The importance of weightlessness and tides in teaching gravitation

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We examine the presentation of the weight, weightlessness, and tides in university-level physics textbooks. Introductory textbooks often do not discuss tidal forces even though their understanding would be useful for understanding weightlessness. The explanations of tides often miss the free gravitational motion of both interacting objects, which is essential for the symmetry of tidal deformation. The shortcomings in the explanations of weightlessness and tides as provided by students and teachers are compared to textbook discussions. We suggest that an explicit discussion of the different definitions of weight and a synergetic presentation of weightlessness and tides might lead to a better understanding of gravitation. Our approach is illustrated by examples of tidal effects appropriate for introductory courses.
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I. INTRODUCTION

The concept of gravitation is commonly introduced through its relation to weight and free fall. Weight is known to present a special problem and physics educators have discussed the definition of weight since the 1960s.[1] Two main interpretations of weight are well known. One identifies weight with the gravitational force exerted on a body (gravitational definition) and the other associates weight with the result of weighing (operational definition[2,3]). The latter approach distinguishes between weight and gravitational force.

Instruction in introductory physics courses traditionally discusses the gravitational effects related to the weight of objects and their movement under the influence of the gravitational force, usually neglecting another important phenomenon of gravitation: tidal forces. This neglect is in spite of a comprehensive publication[4] and available computer-aided tutorial[5] on tidal forces. Moreover, understanding tidal bulges is claimed to be important for high school teachers.[6] The importance of tidal phenomenon follows because although weighing may miss the gravitational force (for example, in a free fall), small-scale measurements of tidal forces can reliably indicate the presence of gravitation.[7] This twofold manifestation of the gravitational force (the results of weighing and tidal effects) is especially important for physics education and brings to the fore an essential issue: the relation of physical concepts to measurement. This issue, with regard to the understanding of weight and weightlessness, is known to be confusing for students regardless of their level of instruction.[8] The relevant knowledge of students was found to fit schemes of knowledge that conflict the scientific understanding of the subject.[9] For example, high school students commonly identify gravitational force with the results of weighing, and ignore the notion of apparent weight. With respect to understanding of the tides, the picture also is discouraging.[10] These findings suggest a further examination of the knowledge and presentation of gravitation at the university and college levels.

We have examined the definitions of weight and explanations of weightlessness and tides as given by high school physics teachers (university graduates), university students majoring in science, and university-level textbooks. Our study provides new data for the problem of understanding gravitation by physics students who are exposed to the currently common way of instruction and its resources.

We suggest that weight, weightlessness and tidal effects, each different facets of gravitation, be integrated into one instructional unit because they share an essential requirement for their understanding: the relation between the concept and its measurement.[11]

Because tidal effects often are perceived as a subject solely for advanced courses, we discuss in the Appendix several tidal effects appropriate for a general physics course.

II. METHOD OF THE STUDY

Information was collected regarding the definitions of weight and explanations of weightlessness and tidal phenomena. We examined these contents in a broad sample of physics textbooks (N=25) for introductory physics courses in universities and colleges.[12] To determine the knowledge of students and teachers, we administered an open questionnaire to high school physics teachers (Group T, N=75) and university students (Group S, N=28) majoring in physics (N=10) and in a prestigious science program (N=18). The teachers were accessed in workshops, and the students were reached in class or invited to a special session. The questionnaire included open-ended conceptual questions (Table I). We did not ask for an explanation of the tides in order to avoid a mere declaration in response to a standard question. Instead, in Question 4 we asked students and teachers to explain a composite tidal phenomenon: spring tides. This question addresses the fundamental aspect of tides: the contribution from each object due to the nonhomogeneity of the gravitational attraction causes a tidal stretch. Both stretches sum up to produce a spring tide. Concept definitions and their coherence with explanations of the phenomena were examined, and the answers from the teachers/students and textbooks were compared.

III. RESULTS AND INITIAL INTERPRETATION

We found that the textbooks treat gravitation in two contexts: (1) When addressing the concept of force (Newton's laws of mechanics), and (2) later on, with regard to Newton's universal law of gravitation. Weightlessness is normally presented in the former context and tides in the latter. The two phenomena remain unrelated topics and are neither compared nor discussed in the same context.

Table I. Questionnaire.

	Questions
Q_1	Define the concept of weight
Q_2	Explain the weightlessness experienced by astronauts in a spaceship orbiting the Earth
Q_3	A passenger in a sealed free falling elevator simultaneously releases a steel ball and a helium filled balloon (the situation was demonstrated by a drawing). Explain the passenger's observation regarding the motion of the two objects
Q_4	When do ocean high tides attain their maximum: during (a) full moon, (b) new moon or (c) half-moon (the situations were demonstrated by a drawing—Fig. 1). Explain your answer

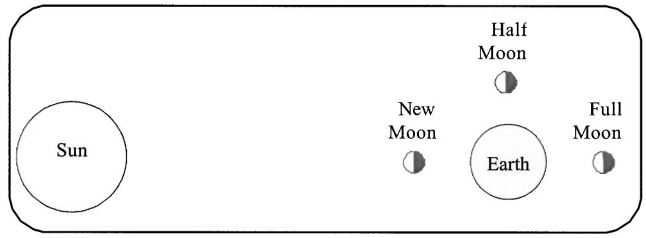

Fig. 1. Relative positions of the Sun–Earth–Moon to be considered with respect to the strength of ocean tides.

A. Definitions of weight

Most of the textbooks (76%) use the gravitational definition of weight (category 1, Table II) and its formula (W =mg). Only five books adopted the operational definition (category 2), while just one[13] utilized both types.[14] About 50% of the textbooks did not distinguish between the results of weighing and the gravitational force and neglected the difference between the two (as manifested in free fall). Those sensitive to this point defined the ''apparent'' (or ''effective'') weight as the scale reading and the ''true'' weight for the gravitational force itself.

