or, as some of them preferred to express themselves, the 'naïveté', of physics practitioners. Leaving aside the comprehensive criticism of operationalism (e.g. Bunge 1959, Suppe 1977, Harré 1985), there is, however, the following important reservation (Powers 1985: 9):

> It (operationalism) fails to recognize that you need a basic vocabulary of words relating to physical objects, to elementary ideas of logic, and to action in order to describe an 'operation'.

The meaning of this criticism is the actual impossibility, and thus meaningless, of the operationalist programme in its extreme sense. In fact, to a great extent, our activity, 'operations', are theory laden. Thus, the fact that the same numerical results for a physical entity may be provided using measurements of different apparatus presents an insurmountable obstacle for radical operationalism.

With regard to the operational definition of weight, the awareness of the limits in the validity of the operational approach would imply a need to insure that no other factor causes the deformation of the spring in a calibrated scale (or the acceleration of a free fall g^*), a recognition of the necessity of theoretical background which should be provided within a description of the standard measurement (weighing), not difficult to provide. In any case, no modern criticism argues that the other extreme, a theoretical treatment without any reference to operations, as takes place within the gravitational weight framework (radical rationalism), is a

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preferable and reliable method to conduct scientific activity. This awareness is strong in modern science.

The problem of demarcation in physics education

The critique of the Newtonian notion of weight came from ideas introduced into physics in the 20th century. In this regard, we note that contemporary educational practice, as a rule, tries to draw a sharp distinction between classical and modern physics, and it is the former that is normally presented in introductory courses. Practicing a complete separation between the two 'physics' however, is often liable to lead the learner to errors and misunderstandings of even the reality of everyday life, let alone about science. Total exclusion of 'relativistic' and 'quantum' ideas, on the grounds of their formal complexity, cannot be justified, especially in instruction seeking scientific literacy (Glashow 1993, Hobson 1995). A similar intention with regard to science majors was displayed by Chabay and Sherwood (1995). For instance, when ignoring the Relativity Principle (as if belonging solely to relativistic physics), we miss its great potential to elucidate such a pure classical topic as: the constraint of a system must be isolated for the conservation laws to hold (e.g. Galili and Kaplan 1997a). In electromagnetism, understanding of velocity dependence of the Lorentz force (regardless of the magnitude of velocity) is impossible without touching on very basic relativistic ideas. It is possible and beneficial to include this knowledge in an introductory physics course (Galili and Kaplan 1997b).

Einstein's Principle of Equivalence provides yet another similar example. It is difficult to promote conceptual understanding in the novice with regard to weight whilst maintaining the pedagogical strategy of protecting the 'immature student' from the ideas of modern physics. The conceptual failure of 'gravitational weight' in physics should motivate educators to change. A switch into 'operational weight' might be an appropriate alternative, though based on ideas of modern physics, the material is far from being too formally complex for the average student.

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Weight in physics textbooks

Despite the doubtful validity of the weight concept when defined as a gravitational force, it is widely presented in educational practice and physics textbooks.[15] An extreme example (reminiscent of the medieval reductio ad absurdum) can be found in the popular textbook of Sears and Zemansky (later with/by Young). Through its many editions, generations of learners read the following definition (Sears *et al.* 1987, Young 1992):

> The weight of a body is the total gravitational force exerted on the body by all other bodies in the universe.

This obscure definition, never introduced by Newton, can be neither empirically employed nor theoretically validated. At best, it may remind the teachers of Mach's problem, a subject of serious theoretical effort (Sciama 1969, Harrison 1981). Newton took great pains to sum over an infinite number of gravitating sources—components of an extended body. For this purpose he invented calculus, applying it to extended but finite material objects. He never tried to sum the attraction of all the objects in the Universe, as is suggested by the quoted definition. Although other authors were more careful, their nominal definitions of true-weight did not greatly differ. The subtle variation in wording, by changing ‘weight is the gravitational force’ to ‘weight is due to the gravitational force’, though useful in legal cases, cannot help the learner, since elaboration on the puzzling ‘due to’ never follows, and nothing prevents one from thinking about the contribution of stars to the weight of the objects around us.

