EXCURSE TO THE HISTORY OF WEIGHT CONCEPT: FROM ARISTOTLE TO NEWTON AND THEN TO EINSTEIN

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Abstract

We address teachers of high school physics course with this excurse which deals with the weight concept in physics. There are two main tasks of physics teaching: to cause learning physics knowledge and to recognize the way this knowledge is obtained and validated. In other words, this means to familiarize with ontology and epistemology of physics. Weight concept provides a unique opportunity to reveal both aspects of physics knowledge closely interwoven and mutually influencing. More precisely, following the history of weight concept, one reconstructs the way physics functions in order to understand reality in terms of conceptual pictures of the world (theories) as well as the requirements to the physical claims to be adopted as scientific truth.

The story of weight concept started with physics itself (and even before), and its present understanding was obtain at the beginning of the 20th century. This progress was not fully copied by physics curriculum for which reason the history and philosophy of this concept could be elucidating and inviting implications in class instruction. The presented excurse into the history of physics reproduces how weight was understood prior to Newton, starting from the Ancient Greek science (Aristotle). From there we followed weight to the scientific revolution of the 17th century when Newton identified weight with the gravitational force and distinguished it from inertial mass. We explained why the Newtonian definition of weight had to be changed in the modern physics and weight was distinguished from the gravitational force, being defined solely through the operation of weighing. This progress followed the new understanding of the nature of gravitation attained in the Einstein's principle of equivalence within the general theory of relativity.

All together, the story represents the development from the weight as a feature of material objects through being determined by the gravitational interaction between material bodies to the complementary combination of the nominal elastic definition with the operational definition of weight by means of a standard weighing. Weight implications to the practice of the modern society are addressed especially in the context of weight changes in acceleration systems, in a state of free falling (satellite of the Earth) and the rotational stations in space as dreamed by the enthusiasts of space exploration, starting by Herman Potocnik in the early 20th century.

* * *

A deceitful balance is an abomination before the Lord: and a just weight is his will.

(The Book of Proverbs, 11:1)[1]

This idea from the Old Testament (the book of proverbs, which collects the wisdom from the text of the Bible), informs us that the Lord wills correct weighing. This obliges us to proceed in understanding what is weight, how to define it in accordance to be true. We believe that we suggest the direction that will please both teachers and students, those who want to be physicists and those who do not, but want to know about the world and the way it is organized and works. So it will be definitely the wish of the Lord that we will make sense of weight. Bible cannot help us in this, only physics can.

* * *

I. Understanding of weight before Newton

The evolution of the weight concept in science started very early from the notions of heaviness (weight) and lightness (levity). Both appeared in the Greek philosophy of nature as fundamental intrinsic properties of objects.

The concept of levity lost its independence only in the Renaissance physics (Galilei 1638). Galileo argued: are two light objects create a lighter one when we combine them? The negative answer was sufficient to abandon levity and think only about heaviness of objects – their weight.

As to the weight, two theoretical conceptions prevailed in Greek science. The first was attributed to Plato. His weight was the tendency or inclination of bodies towards their kin[2]. A different approach was suggested by Aristotle[3]. His weight was a part of his cosmology. Weight manifested the *tendency* of objects to restore the violated order in which fundamental elements (earth, water, air and fire) were spatially organized, along the line from the centre of the Universe outwards, to the heavens. He stated that the permanent seeking of the state of rest at the appropriate location constituted the *teleological* cause of natural motion of any object, while its weight designated the *efficient* cause of such motion.

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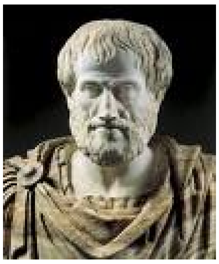
[1] http://www.tldm.org/bible/old%20testament/proverbs.htm

[2] Plato (1952). *The Dialogues of Plato. Timaeus.* Chicago: Encyclopedia Britannica, 63, p. 463.

[3] Aristotle (1952). *On the Heavens* Chicago: Encyclopaedia Britannica. Book II, Ch. 13, 295a, b, 296a.

Aristotle[4] 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 heavy components to the light ones.

In the natural motion of objects weight served the cause of motion: the more weight – the greater motion, whereas in violent, unnatural motion, weight resisted the mover: the greater weight is, the less quickly the object moves.



Aristotle

$$v \propto \frac{F}{W} \text{(violent motion)} \qquad v \propto \frac{W}{R} \text{ (natural motion)}$$

Here v – the speed of motion, F- the intensity of the mover, W – weight of the body, R – resistance of the medium.

Two manifestations of weight were recognized: weight causes the falling of non-supported objects, and weight causes the downward pressure exerted by the object on its support, when available. The heaven bodies were not supported and did not fall; therefore, they were inferred by Aristotle to be weightless.

An alternative approach to weight appeared soon after Aristotle, in the Hellenistic science. Archimedes, saw weight as the quality opposing to the buoyant force that pushed objects immersed in water[5] resulting either its floating or sinking. Euclid took the pressure of a body on the support as measured by balance, to be its weight. This was the first operational definition of weight[6]:

Weight is a measure of the heaviness and lightness of one thing, compared to another by means of a balance.

[4] Aristotle (384 BC-322 BC) – one of the greatest Greek philosophers – actually founded science as a discursive activity dealing with organization of the Nature. He systemized the rules of logical reasoning and suggested the first scientific holistic picture of the world, which was preserved and later modified during the whole history of science.

[5] Archimedes (1978). *On Floating Bodies.* Chicago: Encyclopaedia Britannica. Book II, pp. 540, 543.

[6] Euclid (1959) *The Book of Balance*. In M. Clagett, *The Science of Mechanics in the Middle Ages* Oxford, Oxford University Press. Def. 1.

In fact, balance scale, served as an instrument to measure weight, weighing, much before any theoretical idea regarding weight was established; that is, from the very early civilizations.

Medieval science preserved the Aristotelian interpretation of weight as an *inclination* of the body (not as a force). Thomas Aquinas, a devoted follower of Aristotle, elaborated this distinction[7]:

> *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).

Nicole Oresme – a distinguished scholar of the 14th century

When the medieval scholars discovered that objects accelerate while falling, the original weight had to be modified. They split it into two components, the natural (habitual) *still-weight* (or *pondus*) which always remained unchanged, and *actual gravity, accidental weight* (gravitas), reflecting the apparent rise in the speed of falling. Indeed, within the Aristotelian framework, speed (effect) increase testified for the increasing weight (cause)[8]. The new concepts represented potential and actual gravity[9]. With time, *impetus* (defined as weight multiplied by speed) replaced the actual gravity for Buridan from Paris in describing the accelerating falling[10].

Things changed for weight when the Earth lost its central position in the Aristotelian cosmos. In the new Copernican picture, the world lost its geocentric symmetry. There was an urgent need in science for the new cause for things to fall to the ground. The old Platonic idea of the 'attraction of alike' was revived to justify the

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[7] Aquinas (1267/1952). *Summa Theologica* Chicago: Encyclopaedia Britannica. Part I, Q. 105, Art. 4; Part I, Q. 2, Art. 3.

[8] Brown J. E. (1978) *The Science of Weight.* In D. C. Lindberg (ed.), *Science in the Middle Ages.* Chicago: The University of Chicago Press. p. 180.

[9] Albert of Saxony (1961). *On the Heavens and the World.* In M. Clagett (ed.) *The Science of Mechanics in the Middle Ages*. Oxford: Oxford University Press. p. 139.

[10] Clagett, M. (1961). *The Science of Mechanics in the Middle Ages.* Oxford: Oxford University Press 22, pp. 541-556. Grant (1990). *Physical Science in the Middle Ages*. Cambridge: Cambridge University Press, pp. 45, 53.

natural fall. It was imagined that similar attraction exists in the areas of each planet, instead of the tendency to seek the centre of the universe in Aristotle's world.

Galileo, in the 17th century, followed the same path. He started from the medieval conception. In 1608 he suggested a way to measure the difference between 'dead weight' the weight at rest (pondus), and the weight in motion (gravitas)[11]. Galileo preserved the idea of weight as a quality causing heaviness to a body and used it somewhat similar to Archimedes[12]. Later, however, Galileo regarded weight as proportional to the amount of matter in the object (akin Newton's mass). His statements as[13]:

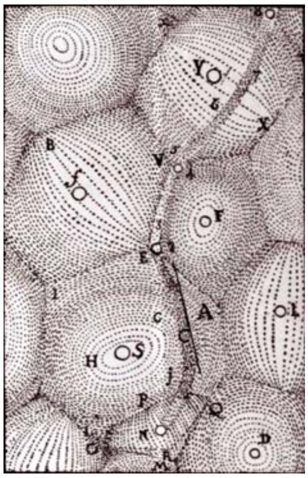
> *. . . as has been often remarked, the medium diminishes the weight of any substance immersed in it . . .*

testify for the cumbersome concept since the amount of matter was apparently the same after the body was immersed into water. In addition, his weight concept had clear operational connotation – it is indeed easier to support the body immersed in water.

At that time, it was common to use the terms 'pondus-gravity-weight' as very close synonyms. As such they were used by Galileo, all conveying the same idea of burden, or heaviness measured by weighing[14].

Descartes

To complete the picture, we mention the original idea of Descartes[15], who tried to explain weight in essentially different manner. He ascribed weight to the residual centripetal push exerted on a body in a vortex of the surrounding matter of the medium ('matiere subtile').



Fine matter particles, which pervade the pores of all

[11] Drake, S. (1978). *Galileo at Work*. Dover, New York, pp. 126-127.
[12] Sharratt, M. (1994). *Galileo: Decisive Innovator.* Blackwell, Oxford.
[13] Galilei G. (1638/1914). *Discourses Concerning Two New Sciences.* Dover, New York, First Day, pp. 78, 81.
[14] e.g. Moody E. A. & Clagett M. (1952). (eds.) *The Medieval Science of Weights.* The University of Wisconsin Press. Madison, Wisconsin. Jammer, M. (1957). *The Concept of Force*. Harper Torchbooks, New York.
[15] Descartes, R. (1647/1983). *Principles of Philosophy.* D. Reidel, Dordrecht, pp. 191-192.

objects, being in a constant very fast whirl experience *centrifugal* tendency. Their radial move *outwards*, however, created the effective *centripetal* (inward) push on the bodies, making them heavy and compelling their falling to the ground. Descartes illustrated that by a thought experiment: A big bowl of gun balls had few pieces of light cork among the balls. During the rotation of the bowl, the pieces of cork moved to the center of rotation because metal balls move outwards.

Needless to say that the situation of the experiment was not even approach the reality of the bodies next to the ground, since real bodies are surrounded by air, much less dense material, but Descartes sought for the mechanism of centripetal push on the first place and kept with it regardless any other factors[16].

Questions to reflect

1. Why we can talk about heaviness of the bodies as their physical characteristics and we cannot do the same for levity?
2. Aristotle did not considered weight to be a force but a tendency of the body. What was the difference?
3. The scholars of medieval science were not satisfied with one a single concept of weight (gravity) and distinguished between *still-weight* (or *pondus*) always remained unchanged, and *actual gravity* or *accidental weight* (gravitas). What was the rationale of this conception?
4. What was the idea of Descartes to explain weight? Was it reasonable to believe to such an idea? Explain

II. Weight in the classical mechanics of Newton

After Galileo, the search for the cause of gravity left the terrestrial realm. The context became astrophysical which in a sense (the number of factors that are considered) presented a simpler physical situation, at least for an initial explanation.

The logical trend of Newton is important to mention.