The textbooks did not mention that using the formula W=mg with a measured g (free fall acceleration) produces only an apparent weight,[15] which is different from the one obtained by using g calculated from Newton's law of gravitation (gravitational field). The same conceptual inaccuracy takes place when the result of weighing is equated to gravitation alone (ignoring accelerated motion): ''The downward force of the earth on an object is its weight. Thus, a spring balance can be used to weigh objects.''[16] ''In practice, the corrections needed to obtain the true weight from the [spring] scale reading are of the order 0.1% and can usually be ignored.''[17] Leaving aside the fact that no international trade can afford such a generosity, we mention that these statements diminish the essential difference between apparent and true weight. Without reservation such a claim by a physics instructor can be misleading.[18]

The weighing procedure often is not specified. This lack ignores the uncertainty in the interpretation of weighing results and the incompatibility of the gravitational definition of weight (category 1, Table II) with the operational one (category 2). Normally, textbooks that introduce the ''true weight'' (gravitational force) do not address how to measure it. This lack is sometimes striking. For example, ''The weight of an object is the net gravitational force acting on it.''[19] ''The weight of a body is the total gravitational force exerted on the body by all other bodies in the universe.''[20]

The distribution of weight definition responses from group T showed a prevalence of what are considered as operational definitions (category 2, Table II). Most of group S upheld the gravitational definition (category 1), similar to the majority of the textbooks. About 17% of the teachers provided both the gravitational and the operational definitions, ignoring whether they are coherent. The notion of apparent weight evidently escaped the attention of most of the students and teachers.[21] The answers in category 3 related weight to inertial forces,[22] which are usually out of the scope of introductory courses. Finally, the definitions in category 4, which appeared only in Group S, related weight to mass either by a mere articulation of the formula W=mg or by the concept of heaviness.

B. Explanations of weightlessness

Only 13 (40%) of the textbooks explained the state of weightlessness (Table III). Definitions of weight and explanations of weightlessness often appear in textbooks in different places.[23] Nine textbooks warned their readers not to interpret weightlessness literally, because weightlessness was fictitious and did not imply the absence of weight (given the gravitational weight definition): ''The condition we call weightless does not mean ''no weight.'' Instead it means no

Table II. Frequencies of weight definitions in the sample (multiple definitions were counted).[a]

	Types of definition	Textbooks	Group-T	Group-S
1	Weight is the gravitational force exerted on the body			
	- without introduction of apparent weight	12[48]	35[46]	17[63]
	- with introduction of apparent weight	7[28]	1 [1]	⋯
2	Weight is the result of standard weighing	5[20]	12[16]	⋯
	Weight is equal to the supporting force	1 [4]	35[47]	2 [7]
3	Weight is a net force of gravitational and inertial forces	⋯	4 [5]	1 [4]
4	Weight is a quantity of matter times gravitation			1 [4]
	Weight is a measure of the mass of the body	⋯	⋯	2 [7]
	Weight is body's heaviness			2 [7]
5	Not defined	1 [4]	⋯	1 [4]

[a]Here and in all subsequent tables, the percentage is given in square brackets.

Table III. Explanations of weightlessness (multiple explanations were counted).

	Types of weightlessness explanation	Textbooks	Group-T	Group-S
1	All the objects share the same "acceleration"	7[28]	14[19]	···
2	Fictitious (inertial) force cancels gravitational force	1 [4]	20[27]	3[11]
3	Little (or no) gravitation	···	17[22]	23[82]
4	No force of support is required to prevent falling	3[12]	8[11]	···
5	Objects are influenced solely by gravitation	···	4 [5]	1 [4]
6	Not explained, but suggested as an end-of-chapter problem	4[16]	···	···
7	Not mentioned/Not explained	11[44]	···	3[11]

"apparent weight"... The man in the elevator still has weight mg—that has not changed—but he has no sensation of weight, as he free falls. The term weightlessness is a very poor one, almost guaranteed to cause confusion because it seems to imply that objects have no weight."[24]

The evidence of our senses is commonly presented as a subjective inference in spite of the fact that, in this case, it agrees with measurements and is qualitatively valid.

Similar to the treatment of weight, some textbooks distinguish between apparent (or effective) weightlessness and true weightlessness (absence of gravitation, a hypothetical case). Textbooks that define weight operationally were free of this subtlety.[25]

The rather common explanation of type 1 (Table III) evidently ignores the fact that "sharing the same acceleration by all parts of the system" is not sufficient for the objects to be weightless. Without free falling, this explanation becomes inadequate.[26] Equally inadequate are claims of the total cancellation of the gravitational force by fictitious (inertial) force (type 2) and that all effects of gravitation cease in a free fall.[27] "... But if the accelerating force is the force of gravity, as is true in a coasting spaceship near the earth, the *fictitious* force *exactly cancels* the gravitational forces"[28] (our emphasis). Such claims ignore gravitational effects that depend on the gradient of gravitation—tidal forces.

Unlike most of the textbooks and despite the fact that inertial forces are not in the standard curricula for colleges and high schools,[29] it is significant that relatively many teachers (similar to high school students[30]) explained weightlessness by the cancellation of gravitation with inertial forces.[31] The explanation of weightlessness by "little" or "absent" gravitation, especially popular among Group S, resembles the views of the high school students.[32] Evidently, many tend to eliminate the gravitational force when addressing the state of "obvious" weightlessness such as in a satellite. The explanations of type 5 were clearly unsatisfactory and merely described the situation. In fact, no student in our sample could adequately explain weightlessness.

Both the T and S groups exhibited much confusion in predicting the behavior of the steel ball and helium-filled balloon in a free falling elevator (Question 3 in Table I). The results in Table IV show that although most of the respondents recognized the state of weightlessness regarding the steel ball (91% in Group T and 79% in Group S), their responses differed with regard to the helium balloon (48% and 7% respectively). The following response is illustrative: "The ball falls together with the man and there is no relative velocity between them, and the balloon will rise up because *it is lighter than the air*"[33] (our emphasis).

The four teachers and five students who erroneously predicted the falling of the steel ball also erred in anticipating the rising of the helium balloon. Only 10% of the respondents correctly explained the absence of buoyancy, stating that the balloon and the air are equally weightless. That is, most of those who correctly predicted the floating of the helium balloon still did not explain it properly. The following student response is illustrative: "As much as I recall from TV movies, they [objects] will all float in a state of zero

Table IV. Students' and teachers' predictions and major types of reasoning regarding the objects dropped in a free falling elevator.

