DO ALL BODIES FALL EQUALLY? ON THE IMPORTANCE OF STATING THE AREA OF VALIDITY IN PHYSICS EDUCATION

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ABSTRACT
Galileo's law of free fall, a corner stone of modern science, is usually accepted without any limits except the condition of vacuum. The present study, following the paradigm of educational reconstruction (Duit et al. 2005), examined Galileo's law both as a scientific topic and as it is commonly understood by students and physics teachers. Clarification of the law includes not only its refinement, but also touches on the nature of physical knowledge: the understanding of the limited validity of any concrete physical statement, law, rule or conception. The research findings clearly demonstrate that students and teachers commonly miss the knowledge that, within the standard framework of Newtonian physics, Galileo's law is only approximately correct since its formulation neglects Newton's third law for falling objects. Unawareness with regard to the limits of validity of Newton's second law, applicable only for an inertial observer, inhibited the subjects from providing any solution for their difficulty. The view that regards Galileo's law as an unlimited truth is usually not challenged either by textbooks or by physics education research. Furthermore, Galileo's law is often presented to provide the first evidence for the equivalence principle. The shortcomings revealed in our study, imply the necessity to elaborate the area of validity of any physical law in physics instruction, in order to adequately represent the nature of physical knowledge.

KEYWORDS
Galileo's law of free fall, free fall, equivalence principle, Newton's laws, Newton's second law, Newton's third law, area of validity, inertial observer.

INTRODUCTION

The present study examined the awareness with regard to the important issue of the limited area of validity of physical laws through the special case of Galileo's law of free fall. As a norm in science, any physical law has its area of applicability within which it is valid. Throughout history, scientists have reconsidered the validity area of theoretical statements whenever they realized the necessity to refine certain knowledge. Laws which had been perceived as unconditional were realized to be stipulated by particular conditions (e.g. the law of velocity addition). In other cases the area of validity was extended to new domains previously considered to be distinct.

The present study endeavours to find out whether physics teachers and university students develop awareness with regard to the borders of validity of a law often presented without its entire restrictions (Galileo's law). It further examines the subjects' reaction when presented with those borders.

Science education usually deals with educational reconstruction, presuming scientific clarification and clarification of students' conceptions (Duit et. al, 2005). Unawareness with respect to borders of validity may affect learners in constructing a coherent physical (scientific) worldview (Lanciano, 1998). The question whether the knowledge of the area of validity evolves spontaneously or could be changed easily, poses a challenge to the physics education researcher.

Galileo's law of free fall, considered to be an empirical law that replaced the Aristotelian claim that heavier objects fall faster than lighter ones, presents an interesting subject to be studied with respect to the general issue of the area of validity. This law is highly appreciated by physics educators who present it as a turning point in physics that had enunciated the ascent of the importance of direct and systematic observation in the discipline methodology (Arons 1990, p. 295). Galileo's law is often restricted in introductory textbooks (we examined above 30 standard university-level textbooks) by the influence of air resistance and the vicinity of the Earth - the distance dependence of the free fall acceleration (e.g. Giancoli, 1995, pp. 31-33).

However, other limitations of the law of free fall, the mass or shape dependence of free-fall acceleration and the frame of reference for which it holds true are rarely, if at all, discussed. Introductory textbooks commonly assert that free fall is always independent of the falling mass. Regularly, the law of free fall is explained by employing Newton's universal law of gravitation together with his second law and the cancellation of the mass of the falling object using the equivalence of inertial and gravitational masses. The observer measuring the free-fall acceleration is not mentioned. The customary formulation of Galileo's law ignores the interaction of the two bodies (the falling body and the Earth) and thus contradicts momentum conservation of the two bodies system. Frequently addressed in physics education research, Galileo's law of free fall is always presented as the appropriate, unlimited claim against which the misconception that heavier objects fall faster than lighter ones is measured (Champagne, Klopfer, & Anderson, 1980; Whitaker, 1983; Gunstone & Watts, 1985; Halloun & Hestenes, 1985; Bar et al., 1994; Haertel, 2003).