First, Newton introduced force-paradigm of the universe's organization, establishing the core of his theory – the laws of motion. Then, in the search for the cause for planets revolving around the sun, the system Sun-planets, Newton elicited

[16] Aiton, E. J. (1959). The Cartesian Theories of Gravity, *Annals of Science*, 15(1), 27-49.

the centripetal force to be in the inverse proportion to the distance between the objects, such as the Moon revolving the Earth[17]:

$$F_{cp} \propto \frac{1}{r_{12}^2}$$

F_{cp} stands for the centripetal force and r_{12} – for the distance between two material points.

This was the attraction central force between the heavenly objects, the first step towards the Law of Universal Gravitation. Then, to relate the established force with gravity he performed a thought experiment[18]:

> *If now the moon is imagined to be deprived of all its motion and to be let fall so that it will descend to the earth with all that force urging it by which (by Cor. Prop. III) it is [normally] kept in its orb… that force by which the moon is kept in its orbit in descending from the moon's orbit to the surface of the earth comes out equal to the force of gravity here on earth, and so (by rules I and II) is that very force which we generally call gravity.*

How could Newton infer regarding the force acting on the Moon or other celestial body? In effect, he drew on the second law of motion (the axiom of his theory) implying that the net force on the body is proportional to the "change of motion": $F_{net} \propto \Delta(mV)$. In our terms, the change of motion become the change of momentum mV. Furthermore, considering the very short time interval, Newton arrived to the inference that the net force acting on a body is proportional to the observed acceleration of its motion: $F_{net} \propto a$. Acceleration was already the quantity that he could calculate from the observed motion of the Moon.

In his thought experiment with the Moon, Newton applied his already established result regarding the centripetal force on the planets:

$$F_{cp} \propto \frac{1}{r_{12}^2}$$

This way Newton could arrive to the inference: the Moon, if deprived of its motion, and placed next to the Earth, will fall exactly with the acceleration of the free

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[17] Newton, I. (1687/1999). *Mathematical Principles of Natural Philosophy*. Berkeley, CA: University of California Press, Book III, Proposition I, II, III, pp. 802-803.

[18] *ibid*. Book III, Proposition IV, p. 804.

fall so well known since Galileo. Therefore, inferred Newton, the force applied on the Moon and the force applied on all bodies next to the Earth are identical in effect:[19]

> *And this centripetal force would cause this little moon if it were deprived of all the motion with which it proceeds in its orbit, to descend to the earth … and to do so with the same velocity which heavy bodies fall on the top of those mountains, because the forces with which they descend are equal.*

Newton inferred:

> *And therefore (by Rule I and II) the force by which the moon is retained in its orbit is that very same force which we commonly call gravity;*

Newton reasoned by his Rules of Reasoning I and II: [20]

> *Rule I: We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.*
>
> *Rule II: Therefore to the same natural effects we must, as far as possible, assign the same causes*

He explained also using the rule of contraries (contradiction under opposite assumption):[21]

> *For if gravity were different from this force, then bodies making for the earth by both forces acting together would descend twice as fast.*

The final claim appears in the Scholium[22]:

> *The force which retains the celestial bodies in their orbits has been hitherto called centripetal force; but it being now made plain that it can be no other than a gravitating force…*

$$F_{grav} \equiv F_{cp}$$

It was the great moment of the great discovery indeed. What hitherto was an obscure concept of gravity, weight, etc. became from now on *the force of gravity*, *the gravitating force*, or as we call it now – *the gravitational force*. Weight previously equated to gravity was now married to the gravitational force.

Newton proceeded and accomplished the campaign by stating[23]:

> *…That all bodies gravitate towards every planet; and that the weights of bodies towards any the same planet, at equal distances from the centre of the planet, are proportional to the quantities of matter which they severally contain.*

---

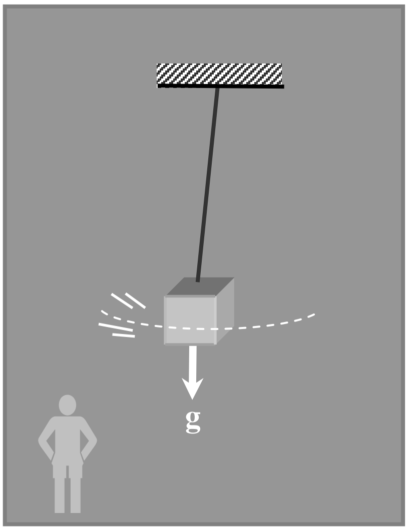
[19] *ibid*. Book III, Scholium, p. 805.

[20] In effect, these both rules present variations of the parsimony principle (the principle of simplicity) known as Ockham's Razor (the rule of economy, or parsimony) from the 14th century.

[21] *ibid*. Book III, Proposition IV, p. 804

[22] *ibid*. Book III, Scholium, p. 806.

[23] *ibid*. Book III, Propostion VI, p. 806.



This fact – the proportionality of gravity to the quantity of matter – was demonstrated by Newton by his experiments with pendulums of equal geometry and shape but different in material. He wrote:[24]

I tried the thing in gold, silver, lead, glass, sand, common salt, wood, water, and wheat. I provided two wooden boxes, round and equal: I filled the one with wood, and suspended an equal weight of gold (as exactly as I could) in the centre of oscillation of the other. The boxes hanging by equal threads of 11 feet made a couple of pendulums perfectly equal in weight and figure, and equally receiving the resistance of the air. And, placing the one by the other, I observed them to play together forward and backward, for a long time, with equal vibrations.

Thus, by showing that gravitating force does not depend on the kind of the matter (all pendulums oscillated exactly the same way), Newton arrived to the gravitational force to be proportional to what he called: the quantity of matter, and we prefer today – inertial mass:

$$F_g \propto m$$

At the same time, here Newton made another giant step. Until him, mass and gravity were confused in one concept. Thus, the medieval concept of impetus was defined as a product of **weight** and speed, whereas momentum (the quantity of motion) for Newton was a product of **mass** and velocity. The revolutionary step was the split between the gravity and mass. Thereafter, the gravitational force was proportional to mass, not gravity.

And finally, for the symmetry of force interaction (Law III), one should add another mass into the dependence of the attraction force:

$$F_g \propto m_1 \cdot m_2$$

If one combines these results, the famous Law of the Universal Gravitation emerges:

$$F_g \propto \frac{m_1 \cdot m_2}{r_{12}^2}$$

[24] *ibid*. p. 807.

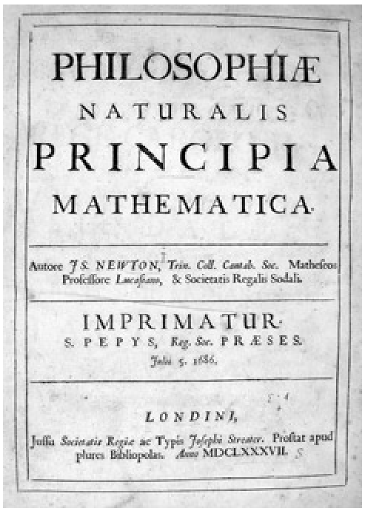
Newton could not accomplish the law beyond the proportionality for he could not make a laboratory measurement of the gravitational force between two known masses. Cavendish, in the same university of Cambridge, performed this measurement a hundred years later in the experiment he called "weighing the Earth".

The *identity* between cosmic attraction and the weight of objects on the Earth seemed natural to Gilbert, Descartes, Huygens, and of course, Newton. Only after more than two centuries, this same identity of the cause (the gravitational force) and its effect (the weight of the object) was recognized as peculiar and a subject of further inquiry.

Following Newton's discovery regarding the nature of weight, as interactive force of gravitation, weight ceased to be a characteristic of objects, while mass (the quantity of matter) remained such. The often forgotten feature of the Newtonian weight was however, that it always came as a pair of forces of interaction. Newton wrote:[25]

> *…the weights of the planets* <u>*towards the sun*</u> *must be as their quantities of matter…* (emphasis in the original).

This meant that the weight of the Earth towards the Sun was equal to the weight of the Sun towards the Earth, and the weight of the Earth towards the Moon was equal to the weight of the Moon towards the Earth, and the weight of the Earth towards the Sun is different from the weight of the Earth towards the Moon. The Newtonian weight was not a characteristic of a body but of the pair of bodies. Such weight could not survive in the everyday life where the only practical meaning was the weight of things towards the Earth.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore JS. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Newton did not forget to define weight operationally, by weighing[26]:

> *Thus the weight is greater in a greater body, less in a less body; and, in the same body, it is greater near to the earth, and less at remoter distances. This sort of quantity is the centripetency, or propension of the whole body towards the centre, or, as I may say, its* <u>*weight*</u>*; and* <u>*it is always known by the quantity of an equal and contrary force just sufficient to hinder, the descent of the body*</u>. (emphasis added)

Here, however, problems began.

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[25] *ibid*. Book III, Proposition 6, pp. 806-810.
[26] *ibid*. Definition VIII, pp. 407-408.

On the one hand, weight was defined by Newton as the gravitational force. On the other – weight is measured by weighing. It was known that the same body weighs differently in the locations of different latitude on the surface of the Earth. How could one explain that the same body weighs differently, is it attracted differently to the Earth? The correctness of the equation: 'weighing results = gravitational force' was questioned.

Despite of this discrepancy, which was resolved in trade and commerce by careful indication of the place where the weights were calibrated and the necessary corrections made, Newtonian equating of weight and gravitation preserved, waiting for a better account. It is this problem of weighing results, which pointed to the fact that Newton's laws are valid only in certain frames of reference – inertial frames. The rotating Earth was not such a frame. One needs to imagine himself outside the Earth, at rest relative the Sun, in order to apply Newton's laws. In any case, weighing does not reliably indicate gravitational force.

The comprehensive understanding of the situation was reached in the twentieth century within the new approach: different accounts of the world by different types of observers. Newton's concern was rather different. He did not care about any other but one picture of the world – the one of absolute space and time. He bothered about the unknown origin of the gravitational force. On this occasion, Newton expressed his vision of the physics knowledge in general. In the last lines of *Principia* he wrote:[27]

> *Hitherto we have explained the phenomena of the heavens and of our sea by the power of gravity, but have not yet assigned the cause of this power. This is certain, that it must proceed from a cause that penetrates to the very centres of the sun and planets, without suffering the least diminution of its force; that operates not according to the quantity of the surfaces of the particles upon which it acts (as mechanical causes use to do), but according to the quantity, of the solid matter which they contain, and propagates its virtue on all sides to immense distances, decreasing always in the duplicate proportion of the distances. …*
>
> *But hitherto I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called an hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy. In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction. Thus it was that the impenetrability, the mobility, and*

[27] Newton, I. (1687/1999). *Op. cit.*, General Scholium, p. 943.

the impulsive force of bodies, and the laws of motion and of gravitation, were discovered. And to us it is enough that gravity does really exist, and act according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and of our sea.

Newton left the problem of understanding gravitation for further exploration, which since then never stopped.

Euler

Euler[28] lived in the 18th century just after the scientific revolution, at the time that the Newtonian mechanics became the fundamental theory. In his treatise on mechanics[29] Euler presented the ideas of Newton about weight as already adopted claim in physical science, although the scientific community still debated on its validity versus Cartesian idea of vortexes which cause weight by the pressure of surrounding medium. Euler wrote[30]:

Definition 16

179. *Gravity is the force, by which all bodies near the surface of the earth are forced downwards; and the force, by which anybody is acted on by gravity, is called the weight of this body.*

Corollary 1

180. *Gravity is the external cause, which forces terrestrial bodies downwards; and therefore it cannot be a property assigned to certain bodies themselves.*

Leonard Euler

Corollary 2

181. *Thus a body sent off near the surface of the earth, even if it should be at rest, is urged on in a downwards motion and meanwhile it sinks until it comes upon obstacles preventing the fall.*

Corollary 3

182. *Moreover as long as the fall is impeded, either the body being held immobile pressing on an object or it suspended, the weight of this body exerts itself by pressing down.* (emphases added)

In accordance with the weight as defined by Newton, Euler mentioned that gravity "cannot be a property assigned to certain bodies themselves" (Cor. 1), meaning that

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[28] Leonhard Paul Euler (1707 – 1783) was outstanding Swiss mathematician and physicist who worked in Russia and Germany. Euler made important discoveries in mathematical analysis (he introduced the notion of function). He is also renowned for his work in mechanics, fluid dynamics, optics, and astronomy.