	Responses	Group-T	Group-S
1	The steel ball floats	68[91]	22[79]
2	The steel ball falls	4 [5]	5[18]
3	The helium balloon floats	36[48]	2 [7]
4	The helium balloon ascends	34[45]	22[79]
	Types of reasoning		
1	"The balloon is lighter than the air (buoyancy)"	23[30]	8[36]
2	"They all fall with the same acceleration/motion"	16[21]	11[50]
3	"There is no buoyancy during free-fall"	8[10]	2 [7]
4	"The resultant force on any object in a free fall is zero"	5 [6]	1 [4]
5	"In a free fall all objects are weightless"	5 [6]	1 [4]
6	"Gravitation is absent in a free fall"	3 [4]	···
7	No explanation	3 [4]	9[41]

gravity, but I do not have a convincing argument. Intuitively, the helium will ascend because it is lighter than air and the steel ball will land.''

The response: ''helium is lighter than air'' (30% in Group T and 36% in Group S), resembled the idea of natural (unconditional) lightness (levity). This Aristotelian-type response contradicts the contemporary concept of weightlessness in every aspect. Many of our addressees seemingly held to ''heaviness'' and ''lightness'' in the vicinity of the earth where the presence of gravitation is obvious.

C. Explanations of tides

Tidal phenomena are rarely mentioned (and even more rarely explained) in the textbooks. Of the 14 textbooks that mentioned tides, five presented them as an end-of-chapter exercise. As mentioned, the discussion of tides is separate from the discussion of weight and weightlessness[34] and except for one book,[35] are never conceptually related. Tidal distortion, as a gravitational effect observed in the state of weightlessness, is usually neglected.

Five textbooks[36] provide a sufficiently complete account of ocean tides and address the essential role of the Earth–Moon mutual free fall. Only such an approach, as was qualitatively shown already in 1883 by Mach, can account for the symmetrical tidal bulges on both sides of the Earth.[37] (For a quantitative account of tidal bulges, see Arons in Ref. 4 for example.) This important feature of tides, which puzzled generations of scholars, was mentioned only in four textbooks.[38] Ocean tides present the sole tidal phenomenon usually mentioned. Only in Ref. 39 does one learn that tidal effects also can be observed over short distances.[39] Other important characteristics of tides (such as their dependence on latitude) are very rarely mentioned. Most textbooks present tides, if at all, to illustrate Newton's law of gravitation. The important role of tidal phenomena in probing gravitation when weighing fails (free fall) is ignored.

Both groups (S and T) failed to explain tides. Our respondents mentioned only the ''new moon'' as the setting for ''spring tides,'' missing the ''full moon'' position as an equally correct response. For example, ''The maximum [of the high tide] is on a new moon for the sum of forces is then the greatest.'' ''On a new moon: it seems to me that here the phenomenon is at its peak because the moon and the sun exert their maximal resultant force (the gravitational force depends on the distance), because they are both in the same direction. On a half moon: intermediate state [height of tides]. On a full moon: minimal state [height of tides].''

Evidently, our subjects mistakenly summed the gravitational forces exerted by the Sun and the Moon and missed the symmetric contribution of each to the spring tides.[40] None considered different gravitational accelerations (or gravitational forces) of various parts of the ocean relative to the Earth's center, which itself is free falling. The inability to use the symmetry of the tides indicates an unfamiliarity with the essential role of the free fall of the Earth as a whole in the explanation of this symmetry.

Only one respondent (in Group T) mentioned free fall, concluding however, that tides (not spring tides as would be correct) appear both on the new moon and full moon: ''Theoretically, if friction were absent, tides had to appear on the new moon and full moon. But, to my best recollection, there is a considerable difference [in timing] in reality. Tides on the earth result from two factors together: the moon's attraction at different locations on the Earth's surface, plus the circular motion around the common center of mass.''[41] This response, although it addresses the mutual movement of both gravitating objects, exhibits a possible confusion of regular and spring tides.

One of the students described high (not spring!) tides as appearing once in twenty-four hours,[42] two summed up the forces from the Sun and Moon to account for spring tides, and the rest exhibited much confusion. For instance, one student predicted a monthly period of tides: ''High tide appears when the moon succeeds in pulling the sea towards it or when the sea is being thrown away from the earth in its orbit around the moon. If I stand on the beach during high tide, then the moon is above me (pulling the sea) and I see it [moon] full. Or it [moon] is in the opposite position and then I stand at the outer side of the circle, the sea is thrown away, and again I see high tide. Low tide appears when I see a half moon.''

The answers revealed a highly fragmentary and incomplete knowledge of the subject from both teachers and students. To summarize our findings and facilitate their interpretation, we juxtapose in Table V the elicited features of the teachers' and students' knowledge and those of the pertinent contents of the examined textbooks. As evident from Table V, those aspects of weightlessness and tides that are not well presented in textbooks correspond to the shortcomings of teachers' and students' knowledge of the subject. Based solely on this comparison, we cannot infer a cause–effect relationship. However, given the importance of textbooks, the unsatisfactory presentation of weightlessness, tides and the concept of weight, all mutually isolated, does not help to correct the conceptual difficulty that we found.

IV. DISCUSSION

The correspondence between the way gravitation is presented in textbooks and the failure of the students and teachers invites appropriate remedial actions. To interpret their difficulty in understanding the tides, diSessa noted the p-prim (phenomenological primitive) of the static Earth (''very big things just do not move'').[43] Our study confirms a lack of awareness of the Earth's fall toward the Moon. We interpret this lack as a confusion regarding the role of free fall in the explanation of tides, which is not necessarily caused by the cognitive reluctance ''to move'' the Earth.[44] We also observed an equally fundamental difficulty in understanding the role of nonuniformity of the gravitational field as an important factor causing tides. A typical error was to explain a tidal effect as due to the ''pull of the gravitational force,''[45] demonstrating itself as summing gravitational forces from different bodies to account for the spring tides.[46] This confusion can be related to the erroneous interpretation of weighing results. These two shortcomings (the neglect of free fall and the belief that the gravitational force can be directly measured) indicate a limited knowledge of the unique nature of the gravitational force with respect to its measurement. In fact, free fall puts into fore tidal effects, making them indicators of gravitation, instead of weighing.