Mass, shape or observer dependence of the law of free fall could be regarded as fundamental constraints since they do not address the experimental conditions in which the law is tested but the accuracy of the law itself. This study examines the knowledge of the approximate nature of Galileo's empirical law with respect to the mass of the "falling" object: in fact, bodies of significant mass relative to the Earth mass fall faster then lighter ones (Baker, 1930/1943).

The case of Galileo's empirical law of free-fall involves a broad span of physical knowledge and its history from Galileo experiments to Einstein's principle of equivalence. It may illustrate the importance of the subject of validity area for novice students of physics.

THEORETICAL BACKGROUND

Galileo revised Aristotle's law of fall through considering the falling of objects in a medium with gradually diminishing resistance (Galilei, 1632/2001 pp. 234-235). Galileo's thought experiment of free fall used to refute Aristotle's claim (Galili 2009) and is still quoted in physics textbooks (e.g. Rogers, 1960 p. 12).

Newtonian progress introduced the framework of force, interaction (of the falling object and the Earth) and laws of motion to account for the free fall phenomenon. Cancellation of the falling object mass (based upon the equivalence of inertial and gravitational masses) on both sides of the equation of motion (Newton's second law) yielded Galileo's claim: bodies accelerate due to gravity regardless of their mass. However, this result is valid only for the inertial (relative to the stars) observer, not for the one standing on the ground (Fig. 1) (Lehavi & Galili, 2009).

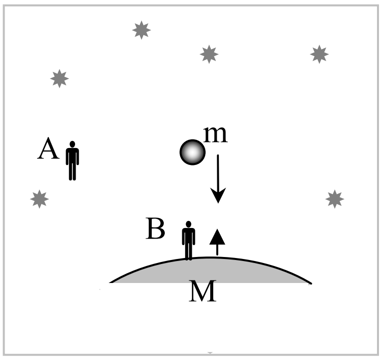

Figure 1: Galileo's law (mass independence of free-fall acceleration) is valid for the inertial observer A and presents an approximation for the on ground observer B who measures the mutual motion of the object and the Earth.

The acceleration measured by the on-ground observer is the result of the mutual fall of the body and the Earth:

$$a = G\frac{M}{r^2} + G\frac{m}{r^2} = G\frac{M}{r^2}\left(1 + \frac{m}{M}\right)$$

This result leads to a qualitative conclusion that the statement "all objects fall equally" is only approximately correct. The required condition for the approximation to hold up - the relatively small mass of the falling body, is rarely stated in educational context (Ohanian, 1977). Thus, the astronaut dropping a hammer and a feather on the Moon demonstrated that "Mister Galileo was right" for small bodies only but not in general.

From the mutual fall of two objects one concludes that the time of fall, the impact velocity and the escape velocity are all mass dependent for the on ground observer. Notably, the time of fall and the impact velocity are mass dependent for the inertial observer as well. Furthermore, the previous characteristics of the motion of the two bodies follow the law of momentum conservation applied to the two bodies system and thus do not present a merely kinematical result but a dynamical one as well.

The following table summarizes the status of the statements with regard to free fall for different observers and conditions:

Table 1: Adequate status of the claims related to Galileo's law of free fall

Statement	**For the on ground observer**	**For the inertial observer**	**In a uniform field (non-inertial observer)**
In vacuum, all bodies fall from the same place with equal *acceleration* regardless of their mass, composition, density, shape, size.	Approximation	True	True for shape and size dependence. Approximation for mass/density dependence
In vacuum, the *falling time/ collision velocity* of all bodies falling from the same place is equal regardless of their mass, composition, density, shape, size.	Approximation	Approximation	Approximation

Normally, the discussion of free fall in educational context ignores the motion of the Earth and thus the possible mass dependence of the phenomenon (Gallant & Carlson, 1997; French, 1997; Mallinckrodt, 1997; Swartz, 1997). Advanced courses in mechanics, while treating the mutual motion within the context of the two-body problem, do not revisit Galileo's law (Goldstein, 1977, p. 101). Size or shape restrictions, relevant in the non-uniform gravitational field and for non-point bodies, are reserved for advanced courses (Misner et. al, 1994, pp. 21-24). At the same time, the claim of mass independence of acceleration by which bodies approach each other does not arise regarding the motion of astronomical objects (Baker, 1943, p. 161 presents a rare exception).