Furthermore, as gravitational force always appears in pairs of equal forces acting on two bodies, a question might arise ‘which body’s weight do we consider?’ Newton would reply ‘both’. With regard to two spheres he wrote (Newton 1687: Book III, Proposition 8, Theorem 8):

> . . . the weight of either sphere towards the other will be inversely as the square of the distance between their centres.

The Newtonian reciprocal nature of weight is seldom mentioned in physics textbooks; we rarely see the construct ‘the weight towards’. But when neglecting it, one actually reverts to the old conception of weight as a primary quality, a characteristic of a single object, or in Galileo’s view, a one-way downward pull. This pre-Newtonian understanding has become a common misconception of students nowadays. If one fails to appreciate the relative nature of gravitational weight, the ‘discovery’ of the ‘second’ weight, equal to the first, may be puzzling. Few would teach about the Earth’s and Moon’s equal weights, or that the Earth’s weight is not unique and different with respect to the Sun and Moon. Such statements however, would fit Newton’s conception.

In fact, the situation is even more complex. Regarding the missed preposition ‘towards’ dropped from Newton’s expression, one may accept that it is tacitly presumed. There is, however, a more serious reservation. A worry about gravitational weights towards the Moon, Sun and all other heavenly objects is irrelevant, not because they are numerically small, but because they are undetectable by means of any local measurement.[16] It is a favourite question of some physics teachers to ask, what correction due to, say, the Moon’s attraction, should one make to the result of a super precise on-ground weighing. Many students rush to calculations (Galili 1995), though those are meaningless, regardless of the precision of the apparatus. Our free gravitational movement relative to all astronomical objects totally prevents us from detecting (by weighing) any contribution of their gravitational attraction. We are in a permanent free fall, relative to all of them.

A small group of authors distinguish between the concepts of gravitational force and weight, using the operational definition of the latter in three variations:

(1) Weight of the body is a contact force acting downwards on the support. If the support is the pan of a scale, weight is measured (figure 1a). (Weight of the object is sensed when it is held. We sense the reaction to our body’s weight.) (Chaikin 1963, Orear 1967, Marion 1980, Marion and Hornyack 1982).

(2) Weight of the body is a contact force exerted upwards on this body by its support. It too is determined by a balance (figure 1b). (We sense the reaction to the weight of the object held. We sense our body’s weight.) (French 1971).

(3) Weight of the body is the force, which acts downwards and causes spontaneous falling. Numerically, weight is given by the product mg*, with

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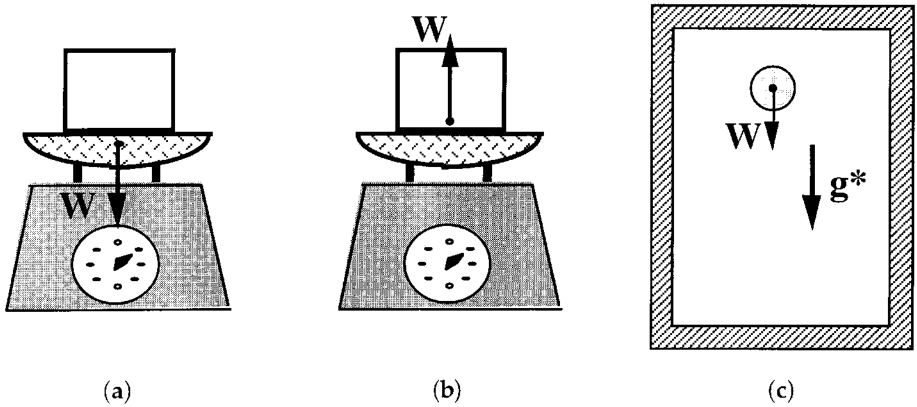

Figure 1. Operational definitions of weight: (a) weight is the force exerted on the *support* by the object; (b) weight is the force exerted on the *object* by the support; and (c) weight is the force exerted on the *object* causing its spontaneous fall with acceleration g*, as measured in the laboratory.