The conceptual split of weight and gravitation, implied by Einstein's principle of equivalence,[47] and introduced by the operational definition of weight provides an alternative. It implies weightlessness simply as a zero weighing result, whereas according to the gravitational definition of weight, weightlessness requires a nontrivial explanation. Notably, both major misconceptions of students, the erroneous ac-

Table V. Juxtaposition of the main findings regarding weightlessness and tides.

Physics textbooks	Teachers-students
Weightlessness	Weightlessness
- often do not address weightlessness	- often confuse weightlessness with the absence of gravitational force (field, influence)
- some use ''apparent weight'' to account for ''fictitious weightlessness,'' and mention ''true weightlessness'' as zero gravitational force, providing no means to distinguish between the two types of weightlessness	- explain weightlessness by low gravitational force (distance attenuation)
- often use equality of acceleration of the body and its support to account for weightlessness	- cancel gravitational force by centrifugal (inertial) force
- rarely consider physical phenomena related to weight (such as buoyancy) in the state of free gravitational movement (free fall)	- often use equality of acceleration of the body and its support to account for weightlessness - are confused with regard to what is and is not measurable in a free gravitational motion - are confused regarding buoyancy at the state of weightlessness
Tides	Tides
- rarely consider tidal effects and almost never on small-scale distances	- very often fail to explain tidal effects
- normally explain tides by the difference of gravitational forces on the extremes of the earth	- in the explanation of spring tides normally sum gravitational forces from Sun and Moon acting on the Earth
- normally do not explain spring tides	- confuse spring and high tides
- in the explanation of tides rarely consider gravitational accelerations of elementary masses with respect to their center of mass	- do not consider force gradient along the body of the free falling Earth or the gravitational accelerations of elementary masses with respect to their center of mass
- are often silent regarding the symmetry of tidal bulges	- miss the symmetry of the tidal bulges

count of weighing where the presence of gravitation is obvious (the falling elevator), and where weightlessness is evident (in a satellite), can be explained by the inadequate interpretation given to the identification of weight with gravitational force.

Apart from the epistemological importance of emphasizing the essential role of measurement in the scientific method, the operational definition brings to the fore the importance of an individual's perception. In fact, the perception of ''heaviness'' of an object, rarely discussed by textbooks beyond the claim of it being misleading, presents a sort of weight measurement and is strongly imbedded in a learner's cognition as a fundamental schema.[48] According to present theories of learning and teaching,[49] this schema should be addressed by instruction to try to bridge the gap between formal knowledge and intuition based on tactile knowledge.[50] The introduction of ''apparent'' and ''true'' weights (an approach adopted by some textbooks) unnecessarily contrasts intuitive and scientific knowledge, requiring a radical conceptual change on behalf of the learners. Distinguishing between weight and gravitational force, on the other hand (the approach adopted by the majority of the surveyed teachers), upgrades sensory-based intuition, reconciling it with scientific knowledge through the operational definition of weight. This approach is in accord with Einstein's epistemology which is that physical theory is built psychologically upon the experiences of the world of perceptions.[51] In our view, the approach of operational definition is preferable and promises to be more effective.

Each textbook in our sample provided one type of weight definition and ignored the other option. We found that some teachers (17% in our sample), defined weight both gravitationally and operationally. The incoherence of the two was never mentioned. In this respect, our findings are in contrast with the claim of Eisenkraft and Kirkpatrick[52] who wrote that ''*Many* physics teachers carefully distinguish between the force of gravity and the weight. Weight is the reading on the bathroom scale, or the support force needed to keep you at rest in the non-inertial reference system. *Other* teachers use the term ''apparent weight'' to refer to the scale reading and use weight to refer to the force of gravity'' (emphasis added).

A knowledge of concept definitions is often regarded as resulting from rote learning and thus to be inferior.[53] We do not agree with this view, especially in its extreme, which neglects concept definitions. Our data illustrate how serious the consequences of confusion regarding concept definition may be.[54] Definitions have their own importance, specifying the meaning of concepts and their connections. They constitute the structure and the substance of disciplinary knowledge.[55] The case of weightlessness exemplifies that a discussion of the advantages and disadvantages of alternative

Table VI. Comparison of the gravitational force with tidal forces.

Gravitational force	Tidal-forces
is not a subject of a direct, local measurement	*is* a subject of direct measurement
⇓	⇓
weighing results have no unique interpretation	tidal effects reliably indicate the presence of gravitational field

definitions may elucidate the subject, contributing to both the knowledge of the subject matter and the specific pedagogical knowledge of physics teachers,[56] besides being important as a foundation of physics knowledge.[57] Tidal effects can enter the physics curriculum as a reliable indicator of gravitation in the state of free gravitational movement (free fall). Because they can be observed and directly measured in the state of weightlessness, tidal phenomena demonstrate what *is* and what *is not* measurable with regard to gravitation (Table VI).

Beyond a mere adoption of the tides as a topic, we suggest a synergetic instruction of the two gravitation-related phenomena—weightlessness and tidal effects. Their juxtaposition is natural because tidal phenomena are pronounced in the state of weightlessness, when in the absence of weighing results, they become the only indicator of a gravitational field in a small laboratory. Contrasting tidal and gravitational forces in the state of weightlessness addresses the confusion of those who miss the gravitational gradient in explaining the tides and of those who tend to totally nullify gravitation in free fall and thus miss the full meaning of Einstein's principle of equivalence. Weight and tides could become mutually supporting topics, facilitating the development of a meaningful understanding of gravitation in introductory-level courses.