[29] Euler, L. (1765). *Theory of the motion of solid or rigid bodies*. http://www.17centurymaths.com/contents/euler/mechvol3/genmotch4.pdf

[30] *Ibid.*

weight characterizes a pair of objects, not one. Almost like Newton, Euler ascribes to weight to cause the downward pressure (Cor. 2).

Here Euler only defined the force of gravity and the weight similar to Newton, that is, stating the fact, without any speculation regarding the cause. This came later, in the Scholium. There, Euler openly expressed his worry of the unclear origin, the cause, of the force of gravity. Unlike Newton, however, Euler speculates and displays his confusion. Eventually, he returns to the Cartezian idea explaining gravitation by "the action of some more subtle matter that escapes the notice of our senses"[31]:

> ***184***. *Those people also, who put the cause of this as a drawing together, recognize these things, that gravity is the external force, which acts extrinsically on bodies and forces them downwards. For bodies are not urged towards the earth by a certain special instinct, but they are set up to be attracted to the earth by a force drawing them together. Clearly the matter can be understood thus, as if the earth were sending out some kind of embracing forces acting on bodies, which forces send the bodies towards the earth; now nor do they consider this to happen with the help of an intervening medium, but they wish the forces to be acting in place equally, even if all the matter between the body and the earth has been taken away. Therefore the force of gravity is not a material force acting on the body, truly thus connected with the earth, in order that with this removed, the force likewise would vanish; and likewise it is therefore as if a certain spirit should move rapidly to force bodies downwards; for how otherwise the force itself is able to propagate through great distances without the support of any kind of intermediate material, cannot in any manner be considered to be understood. …What is perhaps more likely to be true is that the force of gravity arises from the action of some more subtle matter that escapes the notice of our senses; …when the admirers of attraction say that the attractive force has been put in place by a God of the earth, they say nothing else, except that bodies are to be impelled immediately by this god himself.* (emphases added)

Euler went further in establishing the working framework of physics. He demonstrated possibility to use weight for measuring forces and masses[32]:

> **191**. *We may express the forces acting consistently through the equal weights from these.*
>
> ***192***. *This expression of the forces by the weights gives no difficulty; for since the weight of each body is a force, by which that is acted on downwards, the forces acting and the weights are quantities homogeneous between each other; and whatever body may be acted on by some force, a body can always be taken to be acted on by an equal force acting downwards placed on the surface of the earth, so that just the weight of*

[31] Euler, L. (1765). Op. cit. http://www.17centurymaths.com/contents/euler/mechvol3/genmotch4.pdf
[32] *ibid.*

this body will show the measure of that force. And when the question concerns so great a force, that nobody near the surface of the earth is able to be present, that has an equal weight, it is sufficient to know how many times greater that force shall be than the weight of the little amounts of bodies present on the surface of the earth; if hence indeed, the magnitude of this force is surely able to be defined.

Keeping with this tradition, we in modern school laboratory calibrate force-meter by suspending different weights on a spring to calibrate it and use the calibrated spring to measure other forces.

Huygens

The influence of Newton on the framework of physical thought was enormous. However, there was another brilliant mind – Christian Huygens[33], a prominent Dutch physicist, who worked almost in parallel with Newton and produced alternative ideas regarding the fundamental issues in both mechanics and optics.[34] In this excurse, we touch on his fundamental idea with regard to the nature of the centrifugal force – its similarity with the force of gravity.

Huygens' view was highly intelligent and original. In 1659, before the great invention of Newtonian picture of gravitation, Huygens introduced the concept of *centrifugal force*[35] and determined its variables. Today we express this force by means of modern symbolism, as a formula:

$$F = \frac{mv^2}{r}$$

Huygens never wrote this formula. He could only describe the dependence of the force he termed centrifugal on different parameters: weight (not mass, as we today), speed and radius of rotation. Similar to Newton in regarding to the gravitational force, Huygens used to describe the magnitude of the centrifugal force through comparison between two cases of bodies in a similar motion.

Furthermore, the concept of force itself was ambiguous and not well defined, waiting for Newton's touch. And despite of all these, Huygens was the first who tried

[33] Christian Huygens (1629 – 1695) was a renowned Dutch physicist who invented the first pendulum clock, which greatly increased the accuracy of time measurement. He was a pioneer researcher in mechanics, astronomy and probability.

[34] In optics, Huygens confronted the idea of particle (light rays) paradigm with the wave theory of light (elastic distortions in the ether medium).

[35] Huygens, Ch. (1659/1703). On the centrifugal force. From: *De vi Centrifuga*, in *Oeuvres Complètes,* Vol. XVI, pp. 255-301, Translated by M.S. Mahoney. Online: http://www.princeton.edu/~hos/mike/texts/huygens/centriforce/huyforce.htm

to describe the physical situation from the point of view of observer in a rotating system. For that he employed a thought experiment:[36]

> *Let us imagine some very large wheel, such that it easily carries along with it a man standing on it near the circumference, but so attached that he cannot be thrown off; let him hold in his hand a string with a lead shot attached to the other end of the string.*

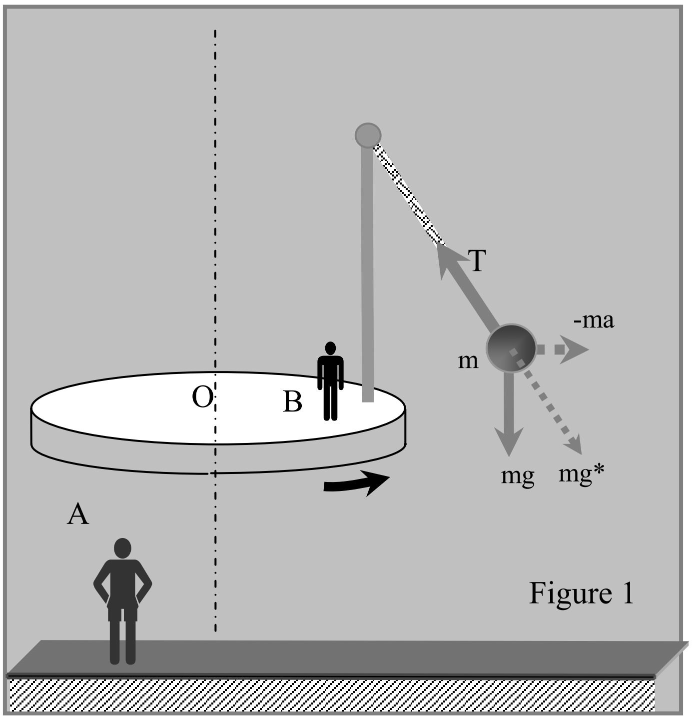

Figure 1

To facilitate understanding of Huygens' experiment we should first present the modern account of a similar case.

On our days, physicists distinguish between the descriptions of the situation by observer A, outside the wheel (Fig. 1) and that by observer B, on the wheel, whom considered Huygens.

Observer A, considered later by Newton, mentions the tension of the rope T and the gravitational force mg acting on the mass m. He fully describes the rotation by means of the second Newton's law. A presents an inertial observer.

Observer B, considered by Huygens, does not observe the ball (mass m) in rotation but being at rest, in the state of equilibrium. Tension T and the gravitational force mg cannot provide equilibrium (they are not parallel). B needs additional force –ma to nullify the net force on the ball. This additional force (-ma), not existed for Newton, but required by Huygens, is termed today *inertial force*. Observer B presents a *non-inertial observer* (the one who needs inertial forces to account of the situation), and the rotating wheel presents a *non-inertial frame of reference.*

We, then, are evident to the important fact that the same situation of motion can be described in physics differently by means of active forces in views of different observers.

[36] *ibid*.

Centrifugal force is similar to the force of gravity

Without Newton's theory of gravitation and Newton's laws of motion, Huygens was very much limited in his treatment of rotation. Nevertheless, he made an ingenious conjecture, which he was able to demonstrate, that the gravitation force is similar to the centrifugal force. Were he know the formulas for both forces, as we know today, it would be simple. Indeed, the forces are:

Christian Huygens

$$F_{cf} = m\frac{v^2}{r} \qquad \text{and} \qquad F_g=mg$$

he would immediately see that both are proportional to the mass of the object, and in this sense they are essentially similar: introducing $a_r= v^2/R$ and $a_g=g$ yield:

$$F_{cf} = ma_r \qquad \text{and} \qquad F_g=ma_g$$

This implies that observer B might be misled regarding the gravitational force, given that he identifies the gravitational force with weighing result – the tension in the thread (heaviness of the suspended body) at the state of rest (mg* in Fig. 1).

At the same time, observer A clearly discerns the gravitational weight (mg), but he must depart from the identity between weight (as the tension in the thread) and gravitation. He may say that the centrifugal force increases the body weight. In effect, this could be the point to split between the concepts of "gravitation force" and "weight force", but Huygens, was still not there.

Lacking this knowledge, but being familiar with the works of Galileo and Descartes, Huygens utilized their conceptions. Unlike Newton, he defined gravity using Descartes' notion of tendency, or *conatus* (Fig. 2)[37]:

Heaviness is a <u>tendency</u> to fall [Gravitas est conatus descendendi].

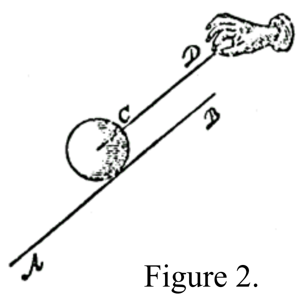

Figure 2.

And then, Huygens considered the body rotating being fastened by a rope. Here Descartes established the radial tension – conatus – in the string connected to the rotating stone. The intention of Huygens was to show that there is no difference between the conatus due to rotation and that due to the gravity.