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> g*—the acceleration of a free fall, as it is measured in a particular frame of reference (figure 1c). (Keller *et al.* 1993, Lerner 1996).

It appears that the forces defined as weight in the first two cases comprise an action-reaction pair. In all cases, the weight-force operationally determines the up-down direction. Although all three definitions are mutually convertible, each possesses a slightly different status. The first two presume a local measurement, *viz.* weighing in a state of rest (in a laboratory frame), while the third draws on a non-local measurement of the free fall acceleration.[17] One can analyse the appropriateness and advantages of each variation, but, rather than do that, we consider each of them to be equally considered operational in this discussion. As mentioned above, only a small fraction of authors define weight operationally.[18] In this regard, it is surprising to read about a kind of symmetry in the currently adopted physics instruction. Eisenkraft and Kirkpatrick (1995) reflected on the subject as follows:[19]

> *Many [?!]* physics teachers carefully distinguish between the force of gravity and the weight. Weight is the reading on the bathroom scale, or the support force needed to keep you at rest in the non-inertial reference system. *Other* teachers use the term 'apparent weight' to refer to the scale reading and use weight to refer to the force of gravity (emphasis added).

Keller *et al.* in their textbook (1993), defined weight operationally, and based on the decision of the General Conference on Weights and Measures (CGPM), argued to adopt the operational definition of weight (in version 3). Perhaps the effective acceleration of the free fall, the apparent g*, was considered to be a subject of greater practical interest (e.g. in geophysics), instead of the theoretical true g, never observed (French 1983).[20] Leaving aside the question as to why the CGPM's decision to adopt the operational definition of weight entailed no changes in most teaching programs (a social phenomenon), one can mention other authors who, probably reflecting their dissatisfaction with the current status of the object, totally excluded the weight concept from their texts (e.g. Chabay and Sherwood 1998). This approach was advocated by Brown (1999).[21]

Although we do not touch on the issue of either the consistency or inaccurate use of the weight concept, we may mention that some physical settings seemingly provoke even those authors who adopt the gravitational definition of weight to apparently switch to its operational understanding. This happens when discussing Archimedes law, addressing the ‘weight loss’ of bodies immersed in liquid. The term ‘weight loss’ may mislead a novice learner (as anticipated by Newton) who perceives it as consistent with the gravitational definition of weight. Albeit more often in lower level instruction, it can happen in college-university texts too (Tipler 1990, 1999). Some texts switch between the previously established (in the course) gravitational, and operational definitions of weight, when the latter appears preferable in a specific context, as for example, weightlessness (Hewitt 1998).

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Students’ knowledge of weight

Although physics educators are normally concerned about students’ understanding (Hestenes *et al*. 1992, Mazur 1997), only after abandoning the behavouristic paradigm in the theory of learning did student knowledge become a subject for interpretation. Cognitive dynamic models revealed ways people establish knowledge, via making sense of the subject and arriving at specific forms of its understanding (e.g. McDermott 1991, Wilson 1991, Redish 1994, Hammer 1996). In doing so, educators are often inspired by the philosophical paradigm of constructivism, applying it to science education (e.g. Staver 1998, Glaserfeld 1989). While, in philosophy, the latter proceeds the rationalists vs. empiricists debate (as old as philosophy itself), in its educational implications, constructivism does not meet great opposition, as long as it is not taken to its extreme. Thus, one can easily agree that learning is not the simple storing of new knowledge, replacing the old by the new. It appears obvious that when learning physics, individuals reconstruct their knowledge of the world and make their own sense of what is suggested by the instructor, basing on the whole ecology of their previous knowledge, developed skills, views, epistemological commitments etc.[22] Thus, the resultant knowledge often conforms with these, and a strong cognitive interaction, between old and new knowledge, normally takes place in learning. This perspective, inviting a careful analysis of students’ knowledge, has already been applied to student knowledge of weight and gravitation, with much confusion being reported (e.g. Gunstone and White 1980, Watts 1982, Ruggiero *et al*. 1985). In a more recent and comprehensive study (Galili and Kaplan 1996), the qualitative understanding of weight and gravitation was tested in high school students. While some of the subjects were enrolled in advanced-placement (AP) physics classes, all were instructed solely within the ‘gravitational weight’ framework. The students’ knowledge about weight emerged profoundly different from the scientific one. Moreover, the maxim ‘everyone makes his own errors in conceiving the same truth’ appeared incorrect,[23] and a few schemes of knowledge were elicited representing students’ conceptions of weight (table 1).