The introductory physics textbooks we have examined often address Galileo's law in the context of ballistic motion, prior to Newton's laws of motion (e.g. Benson, 1996, pp. 42-43; Serway & Jewett, 2006, pp. 36-37; Young & Freedman, 2000, pp. 46-47; Walker et. al, 2008, pp. 24-25). Later in the course, Galileo's law is often quoted within the discussion regarding the equality of gravitational and inertial masses.

GALILEO'S LAW AND THE EQUIVALENCE PRINCIPLE

Following Einstein's discussion of the equivalence principle in the General Theory of Relativity (1950/1970, p. 57), Galileo's law is often related to the mass independence of free fall:

(Inert mass) x (Acceleration)
= (Intensity of the gravitational field) x (Gravitational mass)
It is only when there is a numerical equality between the inert and the gravitational mass that the acceleration is independent of the nature of the body.

Cancellation of gravitational and inertial masses provides the mass independence of the free fall acceleration. This result, however, holds in reality only under the tacit assumption that mass, size and shape independence of free fall require a sufficiently small object (Dicke, 1964, pp. 1-16; Ohanian & Ruffini, 1994). Furthermore, the description is valid for an inertial observer. Only under this assumption, we may relate Galileo's empirical results to Einstein's theoretical claim. In our times, the equivalence principle was checked by Eötvös, who compared the ratio of inertial and gravitational accelerations for different materials (Dicke, 1964).

However, when the approximation of the small body no longer holds, mass begins to be a factor of influence and for the on ground observer the free fall acceleration becomes:

1. $$g^* = g_0\left(\frac{R_E}{r}\right)^2\left(1+\frac{m}{M_E}\right) \text{ with } g_0 = G\frac{M_E}{{R_E}^2}$$

Albeit a small effect in regular environment, the factor *1+m/M* introduces a qualitative change. For two spherical bodies, one with density ρ_r and radius *r* and the other with density ρ_R and radius *R*, the factor *1+m/M* becomes:

2. $$1+\frac{m}{M} = 1+\frac{\rho_r}{\rho_R}\left(\frac{r}{R}\right)^3$$

Evidently, the free-fall acceleration, as observed by B (Fig. 1), depends on the density also in vacuum, and thus on the *"nature of the body"*. To appreciate this effect, consider two spheres (asteroids) of radius 10km falling towards the Earth from a distance of 300 km. If the first sphere has the Earth's density and the second is 500 times denser[i], the impact velocities will differ by 2.5 mm/sec (air resistance being neglected). On the Moon, however, the same results would require the density ratio of 15 only. The fact that free fall acceleration depends on the body's nature (and hence on its constituents) means that the cancellation of the inertial and gravitational masses could not be justified automatically

[i] Such density can be found within stars.

but requires certain elaboration. Such an elaboration, which exhibits sensitivity to the epistemology of science, and in particular to "the range of validity", may be regarded as "cultural".

THE EMPIRICAL STUDY

The refinement of Galileo's law as presented above rests on basic classical mechanics. We have checked the challenge that such a refinement poses for a highly qualified population: students majoring in physics and physics teachers.

Methodology

We administered a questionnaire to a sample of university physics students of both undergraduate and graduate levels (N=51)[ii] and in-service, experienced (20 years on average), high school physics teachers (N=19: 12 from Israel and 7 from Italy). Subsequently, we interviewed five teachers and five graduate students (all from Israel). The questionnaire contained three questions: the first two closed and the third open. The first question asked about the possible influence of mass, density, shape of a body as well as the air resistance on the falling acceleration. The second one asked which of two spheres of equal radius and material – one solid and the other hollow – dropped together, reaches the ground faster. The subjects were also required to address the limits of validity of their answers and to add their comments. The third question, the open one, asked them to reflect on the importance of Galileo's law.

