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# Textbook presentations of weight: Conceptual difficulties and language ambiguities

Rex Taibu[*]

*Mallinson Institute for Science Education, Western Michigan University,*
*Kalamazoo, Michigan 49008, USA*
*and Queensborough Community College–CUNY, Bayside, New York 11364, USA*

David Rudge

*Department of Biological Sciences and The Mallinson Institute for Science Education,*
*Western Michigan University, Kalamazoo, Michigan 49008, USA*

David Schuster

*Department of Physics and The Mallinson Institute for Science Education,*
*Western Michigan University, Kalamazoo, Michigan 49008, USA*

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The term "weight" has multiple related meanings in both scientific and everyday usage. Even among experts and in textbooks, weight is ambiguously defined as either the gravitational force on an object or operationally as the magnitude of the force an object exerts on a measuring scale. This poses both conceptual and language difficulties for learners, especially for accelerating objects where the scale reading is different from the gravitational force. But while the underlying physical constructs behind the two referents for the term weight (and their relation to each other) are well understood scientifically, it is unclear how the concept of weight should be introduced to students and how the language ambiguities should be dealt with. We investigated treatments of weight in a sample of twenty introductory college physics textbooks, analyzing and coding their content based on the definition adopted, how the distinct constructs were dealt with in various situations, terminologies used, and whether and how language issues were handled. Results indicate that language-related issues, such as different, inconsistent, or ambiguous uses of the terms weight, "apparent weight," and "weightlessness," were prevalent both across and within textbooks. The physics of the related constructs was not always clearly presented, particularly for accelerating bodies such as astronauts in spaceships, and the language issue was rarely addressed. Our analysis of both literature and textbooks leads us to an instructional position which focuses on the physics constructs before introducing the term weight, and which explicitly discusses the associated language issues.

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## I. INTRODUCTION

The scientific topic of weight is widely regarded as challenging to teach and difficult for students to understand in various situations, particularly those involving acceleration. The difficulties are partly conceptual, partly language related,[1] and often a mixture of the two. As we will see, weight is conceptualized and defined in more than one way, even among physicists and across textbooks. This is true even without considering everyday uses of the term and notions of the concept, including its common confusion with mass. In particular, disparate views are found amongst physicists about whether the term "weight" is to be used for the gravitational force on an object or for the contact force between the object and a measuring scale. Gravitational and operational definitions are conceptually distinct and also lead to different values for an object's weight in accelerated situations. Even in static situations where the two definitions lead to the same value, the conceptual distinction still exists. Such conceptual and terminological ambiguities are far from ideal for teaching and learning the topic, although the physics of the underlying constructs (and their relationship) is clear.

There have been various attempts to decide or prescribe which should be the correct or preferred definition of weight, and the case for each argued, but nevertheless the term remains polysemous, i.e., it has more than one meaning, which often has to be inferred from context and usage. This situation is likewise reflected in textbooks, as our research shows. Such ambiguities cause confusions in teaching and learning physics, especially if the issues go

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[*] rextaibu@gmail.com

[1] Throughout this paper, the phrase "language issues" and the term "semantics" will be used interchangeably to refer to the issues surrounding the meaning of terms.

unrecognized. As discussed later, we have come to advocate the instructional position of delaying or eschewing using the term weight as far as possible during initial teaching of the two physical concepts, and addressing the language issues explicitly in instruction.

In this paper, we first present a general overview of conceptual and language issues in science education, followed by the debate surrounding weight and related terms as portrayed by various physics experts. Arising from this, we develop a conceptual framework for dealing with language issues in the teaching and learning of scientific concepts. We then present a critical review of related literature, state the research problem and goals, formulate a coding scheme for textbook analysis, interpret the results of the analyses, and discuss findings and implications for instruction. Throughout the paper we hark back to the conceptual perspectives when discussing terminologies for various specific situations.

## II. BACKGROUND

Science education researchers agree on the need for properly defining and explaining scientific concepts in order to improve student understanding. This is particularly important when one considers how easy it is to misinterpret terminological confusions as *misconceptions* about the underlying concept [1]. Language issues become especially pertinent when a term is used in both scientific and everyday contexts [2]. Itza-Ortiz, Rebello, Zollman, and Rodriguez-Achach [3] found that students are more likely to achieve high test scores if they can differentiate and explain scientific and everyday meanings of terms. Some physics education researchers (e.g., Refs. [4–6]) advocate reinforcement of appropriate usage of words in diverse instances (contexts). Others suggest using daily language to introduce a concept before adopting scientific language [7], while Arons [8] advocates introducing ideas first before naming them. Yet others, e.g., Ref. [2], have called for greater consistency in how terms are used. However, Mortimer [9] asserts that word meanings are often polysemous, both in science and in everyday language. Note that polysemy refers to a word having more than one related meaning, rather than having different but unconnected meanings [9]. This is the root of the ongoing problem facing the term weight—it is polysemous, even in scientific usage. The problem of multiple meanings and common usages also arises for other terms such as “heat,” for which the difficulties may be even greater.

The term weight is polysemous in that there is a diversity of views even among scientists, let alone instructors, regarding how it should be defined. Galili, who has done much of the work in this area, notes that the term weight is defined in two main ways [10]: (i) as a gravitational force on an object, and (ii) operationally, in terms of reading on a measuring scale (a scale force). Galili [11] distinguishes the definitions by referring to the first as the *gravitational definition of weight* and the second as the *operational definition of weight*. The first defines weight as the gravitational force on an object, usually by Earth, but it can be by some other specified planet or moon. For the operational (scale force) definition, note that when an object is supported (against gravitational force) by a measuring scale, a contact force is exerted upwards on the object by the support, and a corresponding equal and opposite force is exerted downwards on the support by the object. Galili proposes defining weight operationally as the latter force. Figure 1 illustrates these two major physical constructs that are conceptually different but are given the same name.

Operationally, the meaning of weight is determined by how we would measure it. Thus one could say that weight is what a measuring scale reads, or in everyday terms your weight is what the bathroom scale reads, in whatever situation. Thus one might possibly take the operational definition of weight as the magnitude of the contact force between the object and a support (scale), which involves no

*Gravitational Definition*

$W \equiv F_g$, i.e., Weight is a synonym for the gravitational force on an object.
E.g., weight of a body with reference to the Earth is the gravitational force exerted on it by the Earth.

*Operational Definition*

The weight of a body is the magnitude of the contact force between the body and a support (measuring scale).
(The force by the scale on the body and by the body on the scale are equal and opposite as shown.)