In this study, the established profile of weight knowledge testified to the pronounced failure of the instruction to convey the idea of a discrepancy between

Table 1. Students' schemes of knowledge regarding weight.

	Scheme	*Comment*
1	Only one weight concept is employed.	The conceptual distinction between *true* and *apparent* weights is not held.
2	Weight is represented by an experimental result and corresponds to the sensation of heaviness.	This might indicate that heaviness constitutes the concept mental image held by the great most of students.
3	As distance from the primary source (Earth) increases, weight decreases.	This is a common knowledge which often is the first to consider by students.
4	Movement affects weight.	Various sensations associated with movement (losing support, falling, floating) are interpreted by students as an evidence of weight changes.
5	Forces other than gravitational (e.g. inertial) or pressure (of air, water, ground) *affect* weight.	Students predict weight-changes due to air, water, ground surroundings.
6	Weight is originated by the medium.	This claim extends scheme 5. Weight may be totally due to the medium (air) and/or transferred by it.
7	Weight is an inherent and invariant feature of any object.	This view is traceable to weight-mass confusion. Some students identified weight with the product of two constants—m and g.

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true and apparent weights. The elicited schemata expose the features of knowledge clearly in conflict with that presented in the class. Moreover, no considerable difference was found between the knowledge of AP-students (instructed to distinguish between weighing results and gravitational force) and students in a regular class (without such instruction).[23] This fact suggested that students' failure stemmed from the instructional contents, rather than other factors. The instruction could not resolve the fundamental confusion between weight, gravitational force and weighing results indicating a strong naïve operational commitment of student knowledge.

To complete the picture, I mention the results of another study that investigated weight knowledge in elementary school pupils (Galili and Bar 1997). It appeared that children's naïve knowledge of weight, their mental image, is mainly characterized by two schemes: 'weight is the pressing force featuring particular objects—the sensed heaviness related to a muscular effort' (Piaget 1972), and 'weight is the amount of matter' (in the object), the view prevailing in older individuals. The point to emphasize here is that children do not invent 'the force of attraction to the Earth'. Such knowledge results solely from instruction (in its formal or informal form), unavoidable in modern society. Let's not forget that gravitation as a force, presents an invention made by scientists rather late in history.

As nobody can simply escape the deeply entrenched schemes established at a very young age, the students formally instructed in high school-university commonly show a sort of hybrid knowledge, blending naïve and scientific ideas. Though the idea of weight identification as the gravitational force is usually well internalized on the declarative level, we can clearly identify strong commitments to other ideas which were never taught in a science class. Cognitive scientists explain this phenomenon as a misfit between the mental image of the concept and its formal definition, guaranteed to produce misconceptions (Vinner 1991).

Weightlessness and weight definitions

The state of weightlessness is commonly addressed in almost all introductory physics courses. For years, this phenomenon attracted and challenged the minds of learners, often influenced by the rich para-scientific literature which frequently provides inaccurate and confusing explanations of this phenomenon.