[37] *ibid.*

How could he do that? Huygens showed that if one cuts the sling in which a stone whirled, and it flees away along the tangent line (see Descartes' second law of motion), then, the radial distances, from the stone to the center of the wheel, increase in a sequence that was exactly established by Galileo for the object on a free fall. This testifies, Huygens thought, for the identity in nature of the two tendencies: the rotational conatus (centrifugal force) and gravity. Here is what Huygens wrote in his treatise – *De vi Centrifuga:*[38]

> *Let BG [Fig. 3] be a wheel that rotates parallel to the horizon about center A. A small ball attached to the circumference, when it arrives at point B, has a tendency to proceed along the straight line BH, which is tangent to the wheel at B. Now, if it were here separated from the wheel and flew off, it would stay on the straight path BH and would not leave unless it were pulled downward by the force of gravity or its course were impeded by collision with another body. At first glance it indeed seems difficult to grasp why the string AB is stretched so much when the ball tries to move along the straight line BH, which is perpendicular to AB. But everything will be made clear in the following way. Let us imagine some very large wheel, such that it easily carries along with it a man standing on it near the circumference but so attached that he cannot be thrown off; let him hold in his hand a string with a lead shot attached to the other end of the string. The string will therefore be stretched by the force of revolution in the same way and with the same strength, whether it is so held or the same string is extended to the center at A and attached there. But the reason why it is stretched may now be more clearly perceived.*
>
> *Take equal arcs BE, EF very small in comparison to the whole circumference, say hundredth parts or even smaller. Therefore, the man I spoke of [as] attached to the wheel traverses these arcs in equal times, but the lead would traverse, if it were set free, straight lines BC, CD equal to the said arcs, the endpoints of which [lines] would not, however, exactly fall on the straight lines drawn from center A through points E, F, but would lie off these lines a slight bit toward B. Now it is clear that, when the man arrives at E, the lead will be at C if it was set free at point B, and when he arrives at F it will be at D. Whence we say correctly that this tendency is in the lead. But now if points C, D were on the straight lines AE, AF extended, it would be certain that the lead tended to recede from the man along the line drawn from the center through his position; and indeed such that in the first part of the time it would move away from him by the distance EC, and in the second part of the time it would be distant*

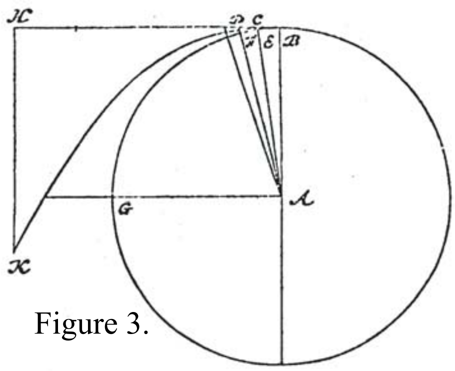

Figure 3.

38 *ibid.*

by the space FD. But these distances EC, FD, etc. increase as the series of the squares from unity, 1, 4, 9, 16, etc. Now they agree with this series ever more, exactly as the particles BE, EF are taken to be smaller, and hence at the very outset they may be considered as if they differed nothing.

Thus this tendency will clearly be similar to that which is felt when the ball is held suspended on a string, since then too it tends to recede along the line of the string with a similarly accelerated motion, i.e. such that in a first certain period of time it will traverse 1 interval, in two parts of time 4 intervals, in three 9, etc.

Huygens' work on the centrifugal force is one of the most remarkable in mechanics of the 17th century. It was highly appreciated by his contemporaries. Newton, who rarely praised his colleagues, wrote about this study[39]:

And by such propositions, Mr. Huygens, in his excellent book De Horologio Oscillatorio, has compared the force of gravity with the centrifugal forces of revolving bodies.

Huygens preceded Newton's treatment of mechanics, but his approach to force description (centrifugal force) corresponded non-inertial observer nobody considered at that time. Newton and all other scholars saw the world as in the theatre: on the stage in front of them. No other observers ever rose in mind as something important and perhaps different. Single static universe was subject to be described in absolute space and time by means of natural philosophy. Therefore, although praised, Huygens' work was not be truly evaluated by anybody, including Huygens himself. The time was not ripe for that in the sense of conceptual worldview.

Weight is the gravitational force

In a way, Huygens' vision of the centrifugal force as a force on the whiling body remained on the margins of theoretical mechanics of those days. He tried to explain gravitational force by means of centrifugal force:[40]

The mechanism envisaged by Huygens involved a fluid vortex rotating at such a high speed that all bodies on the earth are pushed toward its center because their centrifugal force is smaller than that of an equivalent volume of the vortex. Thus gravity results from a difference of centrifugal forces, and in this sense centrifugal force does produce motion, i.e., every time a heavy body falls.

This try to see weight of bodies as caused by a deficiency of centrifugal force was, however, obscure and failed.[41] Newton converted the meaning of centrifugal force in

[39] Newton, I. (1687/1999). *Op.cit.,* Book 1, Section II, Prop. IV, Theorem IV, Scholium, p.452

[40] Meli, D. B. (2006). Inherent and Centrifugal Forces in Newton. *Archives of History of Exact Science*, 60, 319–335

[41] Similar tries were made by Descartes before and Leibnitz after Huygens.

the way it fit his paradigm of force interaction. For him, the centrifugal force was the pair companion of the centripetal force, and acted on the constraint (the sling). Discussing the motion of a body rotating inside a hollow cylinder or circle he wrote:[42]

> *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 practice, however, it was the Huygens' meaning of the centrifugal force that was adopted. Indeed, one may regard our Earth as a giant revolving wheel. By virtue of this revolution the results of weight measurement change with the latitude: the extremely important fact nobody could ignore in trade and technology. The free fall acceleration g at the equator is less than in the northern countries and with it the weight, mg, changes. The period of pendulum oscillations: $T = 2\pi\sqrt{L/g}$, also changes (through g) and increases at the equator, comparative to poles.

However, Newtonian framework reigned in physics, even if he himself used centrifugal force in Huygens' sense to explain the flatness of the Earth as a globe, "the bulges on the equator". Despite the corrections required for practical goals, weight continued to be defined as the gravitational force, especially in presenting the general picture, as it is used in public education. Weight became even more important after Lavoisier's discovery of its conservation in chemical reactions. Atomic weights (although in the meaning of masses, but should we care if the difference is only a numerical factor?) became essential in chemistry, playing central role in its new organization in accord with the atomic paradigm.[43]

The changes began in the 19th century with the recognition of the controversy between the electromagnetism and mechanics. But the general vision of one world, and one true picture of it, preserved. By the end of the 19th century physicists questioned the foundation of the Newtonian framework of thought. Is it sufficiently justified and based on the experiment? Ernst Mach[44] demanded empirical definition for any physical concept.

The operation of weight measurement draws on weighing by means of a calibrated spring. If the body is supported or suspended, we can imagine it being weighed, but if it falls, is weight affected? How can we weigh a falling body? However, all these

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[42] Newton, I. (1687/1999). *Op.cit.*, p.453.
[43] Merz, J. T. (1904/1965). A History of European Scientific Thought in the Nineteen Century. Dover, New York, Vol. I, p. 395.
[44] Mach, E. (1893/1989). *The Science of Mechanics.* La Salle, Illinois: Open Court Classics.

questions did not change anything regarding the conception of weight. As long as the old framework of thought of the true observer preserved, all deviations in weighing, including falling, could be explained within the Newtonian frame of thought and adjusted to the practical needs by means of using the notions of *true* (the gravitational force) and *apparent* (the result of weighing) weights. It all changed when physics entered into the period of conceptual reconstruction in the new scientific revolution.

Questions to reflect

1. How did Newton show that gravitational force is proportional to the quantity of matter (inertial mass)?
2. In what way did Newton change the medieval concept of weight?
3. Characterize Newton's concept of weight. What was in Newton's weight concept that was abandoned in the following use of his definition of weight?
4. Why Newton was not satisfied with his understanding of gravitation?
5. What was, in Euler's view, the condition of weight to manifest itself?
6. What mechanism for gravity did Euler imagine to himself?
7. Huygens demonstrated that gravity force is similar to the centrifugal force. What strategy he used for this purpose?
8. What was the interpretation of the centrifugal force by Newton?
9. Huygens was the first to ask about the description of situation in view of rotating observer. Why do you think this approach was abandoned in physics until the 20th century?

* * *

III. Weight in the Modern Physics of the 20th century

Einstein: the principle of equivalence

Albert Einstein

The great change took place at the beginning of the 20th century. Physicists revealed the special role of observer in physics. Albert Einstein[45] was the first who in 1905 put inertial observers in the center of physical account of the world with his demand for physics laws to be indistinguishable for any inertial observer. The idea of the special theory of relativity was very nice, but the special

[45] Albert Einstein (1879 – 1955), the outstanding physicist and physics philosopher who shaped the modern physics in the 20th century.

status of inertial observers looked awkward to Einstein. His ambition to obtain physical description of the world valid for any observer brought him to the great success in 1916. In his general theory of relativity, all observers were included, inertial as well as non-inertial. The great unification was reached due to the very new idea. Einstein arrived to the conclusion on which Huygens, one may say, was already touched: inertial forces are identical to gravitational. Therefore, the description of the nature by non-inertial (accelerating) observer can be reduced to the description by the inertial observer plus the correspondent gravitation.[46] This idea was formulated as a *principle of equivalence* which Huygens' observer on a rotating wheel was actually able to declare:[47]

> *There is no experiment observers can perform to distinguish whether acceleration arises because of a gravitational force or because their reference frame is accelerating.*

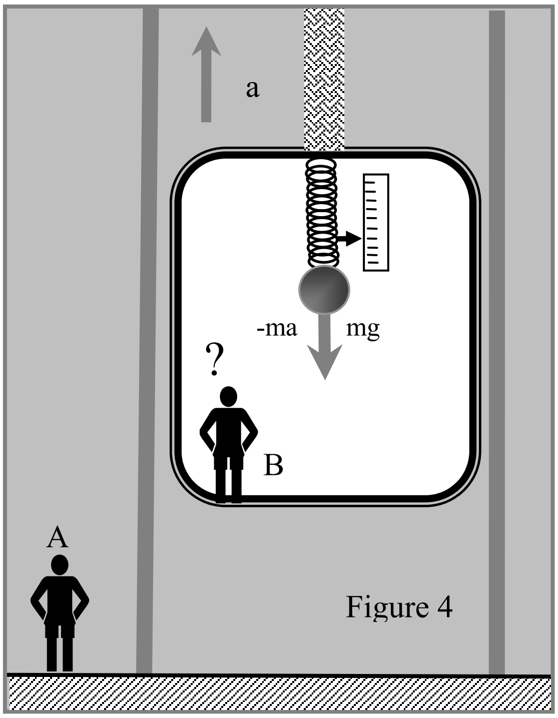


Figure 4

It was clear that Einstein's principle of equivalence had to imply fundamental change to the concept of weight. To obtain them we reproduce the way Einstein arrived to this principle.

Einstein performed a thought experiment, known as *the experiment of the accelerated elevator* (Fig. 4).

This experiment might serve as the key point for our reconstruction of weight definition. Reichenbach[48] wrote[49]:

> *Imagine a box of a room size, in which a physicist suspends a spring with the attached weight. The box has no windows and sits on the ground. Suppose that the box is being pulled up by a rope, like an elevator, in the direction of arrow **a**. Would the physicist inside notice it? – Yes, he would. Indeed, due to its inertia **m** [the weight] would remain*

[46] Einstein, A. (1916/1923). *The Foundation of the General Theory of Relativity in the Principle of Relativity*. Dover, New York, pp. 111-164.
[47] Giancoli, D. C. (1988). *Physics for Scientists and Engineers*. Prentice Hall, Englewood Cliffs, NJ, p. 155.
[48] Hans Reichenbach (1891-1953) was a prominent philosopher of science, the founder of the famous group Vienna Circle who developed the new philosophy of science – logical positivism.
[49] Reichenbach, H. (1927/1942). *From Copernicus to Einstein*. Philosophical Library, New York, pp. 86-89.

slightly behind the motion; the length of the spring would increase a little, accompanied by an increase in its tension. The accelerated movement would thus result in lengthening of the spring. Note, that if the motion were at a constant velocity, no expansion of the spring would take place. This follows Galileo's principle of relativity.