FIG. 1. Alternative definitions of weight.

directional specification. There might not be too much debate about whether the gravitational definition or scale definition is the "correct" one if both always gave the same value; but while they do for nonaccelerating situations,[2] they do not for accelerating objects, and it is here that conceptual and semantic confusions arise and bedevil teaching.

The gravitational definition of weight is preferred by some (e.g., Ref. [12]) arguing that it is a majority view. Goodman [13] advocates the gravitational definition of weight, but does not provide sufficient justification for his preference. Sears [14] suggests that the term weight should be defined as the *resultant* gravitational force exerted on the body by all other bodies. He argues that this definition is pedagogically preferable because it yields a quantity that does not vary with a change of reference system. However, Galili [15] argues against this definition by stating that it can be neither empirically employed nor theoretically validated.

Several (e.g., Refs. [16–18]) have attached importance to the fact that the scale force is accessible to direct measurement unlike the gravitational force. They also argue that the operational definition is consistent with people's everyday notion of weight as experienced on a rotating Earth (either as the reading on their bathroom scales or as the force sensed by their feet). In line with the latter argument, many contend that the operational definition aligns with the notion that "weightlessness" is a valid expression of a real sensation, being a situation of "zero weight." Finally, those preferring the operational definition note that it applies to all situations, e.g., the moon, other planets, and in accelerating situations.

There are some (e.g., Refs. [19,20]) who favor a definition provided by the International Organization for Standardization (ISO) in 1992. Iona [20] reports this definition as "the weight of a body in a specified reference system is that force which, when applied to the body, would give it an acceleration equal to the local acceleration of free fall in that reference system" (p. 238). Galili [15] considers this definition and the operational definition provided in Fig. 1 as mutually convertible; he treats both as operational definitions of weight. Iona [21] faulted the ISO definition of weight saying that it did not clearly specify the reference frame in which free fall and weightlessness are to be measured. Further, he argued that the reference frames to measure free fall and weightlessness may not be the same, and he contends that the ISO definition makes the theoretical value of acceleration due to gravity an approximation to the value that is observed in experiments. But in a later paper, Iona [20] recants this line of argument, offering multiple reasons in support of the ISO definition: it is not influenced by attempts to simplify; it seems to be in agreement with most practices; it has the support of physicists and engineers in many countries; the definition allows use of the surface of the moon or other planets, or falling elevators, or spacecraft as the reference system; it conforms with the meaning of weightlessness; it allows the unqualified use of the equation $W = mg$ with free-fall acceleration; it is the quantity observed in the chosen reference system; and it shifts the burden of explaining weight variation with location, or reference system, to the discussion of free-fall acceleration. Great care has obviously gone into devising this particular precise definition, but we cannot help but remark that strictly speaking the term is not even scientifically necessary for describing the situation or understanding the physics. We could just talk in the normal way about the actual forces on the object in a particular state of motion. But understandably the term's historical practical roots in static cases keep it alive. We also note that properly understanding the ISO definition itself is not trivial, and assumes prior knowledge of the underlying issues. One wonders if these various definitions, sometimes at cross-purposes, may be causing more difficulties than they solve.

The above discussion shows that the term weight is ambiguously defined in science besides in everyday usage, and further that the question of which definition should be preferred depends not merely on the underlying physics, but also on semantic, pedagogical, historical, and other considerations. Disagreements amongst experts about which construct should take priority and how to make meaning clear in various situations have led to the widespread adoption of various weight-related terminologies or phrases, including "real weight," "true weight," "apparent weight," "gravitationally defined weight," and "operationally defined weight" [11,18,20,22]. The different ways of defining the term weight and naming the two major contending constructs have caused endless confusion for physics educators, especially when they attempt to explain weight for accelerating objects such as those in elevators and orbiting spaceships.

The two definitions indeed yield the same numerical value for cases of nonaccelerating objects, where the term is usually first introduced, but give different values when the object is accelerating. For example, in *free fall* in an elevator or orbiting spaceship, the weight of an object according to the gravitational definition would remain the gravitational force (associated with the object's acceleration), while according to the operational definition the weight would be zero since a force measuring scale moving with the object would read zero. The scale definition aligns with the idea and terminology of weightlessness as zero weight in that situation.

Figure 2 illustrates the relationship between the gravitational and scale forces for an object in an elevator undergoing various types of motion. Different weight

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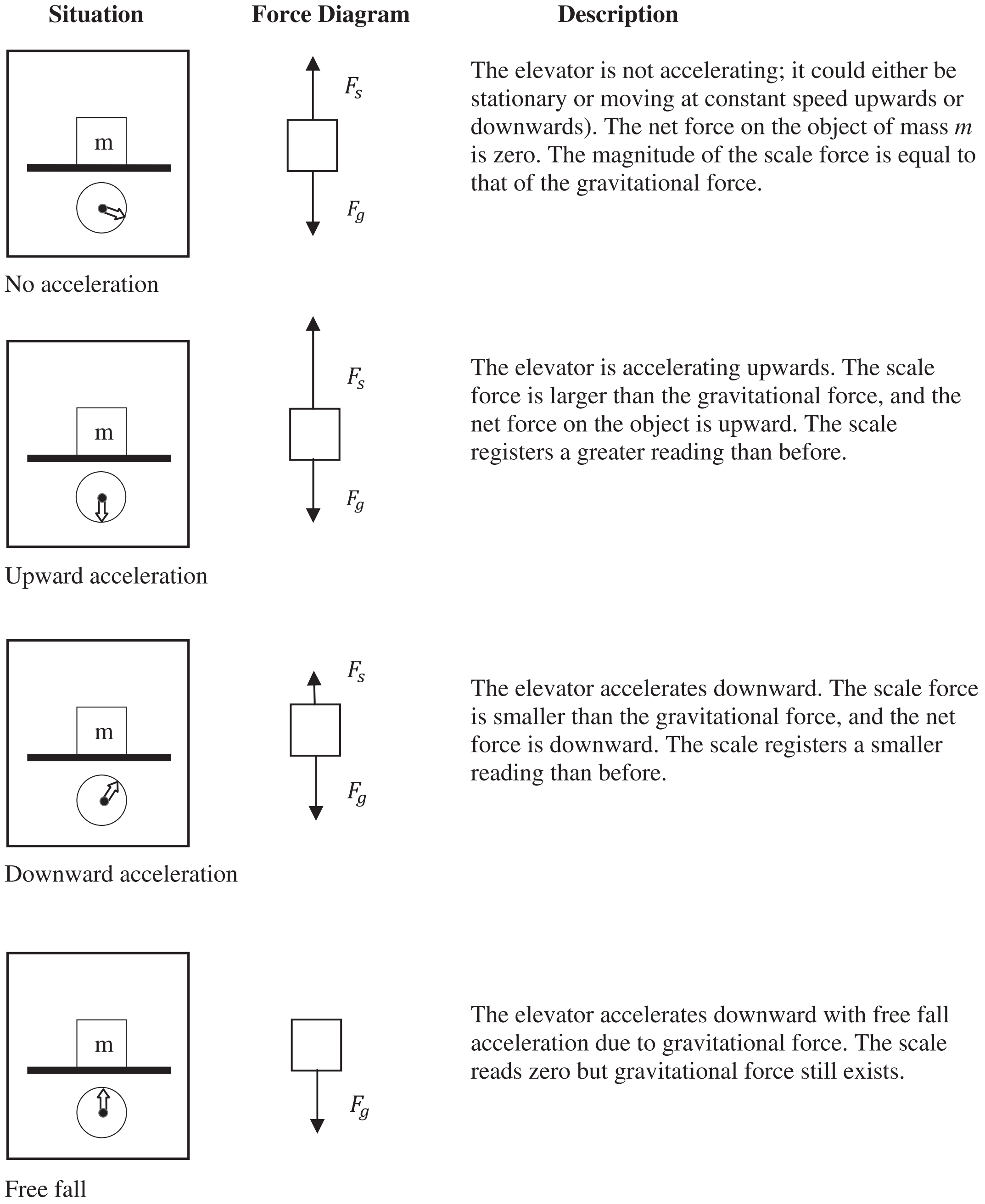
[2] In this paper, "nonaccelerating" or "accelerating" situations, objects, or bodies are used with respect to an observer in an inertial frame.