V. CONCLUSION

It is disturbing that teachers and students often share the same confusion regarding weightlessness and the tides and that textbooks often do not provide the necessary explanations. Difficulties regarding concept definitions, relations between theoretical constructs and measurement, and the coherent account of physical phenomena appeared to be interrelated. Our study suggests that the traditional presentation of gravitation be revised so as to address weight, weightlessness, and tidal effects in an integrated unit to emphasize the common and contrasting aspects of the effects of gravitation. The dichotomy of two weight definitions, the gravitational (introduced by Newton) and the operational (following Einstein), presents a possible discussion topic with the students. Such a discussion that addresses the advantages and disadvantages of each definition could be beneficial for the genuine understanding of the nature of physics knowledge. Observable, small-scale tidal effects might convince the learner that gravitation does not disappear when the results of weighing do. Qualitative explanations of tidal phenomena and weightlessness might be helpful in establishing a solid conceptual basis of gravitation.

APPENDIX: TIDAL PHENOMENA IN AN INTRODUCTORY PHYSICS COURSE

The following examples of tidal phenomena are observable in a small laboratory freely falling in a gravitational field. They may correct the perception of tides as relevant

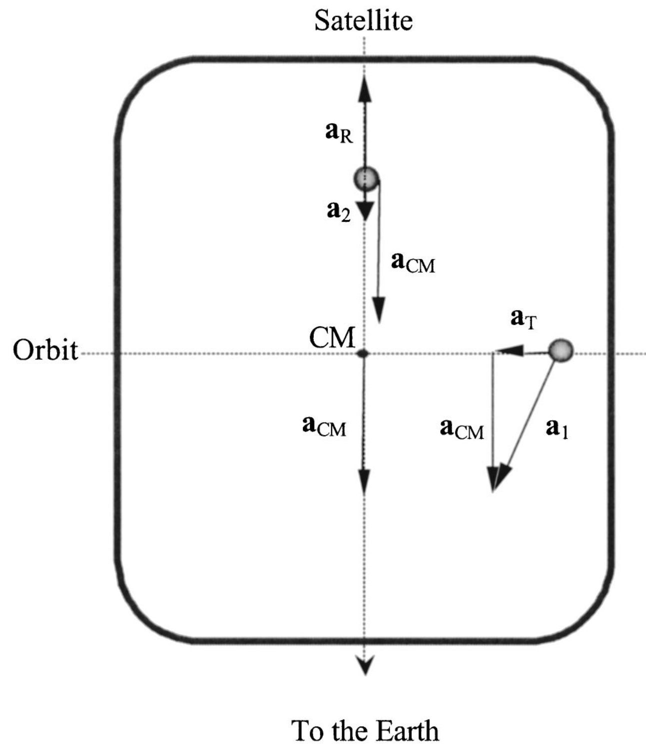

Fig. 2. The acceleration of the grain with respect to the center of mass of the satellite is obtained by vector subtraction: $\mathbf{a}_T = \mathbf{a}_1 - \mathbf{a}_{CM}$ and $\mathbf{a}_R = \mathbf{a}_2 - \mathbf{a}_{CM}$.

only in astronomy. Qualitative and semiqualitative explanations of the following effects are feasible and sufficient at the introductory level.

Tidal distortion: Consider a sphere of sand located at the center of mass of a spacecraft that is orbiting the Earth. If we neglect interactions between the grains, each grain will move with its own gravitational acceleration (see Fig. 2). A vector subtraction yields the acceleration of each grain relative to the center of mass. This acceleration determines how the grain moves, as seen in the spacecraft. The radial component of the acceleration shows the tendency of each grain to recede from the center of mass along this direction, whereas its tangential component reveals that the grain approaches the center of mass tangentially to the orbit. As a result, the sphere of grains will be distorted, creating an oblong spheroid.

If we assume that the group of grains is a model of a real body, we obtain a simple theoretical explanation of tides. If we draw on an analogy with the Earth, we can claim that in its free gravitational movement, the Earth develops, due to the influence of the Moon, the profile of an oblong spheroid, especially pronounced in the ocean. The assumption of noninteracting particles affects only the magnitude of the result. Water molecules migrate from C and D toward A and B, causing two symmetrical bulges at A and B (high tides) and the receding of water at C and D (low tides) (see Fig. 3). The Sun causes a similar, but smaller symmetrical effect (due to its much greater distance). When added, either at full moon or new moon, the two effects account for the spring tides.

The pedagogical merit of this treatment is the explicit use of the gravitational accelerations of the grains relative to their freely falling common center of mass. Such an approach accounts for two symmetrical bulges of tides, whereas neglecting the free fall of the center of mass would

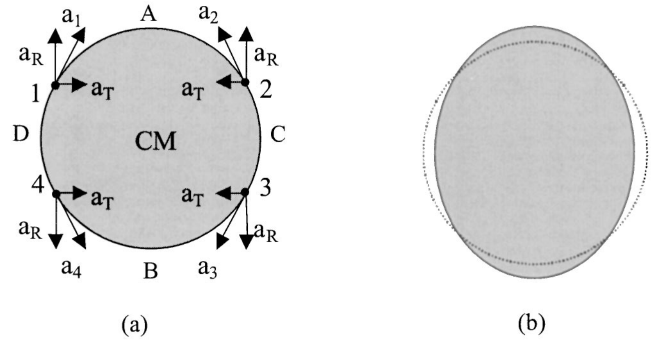

Fig. 3. (a) Accelerations of grains 1, 2, 3, and 4 with respect to the center of mass of an orbiting satellite. (b) The resulting deformation of a spherical ball to an ellipsoid-like shape, elongated along the radial direction of the Earth.

provide a highly asymmetrical result—a single bulge. Another important feature used here is that similar to the grains, the entire Earth is weightless.[58]

Tidal dispersion: Tides are discussed in introductory courses as ocean tides, as if they were unobservable at smaller distances.[59] In practice, however, tidal effects are used in sensitive gravimeters and can indicate the presence of a gravitational field in the state of weightlessness. To stress this point, we can discuss these effects in an orbiting satellite at a height of 300 km. Relative accelerations cause the dispersion of a group of marble balls left within the cabin. A marble, which started 2 cm from the center of mass of the satellite (in the radial direction), will recede to 20 cm in about 30 minutes, a phenomenon easy to observe, in contrast with the often-made statement that objects in an orbiting satellite remain still in mid-air.