Now, says Einstein, was it necessary that the physicist inferred that the box moved? Certainly, not. This is because there is another scenario that could explain the extension of the spring. The other cause that could produce the same effect is gravitation. Indeed the same extension of the spring would happen if we assume that for some reason the mass of the planet suddenly increased. Its attraction would act on the weight in the direction of the arrow **g** *and pull it down. Therefore, from the observed lengthening of the spring the physicist could not decide what exactly happed. The point is, as Einstein stated, that there is no other way of distinguishing between these the two possibilities. No experiment within the box could differentiate between gravitational attraction and an accelerated motion... Two entirely different phenomena, inertia and gravitation, are placed here parallel to each other and either of them leads to the same effect, namely, to the increased tension of the spring...*

There is another way to express the meaning of Einstein's result. As we learned from Newton, each two bodies gravitate to each other with forces proportional to their inertial masses. In principle one could expect that they could attract each other in proportion to their gravitational masses. Therefore, one may see at this Newton's result the demonstration of the fact that inertial and gravitational masses are equal.

$$m_i = m_g$$

Following this fact we may infer the following famous result which was empirically obtained by Galileo with regard to free falling of objects to the ground. If we write the equation of motion, in view of any inertial observer, for a body m_i falling under the gravitational attraction with the body M_i, being at a distance r between their centers:

$$m_i a = G\frac{m_g \cdot M_g}{r^2}$$

If the inertial and gravitational masses are equal we obtain for the acceleration of falling:

$$\cancel{m_i} a = G\frac{\cancel{m_g} \cdot M_g}{r^2} \quad \text{and} \quad a = G\frac{M_g}{r^2}$$

It means that regardless of the mass of bodies in the field of gravity, they fall with the same acceleration (which is commonly labeled as g). This is the explanation of the empirical law of falling which was established by Galileo in the beginning of the 17^{th} century but only as an empirical law. Galileo left it without theoretical account.

Reichenbach wrote[50]:

Hans Reichenbach

Although the equality of the inert mass and the heavy [gravitational] mass was long known, nevertheless Einstein was the first man to recognize the basic significance of this fact. He realized that here lies the reason why the distinction between accelerated motion and gravitation cannot be made and why the physicist in the box cannot, therefore, determine whether he is moving upward in an accelerated motion or gravitational field interferes from. Hence, Einstein calls both conceptions equivalent, and maintains that it is meaningless to look for a truth-distinction between them.

New definition of weight

As we see, the rediscovered identity of inertial and gravitational masses implies uncertainty in the interpretation of weighing in the sense that that weighing results cannot testify for the action of the gravitational force. In this situation, there is no other way but to change the weight concept definition.

In 1928, rather soon after the introduction of the principle of equivalence, Reichenbach wrote[51]:

> *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.*

Newton's distinction between mass and gravitational force became insufficient. Now there was a need for further refinement – to distinguish between gravitational force and weight force. After the alliance of more than two hundreds of years, the gravitational force was conceptually divorced from weight (Fig. 5). Weight of the body was defined as following (theoretical definition):

> *Weight is the force that body exerts on its support at the state of rest as claimed by certain observer (in the correspondent system of reference).*

[50] Reichenbach, H. (1927/1942). *Op.cit*, p. 93.
[51] Reichenbach, H. (1928/1958). *The philosophy of space and time* (p. 223). New York: Dover.

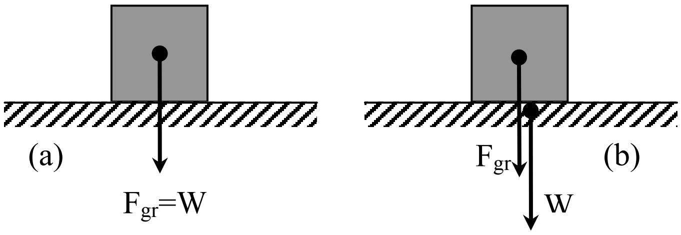
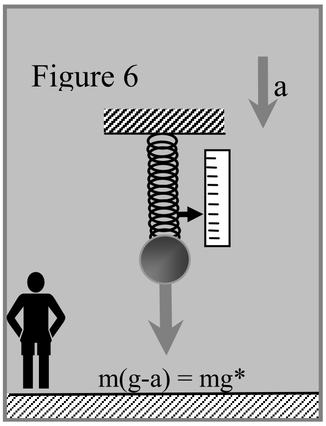


Figure 5. *(a) Old definition of weight: weight force, W, is the gravitational force on the object, F_{gr}. (b) New definition of weight: weight force, W, is the force on the support.*

In accordance with this definition, weight is the force that is measured by the calibrated spring, exactly as the observer in Einsten's thought experiment did. One may also provide the operational definition of weight:

Weight is the result of standard weighing



This definition actually repeats the described above inability of the internal observer to know whether the weight is due to gravitation of accelerated motion. For him the stationary state is interpreted as following:

$$W = F_{elastic} = mg^*$$

The external observer may interpret the weighing differently:

$$W = F_{elastic} = m(g - a)$$

Two observers interpret the same reality differently, unless a = 0. The situation is especially interesting in the special case, when the laboratory is freely falling: a = g. This is the state of weightlessness inside the laboratory. It may be explained by the external observer A (Fig. 4) as cancellation of inertial and gravitational forces. The internal observer B remains ignorant of the origin of the weight or its lacking, reflecting the incapability to distinguish between inertia and gravitation.

This approach allows physicists to generalize the concept of gravity in its old sense, in the meaning of objects being heavy whether due to the gravitational force (mg) or due to the inertial force (-ma). The origin of weight may be unknown as long as the definition of weight relate it to the results of standard weighing (or the force acting on the support at the state rest for the certain observer).

Yet, the important comment may clarify more the modern weight definition. Weight force is spread along the whole body and grows in the direction up-to-down. This can be understood as pressing force of each layer of the body on the subsequent one below, supporting it. Thus, tension gradient within the body is what accompanies weight. Therefore, no magnetic boots, which may stick the body to some surface, can replace weight in the state of weightlessness – the whole body remains weightless.

Weight in rotating systems

Weight in continuously revolving or spinning systems is an especially important case. Such are a revolving container, connected by a beam to the axis of rotation, and the Earth itself, of course. Huygens was the first who considered the phenomena in the rotating systems. In his study, he addressed the observer inside such a system – a revolving wheel.

Detailed analysis led Huygens to the conclusion that the observer on the wheel will account for the reality of the rotating objects without essential distinguishing between the gravity and centrifugal force in radial outward direction. Today we know what Huygens did not: that both forces are proportional to body's mass. Consequently, both forces may contribute to the weight (gravity) of the objects being in a circular motion around certain axis.

The fact that the centrifugal force can be regulated by the rate of rotation allows regulation weight magnitude of objects in a rotating system. This is especially important in cases where one intend to reproduce regular weight in the case the gravitational force cannot provide it. This is the case in a simple satellite, the space station which is in the state of weightlessness. Humans cannot survive this state for a long time (more than a year). Irreversible biological changes eventually cause serious damage to the functioning of organism at the level of biochemical processes resulting in the deterioration of health and ultimately the death of the organism. As living organisms, we essentially need weight. Rotation can help us in the state of a free gravitational movement (free falling) to avoid weightlessness and create weight. This idea is crucial for future space projects.

Questions to reflect

1. What was the idea of splitting the weight concept used after Newton as suggested by Reichenbah? What was the rationale of this split?

2. What is essential for functioning of the human organism gravitation or weight? Why do you think so?

Summary

We may summarize our excurse to the history of weight through thousands of years. From the beginning, the idea of weight reflected the perception of heaviness and quantity of matter. Until Newton, weight was explained as an *inherent feature* of the body. Aristotle related it also to the inherent intention of a body to move and take its natural place, in accordance with the kind of matter comprising this body.

Newton identified the gravitational attraction between any material objects as the cause for their weights. Newton suggested that the supporting hand senses and evaluates weight force of the object. Euler, however, stressed that the pressure upon the support only informs about weight, the weight itself is not the pressure, but is the force of gravity causing the pressure.

Weight concept of Newton became a characteristic of particular pair of objects. The amount of matter was characterized by a different quantity – inertial mass. Newton discovered that inertial mass determines the gravitational attraction as well. For this very fact, in a regular everyday practice, one may often ignore the difference between mass and weight.

During the 17-19 centuries, weight concept was used mainly in the terrestrial environment where the only important gravitational interaction is between the Earth and each object on its surface, not between the objects. In this situation, weight lost again its meaning as a characteristic for a *pair* attraction. Weight of a body was identified with the force of the gravitational attraction to the Earth exerted on the body. As such, weight returned to be a characteristic of any particular object, rather similar to its pre-Newtonian use.

After the introduction of modern physics, the physics descriptions of reality expanded to any observer (inertial and non-inertial) and weight lost its univocal correspondence to the gravitational force. Inertial forces are legitimate contributors to weighing results. Therefore, weight was defined as equal to weighing results or, equally, as the force the object exerts on its support being at rest for certain observer (reference frame).

The important point to discover is that the definition of weight, as defined by us operationally and theoretically appears to be *observer independent*: the weighing results remain the same regardless the forces that the particular observer introduces to explain it. The answer to the question "What is the cause of weight?" is, however, observer dependent: the deformation of the spring may indicate centrifugal force for the rotating non-inertial observer, or centripetal elastic force – for the outside inertial observer.

We may summarize the history of weight in the following conceptual diagram (Fig. 7):

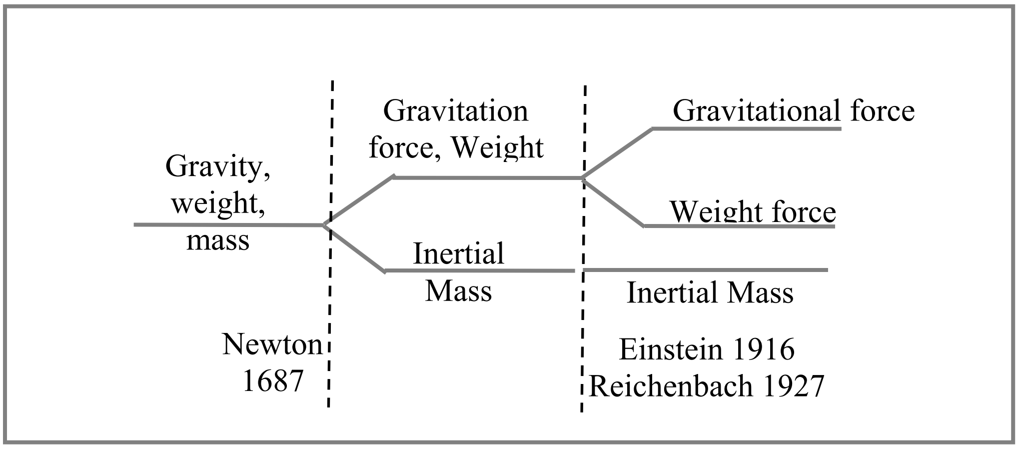


Figure 7. The flowchart of the conceptual change regarding weight that took place through the history.

* * *

Historical and philosophical background including nature of science

Conceptual aspects

The "true" weighing of the Earth by Atlas.

Weight concept initially entered to the Hellenic science as an intrinsic characteristic of any object characterizing its heaviness. As regular in ancient Greek philosophy, it was accompanied with a counter-concept – *levity*, the lightness of objects. Levity was removed only by Galileo through the argument: two light objects together never were lighter but always heavier than separately. In the world-picture of Plato, weight represented attraction of alike whereas for Aristotle, weight manifested an *inclination* of the object to get its natural place, specific for each object. As it seemed to the scholars of that time concepts reflected the reality as it is, rather as a direct description the essence.

Newtonian weight was formulated through an abstract concept – force – that described interaction. Weight appeared in *pairs* of equal forces between each two objects. Newton introduced weight between celestial objects *gravitating towards* each other.[52] In the terrestrial context, due to the unobserved gravitational interaction between regular bodies, weight remained a characteristic of a single body, the force pulling it towards the ground.