The elevator is not accelerating; it could either be stationary or moving at constant speed upwards or downwards). The net force on the object of mass *m* is zero. The magnitude of the scale force is equal to that of the gravitational force.

The elevator is accelerating upwards. The scale force is larger than the gravitational force, and the net force on the object is upward. The scale registers a greater reading than before.

The elevator accelerates downward. The scale force is smaller than the gravitational force, and the net force is downward. The scale registers a smaller reading than before.

The elevator accelerates downward with free fall acceleration due to gravitational force. The scale reads zero but gravitational force still exists.

FIG. 2. Relationship between the gravitational and scale forces (the case of an elevator).

values are obtained for the object depending on which definition one uses. Those who adopt the gravitational definition of weight sometimes avoid describing objects in free fall as being weightless by adopting terms like "apparent weightlessness" (e.g., Ref. [14]) or "weightful" (e.g., Ref. [13]). They insist that objects in free fall have weight, consistent with their gravitational definition.

It is clear from the previous discussions that the term weight poses semantic problems, especially for accelerating objects, and thus represents a potential source of confusion for both teachers and students. It has been shown that students are often confused regarding basic physics principles when discussing weight for accelerating bodies [23,24]. Thus, the goals of the present study are to (i) document how introductory physics textbooks deal with the concepts of weight and weightlessness with attention to language issues, and (ii) examine whether and how the sampled textbooks discuss weight conceptually in terms of gravitational and scale forces for both static and accelerating situations.

## III. CONCEPTUAL FRAMEWORK

This study involves several related areas of interest: physics concepts and laws, language and terminology, science learning and teaching, cognition and conceptual understanding, textbook treatments, and pedagogical approaches. A viable conceptual framework for viewing this and devising improved instruction is one that will connect these. Thus in our work we first identified and clarified the main physical constructs involved in a variety of situations both accelerating and nonaccelerating (e.g., forces, gravitation, statics and dynamics, equilibrium and nonequilibrium cases). We then identified language issues and polysemous terminology associated with concepts of weight, weightlessness, and free fall. Based on this and the literature, we considered alternative conceptual and pedagogical approaches to the topics, and we were able to devise a coding scheme to use for characterizing and analyzing the textbooks' approaches with respect to both physics and language.

Problems arising around the concept of weight and how to teach it are both conceptual and semantic in nature. A pedagogical principle from Arons [25] for approaching new concepts, with support in the literature but not sufficiently found in practice, is that of "idea first, name afterwards" (p. 102); ideas or concepts should be introduced to students and understood conceptually before naming them. The development of ideas ahead of terminology is especially useful in dealing with terms such as weight and weightlessness. Our position is that descriptive phrases for the concepts should be used in initial teaching, rather than the ambiguous terms, which could be discussed once the concepts are established. This idea has support elsewhere: for example, Kuhn [26] argued that verbal definitions have little scientific content when considered by themselves, and Braithwaite [27] argued that academicians are in bondage of symbols which are their own creation.

A second theoretical position is that concepts or terms should be introduced to students using several examples in multiple situations to promote better conceptual understanding [4–6,28]. The third is that language issues be explicitly discussed with students as part of content teaching and learning [5,29,30]. This should be especially valuable for concepts where scientific terminology is polysemous, such as for weight, and would also include making students aware of differences between everyday and scientific usages [2,3]. Finally, while other researchers and writers have argued for which should be designated the "correct" definition of weight, and taking opposing positions, we will work from the alternative perspective of first teaching the two underlying constructs and their relationship, irrespective of naming issues, and making the inherent terminology ambiguities explicit in instruction. Thus our instructional perspective regarding physics and language issues is to introduce and develop concepts prior to naming them, to be explicit about language and ambiguities, and to treat and explicate concepts and terms in multiple physical contexts.

## IV. LITERATURE REVIEW

In this section we briefly review research literature on language issues related to science concepts. This will shed light on some perspectives noted above and, consequently, the need and rationale for this study. Recognizing that language mediates conceptions [31], most studies of interest will be neither solely language nor solely science conceptual studies. This being said, the first few studies discussed below are mostly language related, and are followed by a discussion of studies related to the weight concept in particular. We review research on how use of language can hinder or promote student understanding of science concepts, research on students' ideas about related terms, and research on textbook presentations of weight and related concepts.