Tidal elastic deformation: Four soft elastic springs (sping constant $k=0.1\,\mathrm{N/m}$) of original length L_0 are connected in the form of a cross (see Fig. 4). Four equal masses ($m=10\,\mathrm{kg}$) are connected to the springs. The parameter η, which characterizes the asymmetric deformation of the apparatus due to tidal forces, can be defined as:

$$\eta=\frac{L_{\parallel}-L_{\perp}}{L_0}, \tag{1}$$

where $L_{\parallel}$ and $L_{\perp}$ are the lengths of the radial and tangential springs. For these conditions and the height of 300 km, $\eta=0.04\%$, independent of the size of the apparatus.[60] Thus for the original length of half a meter, the deformation of each spring will be about 0.2 mm, which is a measurable effect.

We can use this deformation to detect satellite orientation: the elongation determines the radial direction. The same apparatus suspended in the laboratory on the ground would show only a vertical elongation, proportional to the gravitational force (the result of weighing), totally masking the much smaller tidal effect. This example demonstrates that free fall is essential for the observation of tidal effects. It also displays the different geometry of deformation when caused by the gravitational force or its gradient.

Tidal clock: Consider a small ball in a frictionless glass tube placed along the direction of the orbital motion (Fig. 5). When the ball is slightly removed from the center of mass of the space station, it experiences a tangential (to the orbit) tidal force, which acts as a restoring force proportional to its

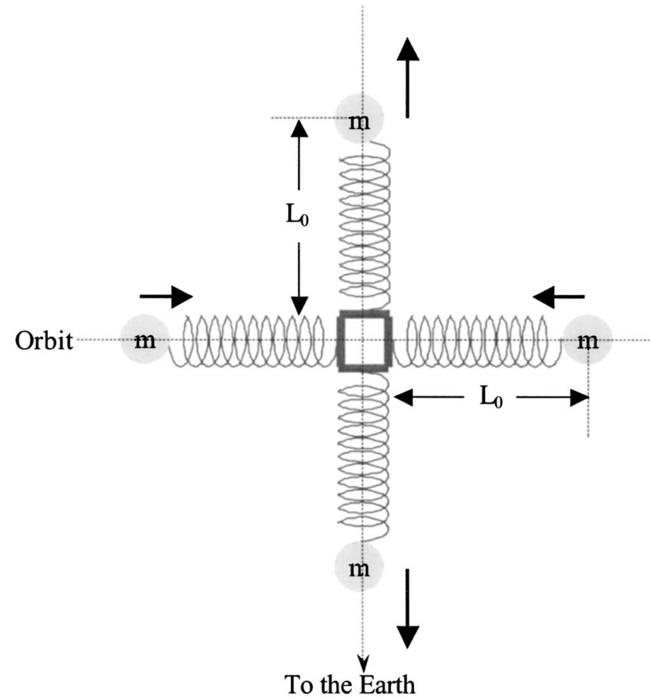

Fig. 4. Elastic springs are deformed differently in the tangential and radial directions, indicating the presence of a nonhomogeneous gravitational field in a satellite.

displacement. The period T of the oscillations will be equal to the satellite orbital period, depending only on the mass of the Earth and the distance to it:

$$T_{\mathrm{tidal}}=2\pi\sqrt{\frac{(R_0+H)^3}{\mathrm{GM}_E}}=2\pi\sqrt{\frac{(R_0+H)}{g^*}}, \tag{2}$$

where R_0 is the radius of the Earth and g^* is the acceleration of the satellite. This period (1.5 hours at a height of 300 km) can inform astronauts when they have completed one revolution around the Earth without looking outside. A simple pendulum (two meters long), placed on an imaginary tower of the height of the orbit would oscillate with a period of

$$T_{\mathrm{grav}}=2\pi\sqrt{\frac{L}{g^*}} \tag{3}$$

which is about 3 s, only a fraction of the period of the tidal clock.

Tidal precession: Consider the simplest gyroscope: a rotating dumbbell in a satellite. The frequency of rotation and the

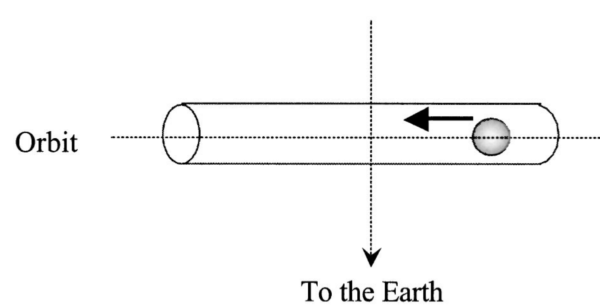

Fig. 5. A ball within a tube oriented along the orbit of a satellite will show harmonic oscillations relative to the center of mass of the satellite, a "tidal clock."

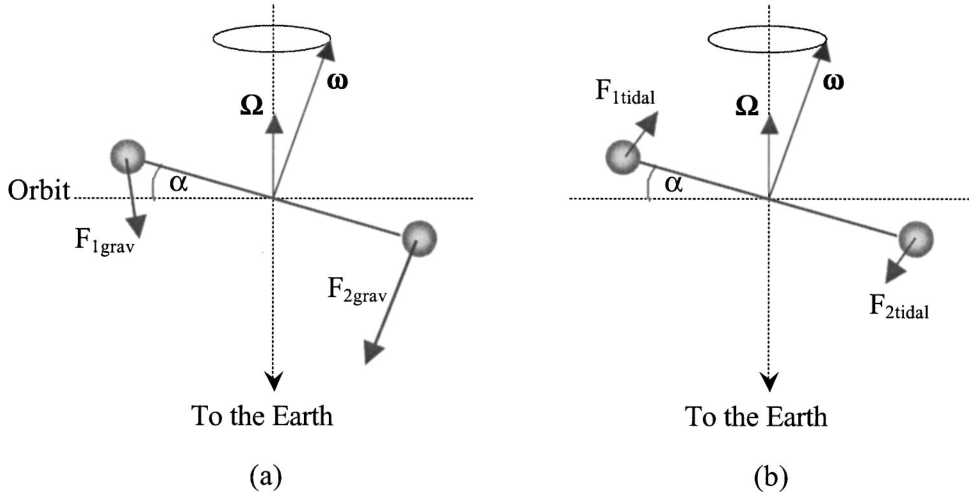

Fig. 6. (a) Rotating dumbbell (frequency ω) in a state of free fall subject to unequal gravitational forces $F_{1\mathrm{grav}}$ and $F_{2\mathrm{grav}}$. (b) The dumbbell precesses (with frequency Ω) around the radial direction to the Earth due to the torque of tidal forces $F_{1\mathrm{tidal}}$ and $F_{2\mathrm{tidal}}$.