The history of weightlessness is surprisingly thin. After Aristotle's weightless stars, Descartes, in modern times went to an even greater extreme by thinking about all matter as inherently weightless (Aiton 1959). However, this idea never took root among scientists and, for the public, was too weird a concept even to imagine. For Galileo, weight was a faculty which did not change regardless of the object's position and motion. Thus, in Galileo's view, weight remained unaffected also in a free fall (Galilei 1632). Fantasies of nullifying gravitation by special materials eventually appeared in fiction,[25] but before Einstein, nobody scientifically considered weightlessness. In his famous Gedanken experiment regarding free fall, the brilliant conception of 'relative existence of the gravitational field' arose.[26]

Important for the present discussion, is the fact that with respect to weightlessness, the polarity of nominal (gravitational) and epistemic (operational) definitions of weight attains its extreme. The adherents of the gravitational definition do not agree to adopt Einstein's conception, and present weightlessness as *fictitious*, reflecting the absence of a weight *perception* (e.g. Giancoli 1988).[27] They use to write the term in inverted commas ('weightlessness') to emphasize its illusory nature. Within the operational paradigm, free fall is a state of *true* weightlessness, the absence of weight *per se* (Bachman 1984, Iona 1987, French 1995). Since weightlessness was first considered regarding falling towards the ground, *falling* became a linguistic twin of weightlessness. In fact, this served, and continues to serve, as a negative aid to learning. Falling is often associated with a descent toward the ground, quickly arriving at the object's impact with the ground. This impact often arrests the attention of the student. In fact, the state of weightlessness is reserved for any movement in the sole presence of gravitation, and may last 'forever'. *Free gravitational movement*, a more adequate name, implies that all astronomical objects are weightless, in exactly the same way that a tossed stone is weightless *throughout* its ballistic trajectory. This idea rarely appears in physics textbooks, where weightlessness is usually considered in the *downward* motion of a satellite or an elevator with a broken cable. Substitution of 'free falling' by 'free gravitational movement' in the textbook description of weightlessness could be helpful in guiding and facilitating the learner's thinking in the right direction.

When the operational definition of weight was first suggested, free fall was a subject of merely theoretical interest to some physicist—and perhaps, of curiosity to pilots who experienced it. The CGPM's decision (see above) to conform learning materials to the ideas of modern physics could not by itself immediately over-

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come a centuries-long tradition of teaching. However, the situation changed when weightlessness, being affiliated with space flights, became a subject of public awareness and literacy. Nowadays, millions observe this peculiar and durable phenomenon, often mistakenly reserved solely for the 'space environment'. Weightlessness ('zero-gravity') is intensively explored in its influence on physical, biological and chemical processes.[28] Currently lasting at most a few months, in the not-too-distant future space missions will last for years, eventually leading to a permanent stay in space. Will people who experience their regular weight in a rotating space station, their permanent home, continue to regard their weight as 'artificial' and weightlessness as 'fictitious'? In fact, even today *weightlessness* is used in all practical cases, and '*weightlessness*' is found only in introductory physics textbooks.

Furthermore, the classroom confrontation with the common misconception of depriving floating astronauts of weight (Galili 1995, Galili and Kaplan 1996), is unnecessary. While much effort is normally invested to encourage students to conceptually distinguish between mass and weight (likewise heat and temperature, force and energy), the case of weightlessness is different. The operational definition of weight, by virtue of its correspondence to what is directly sensed, is so close to (although not totally coinciding with) spontaneous ideas about weight, that it seemingly is a naturally better facilitation for the learner's assimilation.