Descartes ascribed a special value to revealing the mechanism of natural phenomena. He suggested the mechanism of weight of bodies as caused by a deficiency of centrifugal force produced by vortices of fine matter surrounding each body. This mechanism, which Descartes tried to illustrate in his thought experiment with a bowl of gun balls and few pieces of cork among the balls. Today a similar principle bases the function of centrifugal separator. The efforts of Huygens, Leibnitz, young Newton and later Euler could not prevent the total failure of this program. The demands to the medium whiling around objects were contradictive and the reproduction of the features of gravity failed.

Facing this failure, Newton decided that it is upon the Natural Philosophy to describe the gravitation and eschew any speculation of its origin not based on the

[52] e.g. Newton, *Op.cit.,* Book III, Proposition 6, page 806.

direct evidence. This view he expressed in his famous *Hypotheses non fingo* (Latin for *I feign no hypotheses*) which established the new philosophical program of the modern science:[53]

> *I have not as yet been able to discover the reason for these properties of gravity from phenomena, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction*

In accordance to this view, the program of Newton was to provide the mathematical description of the reality, as accurate as possible in the quantitative sense. Indeed, the mathematical formalism produced by Newton, allowed his numerous successes: the account of celestial mechanics, tidal phenomena, flatness of the Earth globe, the account of projectiles and satellites motions and many others, all these at a high accuracy.

In the 20th century, Schrödinger expressed a similar idea when he said that he always felt that his equation was smarter than he was. Although nice and surprisingly powerful, this idea, however, never prevented people from curiousity and inquiry about how and what takes place in reality. They continued to seek the unknown *mechanism* behind the laws and principles, often applying hypothesis and speculations (abduction). Left without explanation, the gravitational interaction-at-a-distance expanded to electricity and magnetism in the 18th and 19th centuries. Eventually, the ontological awkwardness of the interaction-at-a-distance caused the invention of the field theory – reviving the Aristotelian and Cartesian idea of plenum (medium filled space) by Faraday and Maxwell. Interaction-at-a-contact replaced interaction-at-a-distance in the field theory of electromagnetism. By analogy, it expanded to gravitation. This step prepared a completely different mechanism of gravitation which was suggested by Einstein in 1916, in his theory of general relativity. In the modern physics of the 20th century, gravitation became a manifestation of the curved space-time, caused by matter. And the concept of weight, divorced from gravitation, it was identified with the pressing force that the object exerts on its support left at rest without any intrusion.

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[53] Newton, *Op.cit.,* General Scholium, page 943.

One may represent the steps in the development of understanding of weight in the following table.

Table 1. Understanding of weight (historical summary)

Weight – tendency to the proper place (Aristotle)	Weight – measure of heaviness, characteristic of bodies	Still-weight (pondus) – permanent faculty	Weight – the force of gravitational attraction at a distance (Newton)	Weight – stationary pressure of the object on its support; Weighing results (Reichenbach, Einstein)
Weight – attraction of similar (Plato)	(Euclid, Archimedes)	*Actual gravity, accidental weight* (gravitas) – appears at falling	Weight – the residual pressure of medium (Descartes, Huygens)	
		(Buridan, Oresme)		
Hellenic	*Hellenistic*	*Medieval*	*Classical mechanics*	*Modern physics*

Periods in science history

Absolute and relative concepts

Newton never considered how different observers perceive reality, how they would describe the world if want to apply his theory. This was not relevant: he conceived the Universe as an object, if looking from aside, or flying above. The expression of this perspective was that the whole picture was placed in absolute space and time – as a natural container. These concepts were different from all others in physics, they were taken as self-evident, beyond any need for definition,[54] in a sense – metaphysical.

Yet, Newton did distinguish between *true* and *relative rest*; as well as *true* and *relative movement.* However, his understanding of those notions was special. By *true* rest and motion, he understood those in view of his unique observer, the only one, who perceived the universe exactly as it was. And by relative, or apparent, Newton meant any state or quantity as perceived by all other regular observers, humans who unavoidably make errors in their perception and measurement:[55]

[54] Newton, *Op.cit.,* Definitions, Scholium, pp. 408-415.
[55] *ibid*.

Only 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.

Regarding *absolute* and *relative* time, he wrote[56]:

But we may distinguish rest and motion, absolute and relative, one from the other by their properties, causes and effects. It is a property of rest, that bodies really at rest do rest in respect to one another. And therefore as it is possible, that in the remote regions of the fixed stars, or perhaps far beyond them, there may be some bodies absolutely at rest; but impossible to know, from the position of bodies to one another in our regions whether any of these do keep the same position to that remote body; it follows that absolute rest cannot be determined from the position of bodies in our regions… Absolute time, in astronomy is distinguished from relative, by equation or correction of the apparent time.

In case of rotation, Newton discriminated between relative and absolute movement by means of forces that appear only in the true movement.[57] But, even then, Newton never considered anything which would remind us different *frames of reference*.

Koyre summarized this philosophy of Newton [58]:

In the Newtonian world and in Newtonian science, it is not man, but God, who is the measurer of things.

In somewhat similar manner, the notion of *true-weight* was reserved for the gravitational force. As to the *apparent-weight* – the term fitting to the Newton's philosophy – it represents the results of weight measurement in presence of impediment factors, which might deceive a practitioner, but not a philosopher. Newton illustrated by one of such misleading factor: the buoyant force. For him, apparent-weight, similar to relative time, may cause misunderstanding. For the case of an object immersed in liquid he wrote:[59]

But those things (immersed in water) which neither by preponderating descend, nor, by yielding to the preponderating fluid, ascend, although by their <u>true</u> weight they do increase the weight of the whole, yet comparatively, and as <u>commonly understood</u>, they do not gravitate in water (emphasis added by us).

The gravity of bodies in fluids is therefore two-fold: the one <u>true</u> and <u>absolute</u>; the other <u>apparent, common, and relative</u>. <u>Absolute</u> gravity is

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[56] *ibid.*

[57] Newton exemplified by his famous thought experiment of a rotating bucket of water, *ibid:* pp. 412-413.

[58] Koyre, A. (1956). Influence of Philosophic Trends on the Formulation of Scientific Theories. In: P. G. Frank (ed.), *The Validation of Scientific Theories*. Collier, New York, p. 183.

[59] Newton, I. (1687/1999). *Op. cit.* Book II, Proposition 20, Theorem 15, Cor. VI.

the whole force with which a body tends downwards; relative or common gravity is the excess of gravity with which the body tends downward more than the surrounding fluid. … 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 weight above the weight of the air (emphasis added by us).

Nominal definition

The question of relationship between the theoretical and operational knowledge (and hence definition) of weight never rose in classical science. It was not before the end of the 19th century that the new trend in the philosophy of science – positivism – brought into physics a special sensitivity to the empirical basis for any theoretical concept. The goal was to reduce the arbitrary (*metaphysical*, as they were called) statements, especially in the basis of science. Physicists had to worry and eschew the claims non-supported directly by empirical procedures that could determine the objective meaning of the concept.[60] This way, a dichotomy between the theory based and empirical based definitions arose. The definition which introduces a concept basing on the pertinent theoretical knowledge was called – nominal (*nomos* means law in Greek). In the case of weight, Newton was the pioneer of the *nominal gravitational* definition of weight, according to which:

Weight of an object is the gravitational force exerted on that object.

As was mentioned already, the gravitational force, and so the gravitational weight, were introduced by Newton in regarding the gravitational attraction between a couple of material bodies, in pairs. Hitherto, many physics textbooks keep with a half of this definition and consider as weight of an object the force of gravitation towards the Earth acting it.

In the 20th century, after the introduction of equivalence principle, the *gravitational nominal* definition was replaced by the *nominal elastic* definition:

Weight is the force that body exerts on its support at the state of rest as viewed by certain observer in the correspondent system of reference.

[60] In 1893, in his renowned *The Science of Mechanics,* Mach exemplified his critique by his new, operational definition of inertial mass. Mach (1893/1989), *op. cit.*, pp. 213-213.

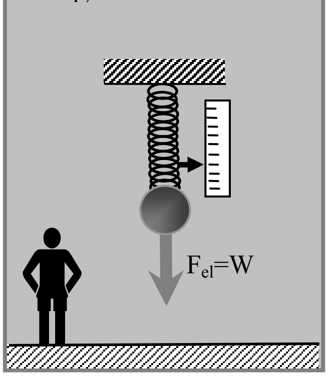
Operational definition

Alternatively, positivists insisted on the operational definitions of all physical concepts. This demand was so important that it gave rise to a special philosophical trend known as *operationalism*. The latter demands definition of any physical concept by an explicit and unique measuring procedure by which the considered concept is defined. Thus, in the case of weight, the operational definition is:

Weight of a body is defined as the result of its weighing.

Since the *operation* itself (such as weighing) is not defined here, numerous procedures could be suggested. This conceptual ambiguity should be avoided and therefore, the type of apparatus and the procedure of measurement all should be clearly mentioned. Hence, in the case of weight, one should use a more accurate definition:

Figure 8



Weight of a body is defined as the result of standard weighing.

Such a definition matches the requirements of Bridgman,[61] and is considered as *the operational definition* of weight, in contrast to the above introduced *nominal* one.

One may refine *standard* in the definition and write:

Weight of a body is determined by weighing it at the state of rest by means of a calibrated spring (spring scale).

Using *spring* scale (Fig. 8) presents an important constraint of the *standard weighing*. This is because *balance*, using horizontal lever, compares the forces (torques, in general), rather than evaluates their magnitudes. Balance, therefore, is more convenient to infer about mass of an object in comparison with some *standard*. Balance is not sensitive to weight changes due to geographical latitude.

Percy Bridgman

The spiral spring deforms (indicating the force of tension or compression) while providing support to the body being weighed.

[61] Percy Williams Bridgman (1882 – 1961) – the Nobel Prize winner in Physics (1946) for his work on the physics of high pressures. He explored the scientific method and established the trend of operationalism in the philosophy of science. Bridgman, P. W. (1952), *The Nature of Some of Physical Concepts*. Philosophical Library, New York.

As described by Hooke law of elasticity, there is a span of load in which spring lengthens in linearly proportion to the force exerted on the spring (weight). This feature makes weighing scale a convenient device for weight measurement.

It is the important requirement of the modern philosophy of science that two definitions – operational and nominal – should be provided for each physical concept.[62] They are complementary in establishing the meaning of physical concepts.

Questions to reflect

1. What was *true* and *relative* (*apparent*) for Newton with regard to physical concepts? In what sense these notions were different from the contemporary conception of the same notions?
2. What are *true* and *apparent weights*? How could they be defined?
3. Try to provide operational definition of the *true weight*.
4. Why do you think is important to provide operational definitions to physical concepts?
5. Why do you think is important to stipulate *standard* operation for weight measurement (*standard weighing*)? Exemplify this importance.
6. Why does standard weighing include scale (calibrated spring) and not balance?
7. Why do you think there is a need to provide a pair of definitions for each physical concept? Is operational definition sufficient to define physical concept? Explain your answer by using weight concept.

* * *

Target group, curricular relevance, and didactical benefit

Teachers of physics, in-service and pre-service, present the target group for this historical excurse. Their familiarity with the provided contents is not expected, since the materials of the history and philosophy of science are not included the regular teacher training programs. Weight is very often defined by the gravitational definition, as was regular in the past and the subject of inertial forces and multiple observers are out of even advanced placement curriculum of high schools.[63]

[62] Margenau, H. (1950). *The Nature of physical Reality*. McGraw-Hill, New York, Ch. 12, pp. 220-244.
[63] This is the situation in our country – Israel.

However, the subject of weight is highly relevant for physics and science teaching at schools. Regular physics/science curricula for schools include the concept of weight through all levels of instruction. Therefore, there is a need to adjust teaching at all levels, making it consistent, from kindergarten to high school (K-12 idea of the 2061 project in the USA).