A study by Clerk and Rutherford [1] examined the possibility that language confusions can be mistaken for student "misconceptions" about subject matter. A test consisting of 20 multiple choice items used to diagnose conceptions in physics was administered to a sample of South African students whose first language was English. A follow-up interview was conducted with a subsample of these subjects to explore the reasoning behind their choices. They found that language usage, for example, different interpretations of the question or terms involved, was frequently the reason behind the students' responses, which might have otherwise been seen as reflecting misconceptions. Williams [2] argues that one reason that many gifted students find introductory college physics difficult is the way language is used in such courses. He analyzed the treatment of Newton's laws of motion and other terms in five well-known introductory textbooks with an aim of revealing language issues. He found certain semantic ambiguities in statements related to Newton's laws and that some terms used in the textbooks lacked precision. He identified terms with technical meanings which are not used consistently within the physics community. Among others, these include weight, force, dynamics, tension, and mass. He suggested the following to improve how language is used in science instruction: (i) agree upon the proper statement of important principles; (ii) agree upon definitions of the common words to which experts ascribe precise meanings; (iii) agree among disciplines on the meanings of shared words; (iv) adopt textbooks which are careful about semantics; (v) apply precision in the use of language in the classroom; and (vi) emphasize precision of definition [2]. A similar study [3] investigated how students perceive the similarities and differences between the everyday and physics meanings of the terms force, momentum, and impulse. They also studied whether these perceived differences and similarities affect student learning of those concepts. The study indicated that students who can differentiate between the everyday and physics meanings of the words also obtain higher test scores. The study suggested that physics instructors should be more careful with both the use of language and the alternative meanings of physics terminology that their students bring. Itza-Ortiz, Rebello, Zollman, and Rodriguez-Achach [3] conclude that instructors should organize writing assignments to enable students to overcome language problems in physics.

Language issues are also noted in biology. For example, Brown and Ryoo [7] conducted a study to investigate whether or not students who were taught by introducing phenomena in everyday terms prior to being taught the scientific language will develop improved understanding of new concepts. Using a pretest post-test control group design, they assessed students' conceptual and linguistic understanding of photosynthesis. They found that students taught with the *content-first approach* had better understanding than those taught traditionally. Like Arons [25,32], Brown and Ryoo [7] advocate content-first approaches to teaching science, involving "use of everyday language to introduce the primary ideas associated with the content, followed by direct language instruction to demonstrate the synergy between everyday and scientific descriptions of phenomena" (p. 533). Flodin [30] analyzed variations in how the gene concept is used and conceived in different parts of a common college biology textbook. Results showed that the gene concept is not presented consistently. The study described and categorized five different gene concepts used in the textbook: the gene as a trait, an information structure, an actor, a regulator, and a marker. Flodin concludes that these conceptual differences are not dealt with in an explicit manner, thereby constituting one of the sources of confusion when learning about genes and genetics. This has some similarities to the situation facing the weight concept and terminology.

There have been various studies focused on students' and preservice teachers' ideas about weight and related terms [11,33,34]. For example, Galili [11] conducted a study on students' understanding of weightlessness and free fall. The study involved analyzing and discussing responses to several weight and gravity[3] related questions, which were given to different groups of students who initially were taught the gravitational definition of weight. A major conclusion of their study is that students confuse weight in the scale force sense with gravitational force. Galili noted that the knowledge presented by students was not necessarily incorrect, but difficulties might result from the weight definitions available in the school curriculum. Galili [11] concludes that there is a need for the adoption of the operational definition of weight in the physics curriculum, and this is consistent with the notion and terminology of weightlessness. A different study by Sharma, Millar, Smith, and Sefton [24] investigated students' understandings of gravity in an orbiting spaceship. Results indicated that many students held the misconception that gravity is effectively zero inside an orbiting spacecraft. The study suggests a way that school and university physics treatments could be reformulated to counter this widespread student view. They suggest teaching the operational definition of weight advocated by Galili [11], Galili [15], followed by application of the scenario of the orbiting astronaut as a case study. Next they suggest introduction of gravitation, frames of reference, contact forces, and Newton's laws concepts. They also suggest that a critical examination of all the main kinds of explanations for weightlessness, both valid and invalid, should be included in learning programs.

While Sharma, Millar, Smith, and Sefton [24] advocate the operational definition of weight, others [33,35] conducted similar studies of children's ideas about weight premised on the idea that weight is a gravitational force. Bar, Zinn, and Goldmuntz [33] pursued an exploratory study to find and interpret children's ideas about weight and free fall. Analysis of student responses to the interview questions indicated that younger children defined weight as a pressing force and older ones defined weight as the amount of matter, similar to mass. Also, the study found that children think that things fall because they are not supported, and this idea remains as they mature, but it becomes more elaborated first by the idea of heaviness, and then by the idea of Earth's gravitational force. In general, they concluded that children's ideas about weight and free fall change with age. They advise the need for effective instruction to deal with the identified conceptions. It is interesting to note that some of the children's ideas of weight in this study agree with the operational definition of weight although they had in mind weight as a gravitational force. For example, they report that younger children defined weight as a pressing force. Ruggiero, Cartelli, Dupre, and Vincentini-Missoni [35] investigated schemes of common sense knowledge that children (aged 12–13 years) employ in relating weight, air, and gravity to the phenomenon of free fall. Interviews with 40 children indicated three common sense schemes. First, the force of gravity acting on the weight of objects causes their fall; second, the force of gravity and weight are two independent causes for the fall of objects; and third, the force of gravity, weight, and the phenomenon of fall are unrelated concepts. Air was sometimes thought to be the cause of either weight or gravity or both. It is interesting that in this study the authors positioned their interpretations on the idea that weight is a force due to gravity by Earth.

While some have been explicit about their definition of the term weight, others have been less clear. For example, Gönen [36] studied student teachers' conceptions and scientifically acceptable conceptions about mass and gravity. In his description of the various physical quantities

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[3] Some use the term "gravity" to imply the effective or observed attraction force (the gravitational effects as they are observed on the rotating earth) and "gravitational force" or "force of gravity" to imply the attractive force theoretically calculated from Newton's universal law of gravitation. In this paper, the term gravity should be interpreted in context.

relevant for the study, he defined weight as the amount of attraction on an object located on the surface of a planet. He continued that it depends on the planet and whether the object is sitting on the surface or accelerating towards or away from a given planet. The former description suggests that he associates weight with the gravitational force, and the latter suggests an operational notion of weight. There is a lack of clarity in distinguishing the scale force from the gravitational force and hence in dealing with weightlessness. Gönen [36] articulated another concept of weightlessness: "Weight is slightly different from the gravitational force that exists from interaction of masses. In the empty space, there are no other bodies; therefore, a body in this space is weightless" (p. 74). The idea that weightlessness results from being far from other bodies has been associated with reasoning that is in agreement with the gravitational definition of weight [11], but most cases where weightless issues arise involve noninertial reference frames rather than isolation from other bodies.