angle of its axis relative to the radial direction from the earth are ω and α, respectively (see Fig. 6). In free gravitational movement, unequal gravitational forces F_1 and F_2 [Fig. 6(a)] act on the balls and produce two tidal forces $F_{1\mathrm{tidal}}$ and $F_{2\mathrm{tidal}}$ [Fig. 6(b)]. The resultant torque causes the axes to precess with the frequency:[61]

$$\Omega=\frac{3g^*}{2\omega \mathrm{R}_0+\mathrm{H}}\sin 2\alpha. \tag{4}$$

Equation (4) yields 8.3° per hour, which corresponds to the behavior of Foucault's pendulum at a latitude of 33°.

This precession can serve as an indicator of the presence of gravitation, which is especially important for a observer in a free falling laboratory. The frequency of the precession does not depend on the size of the dumbbell, but on the mass of the nearby attracting body (the Earth) and the distance from it. This effect is used in astrophysics to determine the mass of the Moon by the rate of precession of the spinning axis of the Earth (the oblate shape of the Earth makes it similar to a dumbbell).[62]

[1]A. L. King, ''Weight and weightlessness,'' Am. J. Phys. **30**, 387 (1962); F. W. Sears, ''Weight and weightlessness,'' Phys. Teach. **1**, 20–23 (1963); M. Iona, ''The meaning of weight,'' *ibid.* **13**, 263–274 (1975); ''Weight—an official definition,'' *ibid.* **37**, 238 (1999); R. C. Morrison, ''Weight and gravity—the need for consistent definitions,'' *ibid.* **37**, 51–52 (1999); R. Brown, ''Weight—don't use the word at all,'' *ibid.* **37**, 241 (1999); R. Bishop, ''Weight—an accurate, up-to-date, layman's definition,'' *ibid.* **37**, 238–239 (1999); A. Sokolowski, ''Weight—a pictorial view,'' *ibid.* **37**, 240–241 (1999); I. Galili, ''Weight versus gravitational force: Historical and educational perspectives,'' Sci. Educ. J. **23**, 1073–1093 (2001).

[2]The force, which is measured by a calibrating scale. Standard weighing requires the body to be at rest and no additional interactions present.

[3]An equivalent to this definition equates weight to mg*, where g* is a free fall acceleration as measured in a particular frame of reference (for example, F. J. Keller, W. E. Gettys, and M. J. Skove, *Physics* (McGraw-Hill, New York, 1993).

[4]A. B. Arons, ''Basic physics of the semidiurnal lunar tide,'' Am. J. Phys. **47**, 934–937 (1979); M. M. Whithers, ''Why do tides exist?'' Phys. Teach. **31**, 394–398 (1993).

[5]H. Härtel, ''The tides: A neglected topic,'' Phys. Educ. **35**, 40–45 (2000).

[6]C. E. Swartz and T. Miner, *Teaching Introductory Physics* (AIP, Woodbury, NY, 1997), pp. 112–115. Tides were advocated to be included in high school programs. See C. Swartz, ''Book report: Survey of high school physics texts,'' Phys. Teach. **37**, 283–307 (1999).

[7]H. C. Ohanian and R. Ruffini, *Gravitation and Spacetime* (Norton, New York, 1994), pp. 38–54.

[8]See for example, J. Cashatt, M. Harmon, L. Kluttz, A. Pitts, D. Saunders, D. Tesh, R. Wilkins, and S. Lea, ''Weightlessness in free fall,'' Am. J. Phys. **43**, 191–192 (1975); D. Chandler, ''Weightlessness and microgravity,'' Phys. Teach. **29**, 312–313 (1991); I. Galili, ''Interpretation of students' understanding of the concept of weightlessness,'' Res. Sci. Educ. **25**, 51–74 (1995); I. Galili and D. Kaplan, ''Students' operation with the concept of weight,'' Sci. Educ. **80**, 457–487 (1996).

[9]Galili and Kaplan in Ref. 8.

[10]J. Viri, ''Students' understanding of tides,'' Phys. Educ. **35**, 105–109 (2000).

[11]I. Galili and Y. Lehavi, ''The importance of weightlessness and tides in teaching gravitation,'' in *Science Education Research in the Knowledge – Based Society*, edited by D. Psillos, P. Kariotoglou, V. Tselfes, E. Hatzikraniotis, G. Fassoulopoulos, and M. Kallery (Kluwer Academic Publishers, Dordrecht, The Netherlands, to be published in 2003).

[12]Although all the textbooks of the sample were published in the United States, the results are relevant to the country of the study, Israel, where the same textbooks are widely used.

[13]D. Halliday, R. Resnick, and J. Walker, *Fundamentals of Physics* (Wiley, New York, 2001).

[14]These findings match those reported by Morrison, Ref. 1.

[15]A. French, ''On weightlessness,'' Am. J. Phys. **63**, 105–106 (1995).

[16]U. Haber-Schaim, J. H. Dodge, R. Gardner, and A. Shore, *PSSC Physics* (Kendall/Hunt, Dubuque, IA, 1991), pp. 57–58.

[17]H. Benson, *University Physics* (Wiley, New York, 1991), p. 86.

[18]A. B. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990), pp. 71–73.

[19]Reference 17, p. 84.

[20]H. D. Young and R. A. Freedman, *University Physics* (Addison-Wesley, Reading, MA, 1996), p. 383.

[21]The reluctance to use the term apparent for the weight might be interpreted in view of the everyday use of the terms apparent and true, as respectively imaginary (not sensed) and real (which is sensed), opposite to the conventional usage in physics.

[22]This option is discussed in K. Taylor, ''Weight and gravitational force,'' Phys. Educ. **9**, 357–360 (1974).

[23]For example, Ref. 16, pp. 58, 455.