However, the situation teaching is as following:

- The curricula of many *elementary* schools (6-12 years of age) usually include *operational* definition of weight: weight of a body is obtained by its weighing.
- The curricula of many *middle* schools (12-15 years of age), however, usually include *nominal gravitational* definition of weight: weight is the gravitational force exerted on the body. The inconsistency with the previous level is especially apparent in the account for the state of weightlessness.
- The curricula of many *high* schools (15-18 years of age) usually proceed with *nominal gravitational* definition of weight. To avoid inconsistency with the operational meaning of weight, the results of weighing are defined as *apparent weight* and the gravitational force exerted on the body – as *true weight*.

Several researches reported the low success of this approach and numerous misconceptions among even good students who confuse weighing results and gravitational force.[64]

Teaching the subject of weight by means of this historical excurse does not stop at the Newtonian understanding (17-19c) but upgrades it to the operational definition and adjusts it to the equality of inertial and gravitational forces, reached in the beginning of the 20th century. The excurse unfolds conceptual refinement of the weight definition. The teacher may use fragments of this excurse at different stages of instruction performed through years of schooling: from elementary to high level.

Several levels may be distinguished in concept teaching. The *first level* is "the level of things". At this level, weight is associated with some known things as their inherent feature. Weight constitutes an intuitive scheme by which the learner ascribes

[64] e.g. Ruggiero et al. (1985), Galili (1993), Galili & Kaplan (1996), Galili & Lehavi (2003), Gurel & Acar (2003), Gőnen (2008).

heaviness to the familiar objects (things are "light" and "heavy")[65]. Weight within this scheme may draw on individual perception and be directly to related to weighing.

At the *second level* the concept of weight is related to other physical concepts. The teacher may define weight as the force exerted by the object on its support (or suspending cord). This definition explains weight through the pressure on the support and tension in the thread. The knowledge becomes theoretical and so the definition – the nominal definition. The teacher completes by adding the operational definition: weight is the result of weighing. Thus the students have a couple: nominal and operational definitions of weight.

The gravitational force (the invention of Newton) is taught as the factor which *causes* falling of objects and their weight. The instruction proceeds to weight changes with geographical location (latitude) explained qualitatively, by Earth rotation. Weight, although caused by the gravitational force, appears different from it.

At the *third level*, one refines the concept of weight pointing to the fact that weight could be due to either gravitational or inertial forces. This step involves introduction of inertial forces (non-inertial observer in a rotating system). The important point to emphasize is that the definition of weight (weighing results) is observer independent. Yet, the account for weight as caused by other forces is observer dependent.

The didactical benefit of this approach is natural introduction of non-inertial observers. While considering weight changes in different situations (accelerating vehicles, satellites), students usually identify themselves with the observer inside the system under acceleration. Thus, introduction of non-inertial observers make this view legitimate and matching the intuition, removing tension and misconceptions.

A special didactical benefit is reserved to the case of weight in the rotational space station. Caused by centrifugal force, this weight strengthens conceptual knowledge of students distinguishing between weight and gravitational forces as independent.[66]

The suggested way to teach weight draws on the scientific diachronic debate and essential appeal to the philosophy of science. The latter is involved with regard to the

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[65] e.g. Piaget, J. (1972). *The Child's Conception of Physical Causality*. Totowa Adams Littlefield, New Jersey; Galili & Bar (1997), Children's operational knowledge about weight, *International Journal of Science Education*, 19 (3), 317-340.

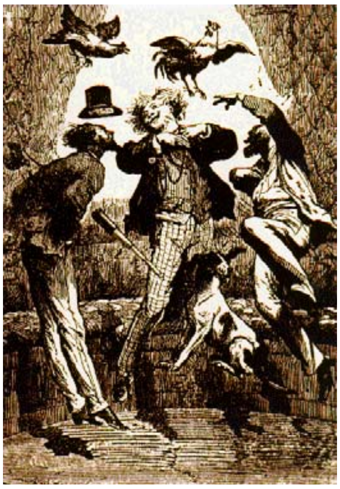
[66] For the rotating space-station and space-ships one may use clips from Stanly Kubrick's celebrated movie *2001: A Space Odyssey*

role of the operational definitions of the physical concepts. The natural involvement of the philosophy presents an important didactical benefit of this excurse.

* * *

Activities, methods and media for learning

1. Teaching about weight could be strengthened by the awareness of the importance of this concept for our life. This may present a subject for an interesting discussion. The role of weight in our lives is central because it is involved in the way we eat and drink, move, and function. Life is impossible without weight, and weightlessness, experienced for a long time, kills. Weightlessness may impede the vital processes taking place in human organism.



The moment of weightlessness on the way to the Moon

2. To appreciate the misleading potential of the gravitational definition of weight, it is recommended to discuss the episode describing the state of weightlessness as provided by Jules Verne (1828-1905), the famous science fiction novelist of the 19th century.

In his novel *From the Earth to the Moon* (1865) he explained in details his understanding which drew on the straightforward application of Newton's tenet: weight is the gravitational force. The well educated novelist, who [illegible] flights, explained that the state of [illegible]ed when the spaceship reached the point of force equilibrium, where the attraction to the Earth is equal to the attraction to the Moon.

Students should be encouraged to discuss this erroneous explanation that implied weightlessness only for an instant during the flight. Criticizing this understanding could be very beneficial in overcoming similar misconceptions which are held by contemporary students, as was documented by several researches.[67]

The moment of weightlessness on the way to the Moon

[67] e.g. Galili, I. & Kaplan, D. (1996). Students' Operation with the Concept of Weight. *Science Education*, 80(4), 457-487

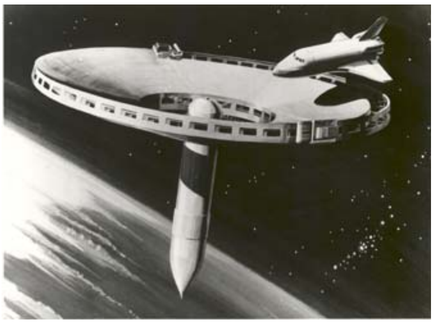
3. A special activity on the subject of rotating space station desrve several meetings.

One of the first projects of rotating space station - *the residential wheel.*

The first to address could be Herman Potocnik[68] [Nordung] (1892-1929), Slovene rocket engineer and pioneer of cosmonautics, He was the first who described rotating space station in his book *The problem of travel in the world space*[69]. His *residential wheel* had the form of a very big torus in which regular weight was reached by rotation of the station at particular rate.

Herman Potocnik

The focus of this activity could be the story of the famous rocket engineer, Werner von Braun. In March 1952, he published an article *Through the Last Border* in a popular magazine *Kolers*. In it, he described a huge rotating space station and a full range of space technique, including reusable launch vehicles (space-shuttle, so well known today), and description of colony of astronauts in space – serving for life out of the Earth and space exploration.



Imaginary station with the shuttle as was really build

This discussion may expand on the topic not directly related to weight. Werner von Braun, the person who carried out the greatest technical project in the history of human civilization – the Apollo project that brought people to the Moon. The personality of this outstanding professional is controversial – a senior SS-officer in Nazi Germany, directly responsible for the bombardment of England by rockets V-2, and rocket industry using slave labor (the factories empowered by prisoners of concentration camps). Only ten years after that he already led the U.S. space program.

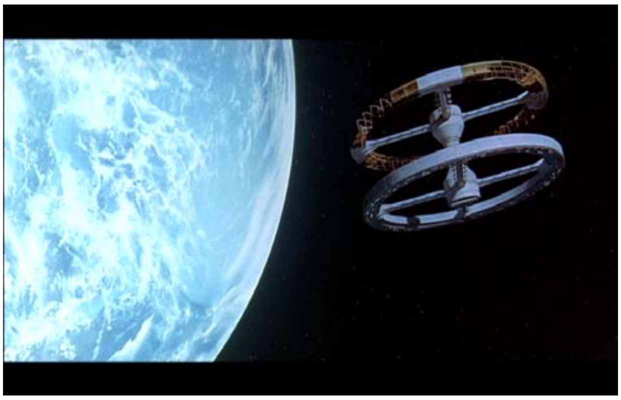
Werner von Braun

[68] http://www.astronautix.com/astros/noordung.htm

[69] Noordung, H. (1929). *Das Problem der Befahrung des Weltraums*. Schmidt & Co., Berlin.

Various questions may arise in this regard: May a distinguished scientist collaborate with the antidemocratic and evil regimes? Are there special moral obligations that scientists should obey in contemporary society? Should this aspect be included into learning physics? Should addressing the great achievements of controversial personalities mention von Brown? The discussion may expand to Heisenberg and his atomic project. The well-known play *Copenhagen* revealing debate between Nielse Bohr and Werner Heisenberg can be used for expanding this activity to a culturally rich event in school life.

4. The essential aspects of weight concept one can found artistically represented in science fiction: movies and novels. For example, the problem of long-distance flights with respect to the creation of weight of the astronauts can be resolved by using rotational space vehicles. Perhaps the most striking example of such products of art is the well known science fiction movie *2001: A Space Odyssey* produced by Stanley Kubrick in 1968 after the novel of Arthur C. Clarke. In the movie, the rotating space station, *Ferris wheel*, colorfully represents the prototype of space stations of the future which will provide weight to their inhabitants: space explorers.



Rotating satellite in the movie *2001: A Space Odyssey*

The same movie shows a spaceship, launched to Jupiter with a special long term mission. The spaceship provided weight to the astronauts in the cabin spinning around its axis. For the purpose of film production Kubrick ordered construction of a 30-ton rotating wheel by Vickers-Armstrong Engineering Group at the cost of $750,000. Today, it serves only as an object in the museum and

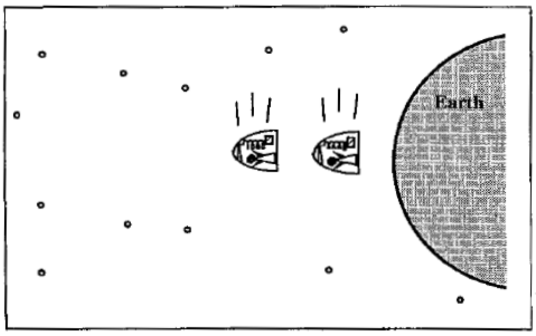
Astronauts running along the circumference of the rotating cabin of the spaceship during the voyage to Jupiter.

keeps igniting people's imagination, because the future of the humankind is seemingly related to space colonies creating weight for their numerous inhabitants who will leave the Earth forever.

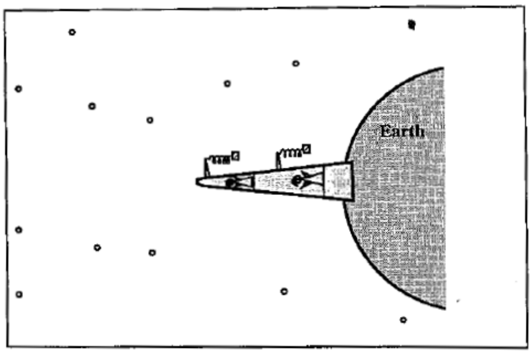
5. Try to calculate the radius of the station, rate of spinning, tangential and angular velocity at the rotational station taking into account that gravity intensity (g) created by the rotation will not change more than 1% along the height of a person (h=2m)[70]. Where the dimensions of the spaceship going to Jupiter shown in the Kubrick's movie "2001: Space Odyssey" realistic?