To our knowledge, only two studies have explicitly examined textbooks' definitions of weight and descriptions of weightlessness. A study by Galili and Lehavi [37] examined 25 university-level textbooks in terms of their presentation of the terms weight, weightlessness, and "tides," and how high school teachers and university science students perceive these concepts. The study was motivated by the lack of the discussion of tides in introductory physics courses, which according to Galili and Lehavi [37] is important for the understanding of gravitational effects. The paper does not share how data were obtained from the textbooks nor how they were analyzed, but presents the results in tabular form. Survey data from high school teachers and university science students was collected using an open-ended questionnaire. The results of textbooks' presentation of these terms (weight, weightlessness, and tides) were compared to the views of teachers and students. The study found that most high school teachers in their sample defined weight operationally while most university students held the gravitational definition of weight, similar to most textbooks. The resulting difficulties prompted them to recommend an explicit discussion of the different definitions of weight and the concurrent presentation of weight, weightlessness, and tides to introduce the concept of gravitation to students. Tural, Akdeniz, and Alev [38] investigated the effect of a lesson plan based on weightlessness on science teachers' understanding. Before implementing the lesson plan, they reviewed a set of physics textbooks and examined the student teachers' understanding of weightlessness. They do not say how data were collected or analyzed, but describe the methodology (a pretest and posttest coupled with semistructured interviews) used to examine the effectiveness of their designed lesson plan on the study participants. All ten reviewed textbooks defined weight as a gravitational force, and omitted discussion of weightlessness. The interviewed subjects indicated a lack of understanding of weightlessness before the intervention, while after implementation of the lesson with nine subjects, it was found that the designed lesson plan (not shared in the paper) was effective in teaching weightlessness. In order to overcome conceptual difficulties with weightlessness, they suggest that physics textbooks and educators should give both the gravitational and operational definitions of weight in a comparative manner, and the concepts of apparent weight and true weight should be introduced to students. In most of the reviewed studies regarding weight, the notions of study participants tended to be analyzed with reference to the researchers' point of view about the definition of weight. While some studies either ignore or are confused about ambiguities associated with the term "weight" (e.g., Refs. [33,36]), Galili [11] discusses them at length. It is clear that several researchers have ignored the pitfalls of polysemous terms in the teaching and learning (and researching) of topics in introductory physics. Studies into textbooks' presentations of weight and related concepts (i.e., Refs. [37,38]) have adopted different definitions of weight and weightlessness for their analyses.

This review has indicated that language issues are crucial in teaching and learning scientific concepts effectively. There is also the possibility of misidentifying a student as having a misconception when he or she is interpreting or using terminology differently. The review also confirms the need for careful use and discussion of language to facilitate student learning and improve understanding. Textbooks are vital learning and teaching resources for both students and teachers alike, playing a major role in determining what content is included and how it is approached [39]. Therefore, this study examines introductory college-level textbooks' treatment of weight in relation to both language issues and the explanation of the relevant physical constructs, in the light of the conceptual framework above and relevant literature.

*Research questions*:

1. How do introductory college-level physics textbooks develop the concepts and use the terms weight, apparent weight, and weightlessness in relation to the physics constructs involved?
2. To what extent do textbooks address the language issues and the different meanings associated with the polysemous term weight?

## V. RESEARCH DESIGN

### A. Sample

An initial sample of 35 introductory physics textbooks was chosen from personal libraries in the physics department at Western Michigan University (WMU). Five physics faculty members were consulted, three were actively involved in teaching introductory physics courses and two had previously taught such courses, and they indicated that the textbooks were indeed typical introductory physics books, both algebra based and calculus based. This convenience sample approach to textbook selection has also been employed by Niaz, Klassen, McMillan, and Metz [40]. From the set of 35 textbooks gathered, 20 with publication dates between 1995 and 2013 were chosen for detailed analysis. Thus the study sample consisted of 20 typical introductory physics textbooks known to be in fairly wide use over the last 18 years. Choosing books published after 1995 was reasonable since the ISO provided a definition of the term weight in 1992 [20], and to our knowledge Galili [10] published the first empirical paper on teacher and student confusions and ambiguities for weight and gravity in 1993. The textbooks analyzed are listed in Table I.

### B. Procedure

Two individuals with strong backgrounds in both physics and education (Rex Taibu and David Schuster) carried out the textbook analyses. They analyzed content from all passages and problems in the 20 textbooks that discussed weight and (or) the related physics. They drew on their knowledge of previous studies in the field and their own experience in physics curriculum development and teaching to determine the task approach and areas of concentration. Textbook sections perused included any in which the book presented forces, Newton's second law, Newton's universal law of gravitation, weight, mass, circular, and rotational motion, orbital motion, and buoyancy, and for each of these they also included the corresponding set of questions and problems provided by the book at the ends of chapters. All relevant sections for study were identified and agreed upon during the initial textbook exploration. Through the analysis of these passages, varying in context and difficulty, information about the range of treatments of weight and related constructs was obtained.

Content analysis methods, cf. Ref. [41], were used to approach the research questions on textbook treatments. Weber [41] contends that a central feature of content analysis is its ability to classify several words of the text into fewer content categories. Content analysis technique relies on categorization and coding of the relevant text data [42]. Ramos and Ibanez [43] used content analysis in their investigation of physics textbooks' presentation of the energy-conservation principle in hydrodynamics because of its flexibility in allowing researchers to analyze the material of interest to them. Content analysis methods have also been employed in a number of other textbook studies [44,45].

After investigators identify research goals, relevant theories (theoretical framework), previous research, and the texts to be analyzed and classified, content analysis generally involves creating a coding scheme and applying it to the sampled text material [41]. Initially, we had limited knowledge and skills in content analysis but familiarized ourselves by relevant reading (e.g., Refs. [41,42,44,46]) and participating in research group meetings. The following procedure outlines the stages that enabled the creation of a coding scheme for textbook treatments of weight and related concepts. An initial sample of 10 textbooks was chosen (from the target sample of 20) to identify the main issues and the range of treatments of weight-related constructs. This initial textbook exploration, along with

TABLE I. List of introductory physics textbooks analyzed.