Weightlessness provides a valuable means to assess physics knowledge; the way people account for it reveals much about their understanding of physics. For example, we can learn much about the understanding of weight by the famous 19th century writer of science fiction, Joules Verne. In his description of a space flight to the Moon, he admirably portrayed the state of weightlessness, as he understood it (Verne 1970). His astronauts experienced weightlessness only for an instant, *viz.* when their space-shell passed the point where the attraction of the Earth was precisely balanced by that of the Moon.[29] Verne explained in detail the gradual lost of weight (in proportion to the inversed square of the distance) that followed the flight from the Earth, in keeping with Newton's law of gravitation. This same erroneous view is familiar to many physics instructors now-a-days: many (like Verne) identify the gravitational force with the perceived weight (Scheme 2, table 1). There is, however, one difference. Verne's understanding could not be affected by any observation; nobody saw astronauts floating in space, as students today do. Yet, guided by the same logic, and being instructed about gravitational weight, many of them continue to explain the floatation of objects in a satellite as being due to their having *near-zero* weight, resulting from their *great distance* from the Earth.[30]

Concluding remarks

Weight is a fundamental concept and thus any change in its definition might inevitably force physics educators to reconsider the instruction of other concepts in the physics curriculum, with which weight is inherently related, such as inertial forces and the frames of reference.

Equivalence of observers in the description of physical reality, the non-unique interpretation of weighing results keeping with the principle of relativity, are all conceptually interwoven with the operational weight framework and may suggest

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the introduction of inertial forces as equal contributors to the weight of bodies. This will question the common policy of avoiding 'inertial forces' in the introductory physics course (AAPT 1987).[31] Inertial forces, in their turn, may enrich the physics curriculum, while simplifying (sometimes even trivializing) the learning of several advanced physical topics, thus making the introductory course more attractive to students (Galili *et al*. 1999).

Another important concept—tidal forces, is often confused with gravitation and badly explained in textbooks (Viri 2000). The operational approach comparing concept pairs, weight vs gravitational forces, and tidal vs gravitational forces (especially in the context of a free gravitational movement) may be appealing and effective. They naturally introduce the learner to epistemological issues and may promote meaningful learning. This topic deserves special study of its own.

Kuhn and Lakatos formulated conditions for the exchange of theories in science (Kuhn 1970, Lakatos 1970). These have been faithfully adopted to provide an understanding of conceptual change in learners (Posner *et al*. 1982). Change occurs when the old knowledge becomes unsatisfactory and the new one appears intelligible, plausible and more fruitful. Weight, in its operational definition, along with the suggested conceptual distinction between weight and gravitational force, matches these criteria and as such, is suitable to replace the gravitational definition. The transition from a gravitational to an operational definition of weight is an ongoing process (Halliday *et al*. 1993 and Halliday *et al*. 2000). In accord with the presented arguments, there is a good basis to believe that such a step will boost students' understanding of science.

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Notes

1. Nominal definition describes the meaning of a concept, by referring to particular theoretical views. This is also known as a constitutive definition.
2. Archimedes is particularly famous for deriving the concept of specific gravity—the comparative heaviness of the same volume of different materials (commonly, water is one).
3. The identity between a cause and its effect could have produced suspicion much earlier, given that in scholastic metaphysics it was reserved exclusively for the concept of God (Aquinas 1267/1952). In physics however, this understanding appeared much later.
4. 'That all bodies gravitate towards any planet; and that the weight of bodies towards any planet . . . ' (Newton 1687/1978: 279).
5. 'Therefore the lowest surface sustains the weight of the ....' (Newton 1687/1978: 196).
6. There are few exceptions where Newton did employ 'centrifugal' force (non-interactive inertial force which he never defined and which conflicted with his Third Law). The 'centrifugal' force appears in the discussion of the flattened Earth (Newton 1687/1978, Book III, Proposition 19, Problem 3). It appears again as the force acting on the Moon (ibid. Book III, Propositions, Scholium). In the latter case, Newton's description reminds one of that of Borelli, who, before Newton, argued for centrifugal force as providing an equilibrium in circular motion (Kuhn 1968: 248).
7. e.g. d'Alembert's principle, introduced in 1742, reduced any dynamic problem into one of static equilibrium, by the introduction of the 'accelerating' force $F = -ma$. The principle did not lead to any new physics. In 1835, Coriolis introduced a *compound-*

centrifugal force to describe relative rotational movement (Dugas 1955/1988: 248, 377-380).