The interviews lasted from 45 to 75 minutes. Each interview began with the questions from the questionnaire. Subsequently, the interviewer described a situation in which two electrically charged bodies, one negative and the other positive, are released simultaneously. He first asked about their relative acceleration and then whether this situation was different from the case of gravitational attraction. The analogy was intended to stimulate the idea of mutual influence between the interacting objects. Following this discussion the interviewer asked the participants whether they could reconsider the claim of Galileo's law. Conceptual comments were registered as well as argumentation and changes of view, manifestations of confidence and evaluative remarks.

Empirical findings

The written answers exhibited great uniformity stating that free fall is independent of mass, shape or density of the falling objects while air resistance presents the only constraint. Comparison of the responses of the various populations in our sample showed no difference in spite of the diversity in academic background, training, countries of origin[iii] and teaching experience. Remarkably, the students' responses were similar to those of the teachers. The repetitive nature of the questions did not affect the claims, either. The first part of the interview (the fixed questions) repeated the results of the written test.

The uniformity found in the responses of such a heterogeneous population, may indicate that Galileo's law of free fall is perceived as an unquestioned truth with air resistance as its only restriction.

The subjects (teachers as well as students) stated confidently that Galileo's law presents a "Law of nature" supported by Newton's theory (quite in accordance with the Galilean view of the Book of Nature, Galilei 1623/1957). They evaluated Galileo's law as an important element of the physics curriculum, which demonstrates the limits of intuition and its inferiority to knowledge based on a controlled experiment:[iv]

S_1: Galileo's law is important for everyday life…for instance, one can measure the depth of a well… It is also important to understand satellites … [Q1]

[ii] All the students who volunteered to participate in the research, study in the same institution.

[iii] We may add that Israeli teachers, graduated in various countries, represent a rather heterogeneous community.

[iv] S stands for student and T for teacher

T_2: Galileo's law enables one to reveal students' misconceptions. It demonstrates that intuition can be misleading and that physical ideas go beyond intuition and draw on experiment. This law can show that experiment may shake one's beliefs… When a student grasps Galileo's law and can apply it, I can say that he has made a real progress. [Q2]

The electric analogy was considered a different case and did not cause the subjects to change Galileo's law:

S_1: The difference is that in electric attraction, the force is not due to the mass but to the charge... *a* [acceleration] depends on the mass. In free fall *a* becomes GM/r^2… it depends only on the mass of the Earth, but not on the mass of the body... [Q3]

T_3: In this [electric] case one has to use conservation of energy and momentum since there are two velocities and the acceleration will depend on both masses….[in the case of free fall] maybe the mass of the Earth is so large that it actually does not move. [Q4]

Question: Can you compare the free falling of a tennis ball with that of the Moon at an equal distance?

T_3: [Pauses and sighs]… They will fall together with the same acceleration. The Moon's motion is determined by the Earth's gravity… let me think… if the mass is of the same order of magnitude as that of the Earth, then it is similar to the charged bodies, and so the tennis ball and the Moon will have different acceleration because the Earth cannot be regarded as stationary. And the third law,… just a minute, I have to think… [decisively] In any case, if they are at the same place, then the Earth exerts a force of *mg*. *g is determined only by the Earth* [emphasize added], and so it will still be the same *g*. Why did I say that the two bodies would approach each other? Because any two bodies should move that way, not just charged bodies…
How will I get out of this? The force exerted by the Earth is *mg*, which equals *ma*… I am very confused… still, if they [the interacting masses] are equal, they will both move, but *g* is determined by the Earth only, and any body will fall with the same *g*, even if it were large… [Q5]

Apparently, T_3, who previously stated that Galileo' law can be derived from Newton's laws, found it difficult to change the claim of mass independent acceleration of falling even after considering other fundamental laws. Perhaps the following excerptions from the interviews may suggest more directly a reason for this difficulty:

S_1: …It will be difficult to change [Galileo's law] since $F = ma$ and $F = GMm/r^2$. These laws tell you about nature. Maybe $F = GMm/r^2$ is an approximation… [Q6]

Even in cases where Galileo's law was considered to be approximate (after the interviewer introduced the mutual fall), changing the law seemed very difficult:

T_2: I have to think [with regard to Newton's laws]: $g = GM/r^2$ is the relative acceleration of a body with mass *m* towards a body with a bigger mass *M*. This is what we measure in *M*'s frame of reference, and it is independent of *m*… This is the second law... [Q7]

Apparently T_2 is not aware that Newton's second law is not valid for the non inertial frame of reference related to *M* (the big body). Consequently, T_3 could not resolve the problem.

Similar difficulty could be observed in the following response:

T_4: …I had a misconception… I regarded the Earth as fixed! Even after your clue regarding the two charged bodies, I did not see it. …At first, I thought that the mutual fall of the bodies solves the problem, but now I am not sure because of Newton's laws … I was rather confident with this subject [Galileo's law], but now I am not sure… [Q8]

The above concern with regard to their knowledge appeared also in other responses (mostly of teachers):

T_2: This change is far from being trivial! It appears that my understanding was incomplete and merely declarative. It is a problem, indeed… [Q9]

We identify the origin of most of the teachers' concerns in the idea that Galileo's law is derived from Newton's second law and the law of gravitation. The approximate nature of Galileo's law implied, in our subjects' minds, a similar inference regarding Newton's laws, which were perceived as precise. The requirement of an inertial observer for the validity of Newton's second law did not arise (except a comment made by one teacher that uniform acceleration of a free fall presumes an inertial observer).

Generally, as stated previously, we found great similarity between the responses of teachers and students in the written tasks as well as in the interviews. However, the teachers seemed to be more concerned during the interviews with regard to their own difficulties whereas the students tended to "trust" physics to solve their difficulties. Table 2 summarizes the claims found in the interviews.

Table 2: Summary and distribution of claims and responses (5 students and 5 teachers)

#	Claims and responses	Teachers	Students
1.	Convinced of the accuracy of Galileo's law	5	5
2.	Refined Galileo's law following electrical analogy	1	0
3.	Stipulated the law by the requirement of inertial observer	1	0
4.	Considered to regard the law as an approximation	1	3
5.	Hypothesized regarding the need to refine the law of gravitation in case Galileo's law is changed	0	2
6.	Convinced that Galileo's law results from Newton's laws	4	5
7.	Convinced that Galileo's law draws on empirical results	2	4
8.	Considered mass dependence of acceleration (refinement of Galileo's law) as a challenge to the theory of general relativity.	1	0

DISCUSSION AND IMPLICATIONS

Our study revealed several confusions with regard to Galileo's law of free fall, which could be related to important shortcomings of common instruction in introductory physics courses. Galileo's law presents an excellent approximation that can be demonstrated in any simple laboratory environment. The law is presented as a turning point, demarcating between Aristotelian thought and modern science. The refinement of Galileo's law requires an elaboration on a two-body system and the relevant observer, seldom performed in classes. The identification of Galileo's law with Newton-Einstein's claims appears regularly at all levels of instruction. Thus, our subjects' strong view against any refinement of Galileo's law is supported by its status in physics instruction: a "law of nature" supported by theory with no reservations. As one of the subjects said after recognizing the problem: "I cannot argue against the whole community..."

The conception that Galileo's law presents a principle, not an approximation, was found in our study to be extremely persistent and survived our attempts to stimulate its refinement during the interviews. The electric charged bodies analogy led, at most, to the recognition of the problem (see for instance Q4+Q5). In most cases our subjects did not consider spontaneously the mutual motion of gravitating objects (Newton's third law). The phenomenological primitive of the motionless Earth (diSsessa, 1993) prevailed (see Q8 for example). When forced by the interviewer to consider the mutual fall of gravitating bodies, none of our subjects (teachers or students) could resolve the difficulty. While students thought that it was resolved in the advanced physics theories, teachers were confused and expressed great concern about their expertise.