6. In the course of the historical excurse and while presenting the historico-philosophical background we provided questions for reflections which can be discussed with the students. Here we present several additional questions that might be used to probe understanding of the concept of weight by the learners.

a. Consider two satellites orbiting the Earth on the heights of 100 and 200 km. Astronauts in each satellite perform weighing of the mass of 1 kg. What are the weighing results in both cases and what are the weights the astronauts obtained in them? Please explain your considerations.



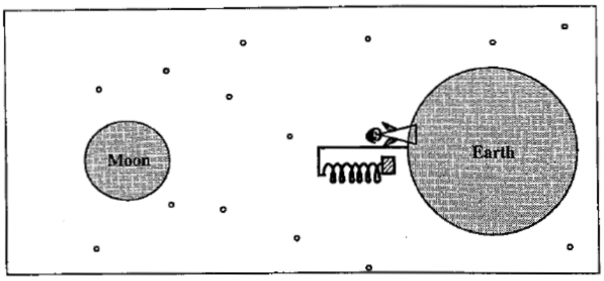
b. Consider a super high tower of 200 km. Two researchers perform weighing of the mass of 1 kg, one on the height of 100 km and the second – on the height of 200 km from the ground. What are the weighing results in both cases and what are the weights obtained by the researchers? Explain your considerations.

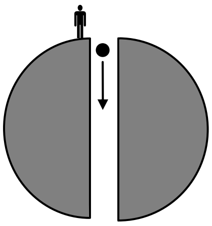


c. Compare the cases (a) and (b). Are they different in the given answers? Explain your answer. What are the implications regarding weight of the objects?

[70] See http://visions2200.com/SpaceHabitat.html for possible help.

d. Suppose a person performs weighing of a box by means of a spring scale of extremely high sensitivity. Exactly at the moment of the measurement, the Moon is passing over the place (see the figure). Will there be an influence of the Moon on the results of weighing? Did the weight of the box change? Explain your considerations.





e. Consider a tunnel crossing the Earth globe along its diameter. A body was dropped into the tunnel (this situation was discussed by the medieval scholars in the University of Paris in the 14th century). As the body starts to fall down what happens to its weight? Explain your considerations.

f. In the following pictures you observe four cases: (i) jumping from the plane, (ii) floating under water, (iii) descending on a parachute, (iv) jumping from a hill.

(i)

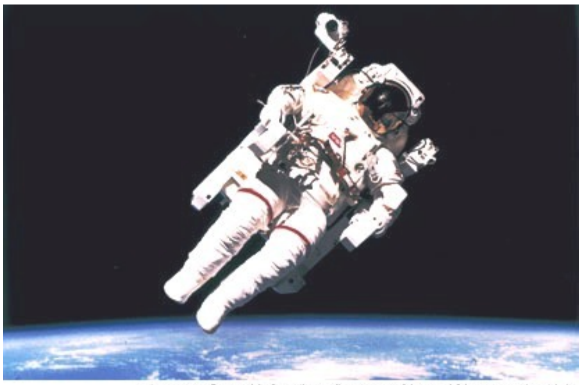
(ii)

(iii)

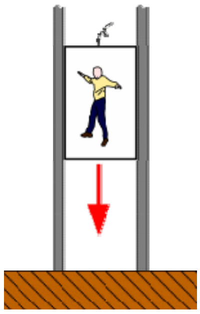
(iv)

Compare these cases in terms of weight changes of the body of the jumpers (assume their equal mass).

g. In the following pictures you observe a person in a free falling elevator cabin, next to the ground, and the astronaut left the satellite for a free "walk" in space. Compare and characterize their situations in terms of their weight and the gravitational force acting on them. Are the situations different, the same, else?



Astronaut Bruce McCandless, first to use Manned Manoeuvering Unit



h. Falling object is in the state of weightlessness. Consider a person throwing a ball at an angle with horizon. At what point one may say that the ball is weightless? Neglect air resistance.

i. What is the weight of the Moon? What would be the answer given by Newton? Are the two answers (yours and Newton's) different? Explain.

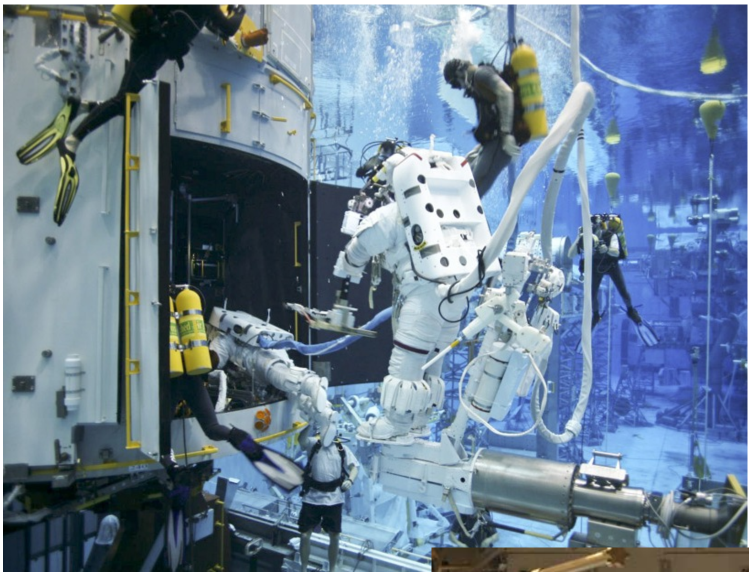
j. On the following two pictures you observe the plane used by NASA for training people to function in the state of weightlessness (left) and a person in the cabin of this plane (right).

Explain how it is possible to reach the state of weightlessness flying inside the atmosphere. At what stage of the flight weightlessness is reached?

k. In the state of weightlessness, is it possible to create weight by using magnetic boots in a spaceship (as was shown in the movie by S. Kubrick "2001: Space Odyssey")? Explain your considerations.

l. American Space Agency – NASA – uses water pools for training astronauts. Does floating in water put divers into the state of weightlessness? What could be the rationale of using water pools in astronauts' training?

m. Discuss the different and common with respect to weight in the four following pictures.



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Obstacles to teaching and learning

Several difficulties are expected in learning about weight concept.

Firstly, the very dealing with concept definition might seem unusual and of secondary importance. In fact, it is the focus on the concept definition of weight, its controversy, which demonstrates the essential importance of philosophical issues in physics teaching.[71] The direct implication of this subject of learning is the appreciation of the importance of the operational definition of physical concepts, which can be illustrated by the advancement of contemporary physics (Einstein theory of relativity), as well as pedagogical benefits.[72]

[71] Galili, I. & Lehavi, Y. (2006). Definitions of Physical Concepts: A study of physics teachers' knowledge and views. *International Journal of Science Education,* 28(5), 521–541. Also Vinner, S. (1991). The Role of Definitions in Teaching and Learning Mathematics. In: D. Tall (Ed.) Advanced Mathematical Thinking (pp. 65-81). Academic Publishers, Boston.

[72] Arons, A. B. (1990), *A guide to introductory physics teaching*, Wiley, New York; Reif, F. (1994), *Understanding Mechanics* (p. 5), Wiley, New York.

Another serious difficulty might follow from the fact that many teachers were instructed within the curriculum, which adopted the gravitational definition of weight, as still prevailing in many countries.

Thus, among the textbooks in English, one may distinguish between two groups. The authors from the first group are adherent to the old tradition of the gravitational definition of weight[73], whereas the authors in the second group follow the new trend presented in this excurse. The new trend which started at the 60th of the previous century defines weight as the result of weighing by a calibrated spring scale.[74] The curriculum policy is determined by the educational institutions,[75] and the debate between physics educators continues.[76] Facing this difficulty one may suggest to the teachers to learn the historical arguments for the change of the weight definition and the requirements of the contemporary philosophy of science as common in physics practice.

The operational definition of weight might help in removing another obstacle in teaching – neglecting multiple observers. It may make apparent that keeping with the restriction of school teaching solely to the inertial observers may clash with students' approach who usually prefer, albeit intuitively, the point of view of the accelerated observers – the active participants of the situation and not its passive observer. Naturally, any change of curriculum should start from learning the alternatives.

For example, the explanation of the state weightlessness under the restriction to the inertial observers is known as very difficult to students and teachers[77]. Indeed to ascribe weight to the floating in space astronaut, being at the state weightlessness, is

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[73] e.g. Young, H. D. & Freedman, R. A. (2004). *University Physics* (pp. 120, 441, 459-460). Pearson, Addison Wesley, New York.

[74] e.g. Orear, J. (1961), *Fundamental Physics* (p. 82), Wiley, New York; Halliday, D., Resnick, R., & Walker, J. (2000), *Fundamentals of Physics* (6th ed., p. 80), Wiley, New York; Keller, F. J., Gettys, W. E., & Skove, M. J. (1993), *Physics* (pp. 99-100), McGraw Hill, New York; Lerner, S. L. (1996), *Physics* (p. 62), Jones & Barlett, Sudbury, Mass; Marion, J. B. & Hornyack, W. F. (1982), *Physics for Science and Engineering* (Vol. 1, p. 129), Saunders New York; Hewitt, P. G. (2002), Conceptual Physics (9th ed., p. 160), Addison Wesley, San Francisco.

[75] Physics textbooks in Russian unanimously follow the operational approach to weight definition, as presented in this excurse.

[76] Morrison, R. C. (1999). Weight and Gravity – The Need for Consistent Definition. *The Physics Teacher*, 37, 51-52, Galili, I. & Lehavi, Y. (2003). The importance of weightlessness and tides in teaching gravitation. *American Journal of Physics*, 71(11), 1127-1135.

[77] Galili, I. & Lehavi, Y. (2003). The importance of weightlessness and tides in teaching gravitation. *American Journal of Physics*, 71(11), 1127-1135.

not a simple task. Legitimizing non-inertial observers in school curriculum may simplify the transition to the new understanding matching the modern physics.

The cultural approach to teaching physics would imply discursive teaching, the one that presents a wider perspective of more than one explanation: the one by an on the ground (on the Earth surface) observer, as well as by one inside the satellite. The operationally based definition of weight as a contact elastic force suites this teaching approach.

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Pedagogical skills

Besides the numerous skills required from the teacher in regular teaching of science[78], one may mention here that using the history and philosophy of science in physics lessons needs a special skill to teach culturally rich materials. The characteristic feature of cultural material is its dialogical character which presents the knowledge in its conceptual variation.[79] The position of Newton was shaped in a dialogue with Aristotelian ideas as well as with those of Descartes, Hooke and Huygens. Einstein struggled in the very aggressive debates with many scholars until his theory was adopted. Accordingly, the teacher may organize a dialogue in class to promote students understanding and success in learning. The validity of this strategy draws on the dialectical nature of the scientific truth, the complementary contribution of several aspects to the contemporary scientific knowledge.

Within such teaching it is a special skill to monitor incorporation of metaphysical components (knowledge about science: historical, philosophical, social) into the actual teaching of scientific disciplinary contents. A "free" discussion in the class can indeed lead the students astray of the topic to be learned. It is upon the teacher to facilitate by mediation the discussion that will lead the students to the construction of the valid knowledge of weight and gravitation from a culturally rich context. The materials of this excurse were directed to suit this strategy.

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[78] See for example, Hassard, J. (2005). The Art of Teaching Science. Oxford University Press, New York.

[79] Tseitlin, M. & Galili I. (2005), Teaching Physics in Looking for Itself: From a Physics-Discipline to a Physics-Culture, *Science & Education*, 14(3-5), 235-261. Marton, F. Runesson, U. & Tsui, A. B. M. (2004), The Space of Learning, in F. Marton, & A.B.M. Tsui (Eds.), *Classroom Discourse and the Space of Learning* (pp. 3-40). Lawrence Erlbaum, Mahwah, New Jersey.

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