[24]R. D. Knight, *Physics, Contemporary Perspective* (Addison-Wesley, Reading, MA, 1997), p. 168.

[25]See, for example, Bishop, Ref. 1, and L. S. Lerner, *Physics for Scientists and Engineers* (Jones and Bartlett, Sudbury, MA, 1996).

[26]Sharing acceleration with a car does not make the driver weightless.

[27]See for example, P. Hewitt, *Conceptual Physics* (Addison-Wesley, Reading, MA, 1998).

[28]Reference 16, p. 455.

[29]''Course contents in high school physics'' (AAPT Committee on Special Projects for High School Physics, College Park, MD, 1988). A brief survey of physics textbooks published in the UK (6) and in Israel (5) testifies to a similar situation.

[30]I. Galili and V. Bar, ''Motion implies force. Where to expect vestiges of the misconception?'' Sci. Educ. J. **14**, 63–81 (1992).

[31]Gardner reported that people with an engineering background account for the stationary circular motion by balancing gravitational force with cen-

trifugal force. P. Gardner, ''On centrifugal force,'' J. Aus. Sci. Teach. **27**, 69–74 (1981).

[32]This misconception was interpreted as being induced by the gravitational definition of weight not fortified by the notion of apparent weight. Galili and Kaplan in Ref. 8.

[33]All students' and teachers' quotes were translated from Hebrew and thus might lose some of their authentic form.

[34]See, for example, Chaps. 5 and 13 in Ref. 17 and Chaps. 4 and 12 in Ref. 20.

[35]H. C. Ohanian, *Physics* (Norton, New York, 1989).

[36]Ref. 17; P. M. Fishbane, S. Gaziorowicz, and S. T. Thoronton, *Physics for Scientists and Engineers* (Prentice-Hall, Englewood Cliffs, NJ, 1993); Ref. 27; Ref. 35; M. M. Sternheim and J. W. Kane, *General Physics* (Wiley, New York, 1991).

[37]E. Mach, *The Science of Mechanics* (Open Court, La Salle, IL, 1989), pp. 255–264.

[38]Fishbane *et al.* in Ref. 36, Ref. 27, Ref. 17, Sternheim and Kane in Ref. 36.

[39]Reference 35.

[40]Students give the same account for the results of weighing on the ground, mistakenly summing the attraction to the Moon with the attraction to the Earth. Galili and Kaplan, Ref. 8.

[41]The account for tides by considering ''circular motion around the common center of mass'' is equivalent to ''mutual free fall'' (Ref. 17, p. 273).

[42]The ''one bulge'' view is reported in Ref. 10.

[43]A. diSessa, ''Towards an epistemology of physics,'' Cognit. Instr. **10**, 105–225 (1993); D. Hammer, ''More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research,'' Am. J. Phys. **64**, 1316–1325 (1996).

[44]There is a similar confusion regarding the meaning of weighing results. See for example, Galili and Kaplan in Ref. 8.

[45]Reference 10 reported the prevalence of this reasoning.

[46]In fact, a mere pull, such as in a homogeneous gravitational field, would not cause tides.

[47]H. Reichenbah, *The Philosophy of Space and Time* (Dover, New York, 1927/1958), p. 223; Bishop in Ref. 1.

[48]J. Piaget, *The Child's Perception of Causality* (Littlefield, Adams, Totowa, NJ, 1969).

[49]*The Practice of Constructivism in Science Education*, edited by K. G. Tobin (Lawrence Erlbaum, Hillsdale, NJ, 1993); *Constructivism in Science Education*, edited by M. Matthews (Kluwer, Dordrecht, Netherlands, 1998).

[50]See for example, Brown in Ref. 1.

[51]A. I. Miller, *Imagery in Scientific Thought* (MIT Press, Cambridge, MA, 1986).

[52]A. Eisenkraft and L. D. Kirkpatrick, ''Weighing an astronaut,'' Quant. **5**, 36–39 (1995), p. 37.

[53]Bloom's taxonomy states that the knowledge of definitions requires low-level cognitive resources. See B. S. Bloom, M. D. Engelhart, H. H. Hill, E. J. Furst, and D. R. Krathwhol, ''The taxonomy and illustrative materials,'' in *Taxonomy of Educational Objectives. The Classification of Educational Goals, Handbook 1: Cognitive Domain*, edited by B. S. Bloom (McKay, New York, 1956).

[54]Also in Morrison, Ref. 1.

[55]J. Schwab, ''Structure of the discipline: Meaning and significance,'' in *The Structure of Knowledge and the Curriculum*, edited by G. W. Ford and L. H. Pugno (Rand McNally, Chicago, 1964), pp. 6–30.

[56]L. S. Shulman, ''Those who understand: Knowledge growth in teaching,'' Educ. Res. **15**, 4–14 (1986).

[57]H. Margenau, *The Nature of Physical Reality* (McGraw-Hill, New York, 1950), pp. 220–244.

[58]The claim that ''the earth is weightless'' contradicts the intuition of students (Galili and Kaplan, Ref. 8). It also conflicts with the common reference to Cavendish's measurement (1787) of the gravitational constant as ''weighing of the Earth.''

[59]M. Sawicki, ''Myths about gravity and tides,'' Phys. Teach. **37**, 438–441 (1999).

[60]The calculations providing this result are similar to those appeared in Ref. 7, pp. 38–54.

[61]Reference 7.

[62]See for example, K. A. Kulikov, *Fundamental Constants of Astronomy* (English translation Israel Program for Scientific Translation, Jerusalem, 1964, Translated from the Russian ''Gosudarstvennoe izdatel'stvo Tekhniko-teoreticheskoi literatury,'' Moskva, 1956), pp. 99–101.

OBSEQUIOUS ELECTRONS

Even electrons, supposedly the paragons of unpredictability, are tame and obsequious little creatures that rush around at the speed of light, going precisely where they are supposed to go. They make faint whistling sounds that when apprehended in varying combinations are as pleasant as the wind flying through the forest, and they do exactly as they are told. Of this, one can be certain.

Mark Helprin, *Winter's Tale* (Harcourt Brace Jovanovich, San Diego, 1983), p. 359.