During the interviews, when our subjects revealed that the Earth's motion may cause a correction to Galileo's law, they erroneously inferred that such a correction implies a correction to Newton's laws. This inference inhibited any refinement of the law of free fall. We infer that unawareness with regard to the area of validity of Newton's second law, valid solely for an inertial observer, seems to be the cause for the revealed difficulty.

In summary, the lack of a systematic practice to test the validity range of physical statements (Galileo's and Newton's laws in our case) and their status (empirical law or theoretical statement) resulted in the formation of the ideas which are conceived as unlimited truths that were very difficult to challenge.

What would be the educational benefits of elaborating on Galileo's law beyond restating its borders of validity?

Customarily, Newton's second law, elaborated exhaustively in physics instruction from the inertial observer view point, addresses the behavior of a single body, not of the system. Discussing the validity and status of Galileo's law would involve a systemic treatment of the falling body and the Earth, emphasizing interaction and mutual movement. Such an approach may help a better adoption of Newton's third law, known to be a difficult issue in physics education (Brown, 1989; Poon, 2006).

Moreover, elaborating on the validity range of Newton's second law could foster a better appreciation of the need to determine the frame of reference, so far as the kinematic quantities – acceleration and velocity – are addressed. This would strengthen the status of Newton's laws and render the knowledge of the frame of reference (the observer) more meaningful.

Shaking the conception of motionless Earth in learning about free fall, could lead to a better understanding of tides, also explained by the *mutual* fall of the Earth and the Moon. This may foster a deeper comprehension of the phenomena of gravity in general (Galili & Lehavi, 2003).

The refinement of Galileo's law conveys the important feature of physics knowledge: one needs to know the epistemological status of any physical statement (in our case: "all bodies fall with the same acceleration"). This implies the need to address this status as a norm and explicitly mention the conditions of validity of any physical claim.

Our study focused on physics teachers' and university students' knowledge. Nevertheless, we can recommend some classroom activities to foster awareness with regard to the validity range of physical laws. For example, teachers may discuss in class what will happen to the acceleration of a body towards the Earth if the body's mass will be gradually increased until it will equal that of the Earth. Such a discussion should also involve the implication of changing the body's mass on the motion of the Earth. As another example, teachers may suggest their students to consider a case of dropping bodies with different mass on the surface of a small celestial object such as an asteroid. We also recommend using air track experiments with two interacting carts to demonstrate that changing one cart's mass changes both carts motion and relate this to the case of the gravitating bodies. A discussion of the case when one cart's mass is many times larger then the other's mass should be part of this activity. Finally, when teaching electricity, we recommend discussing the case of two charged bodies and relate it to the case of free fall. All such activities should involve a reflection on the area and conditions of validity: to what extent certain arguments hold up and when do we have to reconsider their accuracy.

Galileo's law presents no unique example of the need to emphasize the validity range of scientific claims. Similarly to the above mentioned view that Newton's laws hold true in any situation, many students perceive Ohm's law to be generally correct (Meacutetioui et al., 1996); in chemistry, unawareness to the borders of validity was stated to generate misconceptions (Ashkenazi & Weaver, 2007); the conception that larger electric resistance always correlates to larger power (heating) is another example of the same (Schwatz et al., 2000). These examples may suggest that learners tend to view physical claims as universal truths. Or, as one of our subjects phrased it: "[they] tell us something about the nature." Our study demonstrated the implications of such a tendency. We suggest that teachers will develop awareness for such implications and introduce validity range of physical claims into their instruction.

We conclude that revisiting Galileo's law in Newtonian dynamics, its refinement for the on ground observer, will upgrade students' knowledge and realize the idea of spiral curriculum, preparing the ground for the full account of the two body problem and the concept of reduced mass. We believe that more effort should be put in teachers' training on the need to emphasize validity range of scientific statements. Such a pedagogy, which incorporates epistemology considerations with knowledge of concepts, may foster a conceptually rich learning.

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