8. Both relativistic physics and quantum physics, each in its own way, completely revised the observer's role, refuting the old tendency of classical science. Instead of the observer as a factor impeding observation of the objective reality, quantum and relativistic physics reserve for the observer the central role of determining the observed reality.
9. The term 'atomic weight' in chemistry was replaced by 'atomic mass'.
10. Conceiving reality in these terms was shown by Galileo, Descartes and Locke (e.g. Losee 1993: 55-56, 75-76, 102-103).
11. Percy William Bridgman (1882-1961), Nobel Prize recipient in Physics in 1946. Bridgman formulated a careful methodological orientation, operationalism, practiced by many before and after him.
12. Similar praise for operational definitions of physical concepts appears in Arons (1990): 'Students must be made explicitly aware of the process of operational definition and must be made to tell the 'stories' involved in generating numbers for velocity, acceleration, and so forth in their own words. . . . Operative knowledge involves understanding where the declarative knowledge came from.'
13. Not always, however. If for any reason, one defines the apparent weight as due to gravitational and inertial forces only, weighing an object immersed in water does not provide even apparent weight. The correction on the buoyant force, is however, always possible.
14. Measurement of acceleration (or trajectory) is not a local measurement. Newton elicited his Law of Gravitation treating trajectories in astronomically large system.
15. In our study, we draw mainly, though not solely, on the physics textbooks published in the USA those that address the introductory physics courses at the level of college-university instruction.
16. Tidal forces are not relevant for weighing by means of a calibrated scale, since it is a local measurement.
17. This definition is directly related to the historical discovery of the gravitational force in seeking the cause of planets elliptical trajectories around the sun.
18. Some use weight in its operational meaning, ignoring the conflict with the majority of physics textbooks (e.g. Swartz 1989).
19. An illustrative example of the teachers who teach operational weight is Sokolowski (1999). Recent debates in PHYS-L and PHYSLRN e-mail forums for physics educators show that the operational definition of weight is rarely employed.
20. In geological search for ore deposits, changes in the period of pendulum oscillations, g*-changes, present important evidence. In general, any on-ground experiment provide information solely about g* ('effective') and not g ('true').
21. The same holds with regard to the advanced physics course in Theoretical Physics, e.g. L. D. Landau and E. M. Lifshitz, *Mechanics* (Oxford, Pergamon Press, 1960).
22. Reconstruction should not be interpreted as a 'discovery', as made in science. Education, although to a different extent presumes guidance to a well defined result.
23. As Locke put it ' . . . there are not so many . . . wrong opinions as is commonly supposed'.
24. The curriculum of the AP physics courses matches the requirements of the introductory physics course in many colleges and universities. For many years, the second edition of College Physics by F. W. Sears and M. W. Zemansky, translated into Hebrew, served as the major textbook in AP physics classes in Israel.
25. e.g. a fictional method of nullifying gravity for propulsion into space by using anti-gravity material was described by H. G. Wells in 'The First Men in the Moon', in 1900.
26. ' . . . there occurred to me . . . the happiest thought of my life... the gravitational field has only a relative existence . . . because for an observer falling freely . . . there exists . . . no gravitational field' A. Einstein (Pais 1982).
27. Giancoli (1997) distinguishes between 'real' and 'apparent' weightlessness. The real weightlessness is reached only 'far from the Earth and other heavenly bodies'.
28. A long list of such studies can be found in the NASA home page on the Internet.

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29. The first Lagrange point. In fact, nothing physically happens as an object passes this point. Astronauts could be blissfully unaware of this event.
30. Some students may draw on the common term 'microgravity', which is used to designate a different phenomenon—small weight (apparent weight) due to friction with the environment of the ship.
31. The topic of inertial forces is normally out of the scope of high school and college curricula. This contrasts with the research based claim that inertial forces are informally widely used by students (e.g. Galili and Bar 1992).

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