1. W. Bauer and G. D. Westfall, *University Physics with Modern Physics* (McGraw-Hill, New York, NY, 2011).
2. D. Cassidy, G. Holton, and J. Rutherford, *Understanding Physics* (Springer-Verlag New York, New York, NY, 2002).
3. J. D. Cutnell, *Physics* (John Wiley & Sons, Hoboken, NJ, 2009), 8th ed.
4. D. S. Giancoli, *Physics for Scientists and Engineers: With Modern Physics* (Prentice Hall, Upper Saddle River, NJ, 2000), 3rd ed.
5. D. Halliday, R. Resnick, and J. Walker, *Fundamentals of Physics* (John Wiley & Sons, Hoboken, NJ, 2005), 7th ed.
6. E. Hecht, *Physics: Algebra/Trig* (Brooks/Cole, Pacific Grove, CA, 1998), 2nd ed.
7. P. G. Hewitt, *Conceptual Physics* (Pearson Education, San Francisco, 2006), 10th ed.
8. A. Hobson, *Physics Concepts & Connections* (Pearson Education, Upper Saddle River, NJ, 2007), 4th ed.
9. E. Jones and R. Childers, *Contemporary College Physics* (Mc Graw-Hill Companies, Boston, 1999), 3rd ed.
10. L. D. Kirkpatrick, and G. F. Wheeler, *Physics: A World View* (Harcourt College Publishers, Fort Worth, 2001), 4th ed.
11. L. D. Kirkpatrick and G. E. Francis, *Physics: A Conceptual World View* (Brooks/Cole, Australia, 2010), 7th ed.
12. R. D. Knight, *Physics for Scientists and Engineers: A Strategic Approach* (Pearson Education, Boston, 2013), 3rd ed.
13. P. J. Nolan, *Fundamentals of College Physics* (Wm. C. Brown Communications., Dubuque, IA, 1995), 2nd ed.
14. V. J. Ostdiek and D. J. Bord, *Inquiry into Physics* (Brooks/Cole, Australia, 2005), 5th ed.
15. R. A. Serway, *Physics for Scientists and Engineers* (Brooks/Cole, Belmont, CA, 2010), 8th ed.
16. R. A. Serway *et al.*, *College Physics* (Brooks/Cole, Australia, 2006), 7th ed., Vol. 1.
17. J. Trefil and R. M. Hazen, *Physics Matters: An Introduction to Conceptual Physics* (John Wiley & Sons, River Street, Hoboken, 2004).
18. J. S. Walker, *Physics* (Prentice-Hall, Upper Saddle River, NJ, 2002).
19. J. D. Wilson and A. J. Bufa, *Physics* (Prentice Hall, Upper Saddle River, NJ, 1997), 3rd ed.
20. H. D. Young and R. M. Geller, *Sears & Zemansky's College Physics* (Pearson Education, San Francisco, CA, 2007), 8th ed.

relevant theoretical positions in the literature, characterization of the constructs, teaching experience, project goals, and discussions, informed project conceptualization. The two major definitions of weight (the gravitational and operational definitions) provided two distinct physical constructs associated with weight. As noted, these different but related constructs are commonly given the same name, leading to teaching and learning difficulties especially for accelerating objects. Thus, our coding scheme needed to consider both physics and language issues, consistent with our research goals and conceptual framework. Emphasis on the underlying physical constructs, and recognizing that ideas exist outside of words used to denote them [7] distinguishes this from other work [38]. This perspective and analysis goes beyond previous work on weight in textbooks.

In our work we first considered the nature and merits of the two major physical constructs associated with weight, at the same time recognizing the associated language issues. In initial textbook exploration we examined the following: (i) weight definitions, (ii) how the concept and term weight was introduced, (iii) terminologies used for the gravitational and scale forces, (iv) the terms or phrases associated with objects in the state of free fall, and (v) semantic ambiguities surrounding naming and use of the two physical constructs. We also examined whether or not textbooks presented the name first or treated the idea first before naming it, per Arons [25] and Brown and Ryoo [7], to minimize possible semantic confusions or risking students focusing on terminology rather than concepts. The need to properly distinguish weight from *mass* is another important issue, but although it does present conceptual difficulties for students it does not have the semantic problem of different scientific concepts associated with a single name. Brown [22] strongly advocates teaching the distinction between weight and mass.

After conceptualizing language issues, we noted that the two physical constructs associated with weight may best be understood by considering a variety of situations and comparison cases involving nonaccelerating and accelerating objects. Thus the study devotes some time to the applicable physics of these issues, in keeping with the advice of Touger [5] that reinforcement of appropriate usage of words in diverse instances can help establish the scope of the concept. This then helps to answer the second research question on how textbooks explain the various conceptual issues or meanings associated with weight. Some cases may be familiar to people from either their own experience or portrayal in books and movies, e.g., riding in an elevator, objects in water, and astronauts in spaceships. The following classification of situations was helpful in addressing the different ways that the term weight is used: (i) First, treatment of "static" cases in nonaccelerating situations (or almost nonaccelerating), e.g., familiar measurements of the weight of objects on Earth. This could extend to discussion of forces for objects submerged in water. (ii) Second, treatment of dynamic situations involving accelerating objects, and the idea that scale force depends on whether the object is accelerating or not; and (iii) specific discussions for particular cases: an object on the moon or another planet, an accelerating elevator, orbiting spaceship, rotating Earth, and rotating space station. (The last situation is often referred to as involving "artificial gravity" which may further muddy the semantic waters).

A preliminary coding scheme was devised based on the issues we identified, while leaving open the possibility that further insights and coding categories would arise during textbook perusal, leading to modification of the scheme. The coding was arrived at following Weber [41]; the preliminary scheme was pilot tested on a first sample of four textbooks (20% of the total), consequently revised, then applied to a different set of 4 books, independently coded by the two of us to ascertain the extent to which the scheme was appropriate to the task and produced agreement. A Cohen's *kappa* value of 0.8 was already obtained by this first comparison stage, showing fairly strong agreement [47], and with known reasons for marginal decisions. This constituted a pilot test of initial reliability (e.g., Ref. [46]). Some discrepancies were then resolved through discussions, resulting in further scheme refinement and extension, while at the same time the occurrence of new aspects in textbooks was diminishing. The choice of a 20% subsample size was in agreement with social science research methods [48].

In this manner, and based on our theoretical perspectives on potential approaches to dealing with the constructs and language, a 15-item coding scheme for textbook treatments was developed. Modifications leading toward the final scheme involved refinement of the categories or wording changes to eliminate ambiguities in the scheme, as suggested by Weber [41]. The coding scheme is conveniently divided into two sections: (i) language and concept introduction aspects (Items 1 to 7), and (ii) the physics concepts and principles (Items 8 to 15). These two sections target mainly the first and second research questions, but note that the language and the physics are interrelated in practice; it nevertheless proved useful to cluster them as we did. The coding scheme is provided in Table II, with descriptions of the 15 coding aspects and the rating rubrics used. The following letter notation was used to rate the textbooks on their treatments of the *physics* regarding weight (items 8 to 15) in relation to our coding scheme: A = Excellent, B = Good, C = Satisfactory, and D = No Mention. This rating is similar to the one used by Niaz, Klassen, McMillan, and Metz [40]. The *language-related* items (items 1 to 7) did not receive the same treatment because they deal with the somewhat more subjective question of semantic preference. By design, an entry in each item can only be classified as one of the alternatives provided. Using

TABLE II. Coding scheme and number of books in each classification.

| Language and concept introduction | | |
|---|---|---|
| Item: description | Classification | Number of books |
| 1. **Book's primary or preferred definition of the term weight:** A preliminary textbook analysis and literature review showed that we could classify weight definitions in several categories. | A. Earth's gravitational force | 11 |
| | B. Net gravitational force | 2 |
| | C. Scale force | 3 |
| | D. ISO definition | 1 |
| | E. Magnitude of Earth's gravitational force | 3 |
| 2. **Introducing weight:** Textbook perusal indicated that some authors start with the term weight and then define it using concepts that are not yet known. Others start with a physical description of a concept (e.g., gravitational force) and name it later as weight. Yet others give name before concept in one section and the reverse in another subsection, and these were classified as mixed or unclear. It was sometimes not clear where such textbooks formally introduced the term. | A. Idea first before name | 9 |
| | B. Mixed or unclear | 5 |
| | C. Name first before idea | 6 |
| 3. **Special name (or preferred name) for the gravitational force:** A gravitational force exists due to the existence of at least two masses. A special name is any other familiar name that appears as a synonym for gravitational force. Textbooks that named gravitational force first as weight and then next as true weight in trying to distinguish apparent weight are classified as weight then true weight. Here true weight also stands in for terms normal weight, real weight, or actual weight. Textbooks that distinguish between weight and gravitational force, have no other special name for gravitational force. | A. Weight | 4 |
| | B. Weight then true weight | 9 |
| | C. Gravitational force | 7 |
| 4. **Special name (or preferred name) for scale force:** A scale force is the force exerted by the scale or supporting surface on the object or vice versa, and is given by the scale reading. Various names are attached to this concept. | A. Weight | 2 |
| | B. Apparent weight | 9 |
| | C. Effective weight | 1 |
| | D. Scale force or reading | 8 |
| 5. **The book's preferred term or phrase for the state of free fall:** Free fall is often defined as moving under the influence of gravity only. Special names or phrases are attached to the state of an object in free fall with regard to weight. | A. Weightlessness | 7 |
| | B. Apparent weightlessness | 10 |
| | C. Effective weightlessness | 1 |
| | D. Not mentioned | 2 |
| 6. **Semantic ambiguities:** For textbooks that addressed the two constructs as distinct, we were here not concerned with name or phrase, but whether the two concepts were used *consistently* and named *differently* within the book. | A. No ambiguities | 10 |
| | B. Inconsistent *use* of weight as a gravitational force | 7 |
| | C. Same term weight for gravitational and scale forces | 2 |
| | D. Weight vs apparent weight unclear | 1 |
| 7. **Acknowledgment of ambiguity:** The textbook explicitly discussed the ambiguity of the term weight. | A. Discussed ambiguity | 1 |
| | B. Did *not* discuss ambiguity | 19 |
| 8. **Characteristics of weight:** Textbook treatments of the following: (i) weight (either construct) is not a property of a single object, differing in that regard from mass, or it is an extrinsic feature of an object unlike mass; (ii) weight does not have a unique value but depends on situation; (iii) statement or equation relating weight to the gravitation mathematical expression, and (or) being explicit that scale reading depends on whether an object is accelerating or not. | A. Excellent—aspects (i)(ii)(iii) | 13 |
| | B. Good—aspects (ii)(iii) | 5 |
| | C. Satisfactory—aspect (iii) | 2 |
| | D. Not treated | 0 |
| 9. **Treatment of basic nonaccelerating case:** Explication of the relation between gravitational and scale force, for an object at rest. This item is satisfied by the following aspects: (i) at rest (on Earth's ground), the gravitational and scale forces are equal in magnitude; (ii) the book reminds readers that aspect (i) is true when Earth is assumed to be a nonaccelerating frame; and (iii) an illustration of both force vectors acting on an object at rest. | A. Excellent—aspects (i) (ii) (iii) | 5 |
| | B. Good—aspects (i) (iii) | 13 |
| | C. Satisfactory—aspect (iii) | 0 |
| | D. Not treated | 2 |
| 10. **Treatment of buoyancy effects:** Archimedes' principle discussions have the potential to extend the discussion of gravitational and scale forces in static cases. This item is satisfied by the following aspects: (i) statement or equation relating gravitational and scale forces to buoyant force on a submerged or floating object; and (ii) an illustration indicating buoyant, gravitational, and (or) scale forces. | A. Excellent—aspects (i) (ii) | 10 |
| | B. Good—aspect (i) | 1 |
| | C. Satisfactory—aspect (ii) | 4 |
| | D. No or treated without emphasis to both aspects | 5 |

*(Table continued)*

TABLE II. (*Continued*)

| Item: description | Classification | Number of books |
|---|---|---|
| Language and concept introduction | | |
| 11. **General idea of accelerating situations and weight:** The situations in which weight is relevant fall into two fundamental categories: (1) nonaccelerating situations and (2) accelerating situations. We looked for (i) explicit recognition of the two fundamental categories and the distinction, and (ii) treatment of at least two accelerating situations. | A. Excellent—aspects (i) (ii) | 4 |
| | B. Good—aspect (i) | 1 |
| | C. Satisfactory—aspect (ii) | 7 |
| | D. Little or no recognition of non-accelerating and accelerating situations as they relate to weight | 8 |
| 12. **Elevator example:** The relationship between gravitational and scale force is commonly demonstrated by using a scale in an elevator. Here we looked for (i) force diagrams for various elevator motions, (ii) descriptive comparison of gravitational and scale forces, and (iii) use of Newton's second law to relate forces. | A. Excellent—aspects (i) (ii) (iii) | 11 |
| | B. Good—aspects (i) (ii) | 1 |
| | C. Satisfactory—aspect (ii) | 6 |
| | D. Elevator problem left as an exercise or absent | 2 |
| 13. **Spaceship example:** The case of astronauts in an orbiting spaceship involves issues of gravitational force, scale force, orbital motion, free fall, weightlessness, and the distinction between constructs, whatever the names used. We looked for treatments explicating these aspects clearly (see the discussion section). | A. Excellent—full treatment | 8 |
| | B. Good—most aspects dealt with | 2 |
| | C. Satisfactory—correct statements with little explication | 5 |
| | D. Not noted or treated | 5 |
| 14. **Artificial gravity:** This case, for example, a rotating space station, has the potential to further clarify the distinctions between forces and the notion of weight. Aspects: (i) discussions using physics principles, (ii) use of illustrations, (iii) descriptive statements, (iv) left as an exercise or problem. | A. Excellent—aspects (i) (ii) | 9 |
| | B. Good—aspect (iii) | 0 |
| | C. Satisfactory—aspect (iv) | 6 |
| | D. Not done or mentioned | 5 |
| 15. **Effect of Earth's rotation on weight:** Aspects: (i) the centripetal force is the resultant of the gravitational and scale forces resulting in circular motion, (ii) mentions that Earth's rotation affects scale weight, or (iii) left as an exercise or problem. | A. Excellent—aspects (i) (ii) | 6 |
| | B. Good—aspect (ii) | 5 |
| | C. Satisfactory—aspect (iii) | 4 |
| | D. Not mentioned | 5 |

this coding scheme, the first author then continued to analyze all the remaining textbooks, with the analysis process checked repeatedly during this stage. Toward the end of analyzing all 20 textbooks, no further variations in treatment or additional examples relevant to the study goals were being found, suggesting saturation. The numbers of books fitting in each category are found in the right-hand column, and are also discussed with the results.

## VI. RESULTS AND DISCUSSION

Table III gives the results of the analysis, by textbook and coding item, using letters from A to E to characterize the way the identified aspects were treated in the textbook (per coding scheme in Table II).

These overall results were analyzed in sections below in relation to the research questions. The discussion is broadly divided into language issues and physics issues, though these are of course connected, and the subsections relate to numbered items in the coding scheme.

### A. Language and concept introduction (items 1–7)

Items 1–7 of the coding scheme were used to examine the language issues associated with weight as treated in textbooks. These items ask about definitional preferences for the term weight, how the term is introduced, terminology preferences for gravitational force, scale force, and the state of free fall or weightlessness. This is followed by a discussion of relevant semantic ambiguities or inconsistencies. The section ends with a discussion of what (if anything) textbooks do to help readers understand the ambiguities and confusions surrounding weight.

#### *1. Definitions (item 1)*

Eleven out of the twenty textbooks (Table II, item 1) defined the term weight as Earth's gravitational force. Textbooks that gave a *net* gravitational definition presented it as an extension to the former definition. For example, Hobson [49] stated that, "It is useful to extend the meaning of the word 'weight'… The weight of an object refers to the net gravitational force exerted on it by all other objects" (p. 78). The scale force (operational) definition of weight was much less preferred in textbooks, despite its strong advocates in the literature. Interestingly, scale force definitions came in different forms and not always precisely; for example, Hewitt [50] states

> *When we discussed rotating environments in Chapter 8, we learned that a support force can occur without regard to gravity, so a broader definition of the weight of something is the force it exerts against a supporting floor or a weighing scale (p. 167).*

It is unclear why Hewitt [50] describes this as a "broader" definition than his initial definition as gravitational force, when in fact it is a definition of a distinct concept (scale force). The following is a discussion of the issue by Knight [51]: "Some textbooks define weight as the gravitational force on an object, $w = (mg, \text{down})$. …This textbook prefers the definition of weight as being what a scale reads, the result of weighing measurement" (p. 147). Thus, while Hewitt [50] surprisingly designates the scale force as a *broader definition* of the term weight, Knight [51] notes that it is a *definitional preference*. The scale force definition by Halliday, Resnick, and Walker [52] comes in a different form: "The weight $W$ of a body is the magnitude of the net force required to prevent the body from falling freely, as measured by someone on the ground" (p. 96). They impose conditions on this definition by saying that the weight of a body must be measured when it is not accelerating.

Scale force definitions were also associated with other phrases like apparent weight and "effective weight." For example, Hecht [53] stated, "We define effective weight of an object as the force it exerts on a scale" (p. 162). Note that these are not put forward as definitions of weight, but rather as definitions of apparent weight or effective weight, and most of these textbooks define the term weight as a gravitational force. An item in our coding scheme that looked for the naming issues of the scale force (Table II, item 4) addresses this point. Galili [11] refers to the scale force definition of weight as the operational definition.

Other interesting definitions arose from the textbook sample. Three textbooks defined the term weight as the *magnitude* of gravitational force; e.g., Bauer and Westfall [54] stated, "the magnitude $F_g$ is called the weight of the object" (p. 103). The definition suggested by the ISO in 1992 was mentioned only by Jones and Childers [55] as "The weight of a body in a specified reference frame is the force which, when applied to the body, would give it an acceleration equal to the local acceleration of free fall in that reference frame" (p. 110). Jones and Childers [55] consider this as a more precise definition of the term weight than the gravitational definition of weight, which they give earlier in the chapter. The net gravitational force and the magnitude of gravitational force definitions may be associated with the gravitational force definition, and all give a nonzero value for weight in free fall. Galili [15] contends that operational definitions of weight may also take various forms, including the force exerted by an object on a scale, the force exerted by the scale on an object, or the force exerted on an object causing its spontaneous fall with an acceleration which can be measured. Thus, despite some variants, the two categories for our main weight definitions remain gravitational and operational.

### 2. Concept introduction (item 2)

About half of the textbooks in the sample described the idea behind weight before introducing the name itself (Table II, item 2), a recommended approach that has been shown to be effective in student learning [7]. It typically involved either explaining the nature of gravitational force or systematically applying Newton's second law to a falling object and then attaching the name weight to the established idea. The other half of the textbooks took the reverse approach, tending to introduce terminology before ideas; e.g., Hecht [53] wrote, "Weight is the downward force experienced by an object (usually near the surface of the planet) as a result of the earth-object gravitational interaction" (p. 101). This definition is presented before the notion of "gravitational force" has been clarified. Although words may be important for communication they are in fact "symbols" which can be replaced while keeping the physical idea the same [56]. Part of the problem in failing to put the idea first is that of topic sequence. For example, Newton's law of universal gravitation often appeared later than formal weight definitions. However, some textbooks (e.g., Ref. [52]) briefly introduced gravitational force before talking about weight. Nevertheless, a few textbooks were unclear. For example, Giancoli [57] introduces the term weight as a gravitational force in a heading, then goes on to briefly describe the idea of gravitational force and naming it afterward as weight. Such textbooks were classified as mixed or unclear for this coding item.

### 3. Terminologies (items 3, 4, and 5)

Gravitational force was associated with the terms weight and true weight by nine textbooks (Table II, item 3). Seven textbooks did not associate the gravitational force with any special name. These textbooks defined weight as either a scale force, net gravitational force, magnitude of gravitational force, or gave the ISO definition. For such textbooks, weight is not a synonym for gravitational force. Gravitational force was associated with true weight to distinguish it from the scale force. Phrases similar to true weight were found, including "normal weight," real weight, and "actual weight." This illustrates the semantic problems that necessarily arise when two distinct constructs are known by the same name, and the adjectival attempts to discriminate. As noted, some textbooks change from calling the gravitational force weight to true weight when discussing the elevator or spaceship problem, and refer to the scale force as the apparent weight, with these phrases presumably aimed at differentiating gravitational force and scale force. While some textbooks assign special names to the scale force, others do not; they instead use a direct phrase such as the force exerted on a scale by an object or the force the scale or support exerts on a body. This is a direct way of referring to a concept, unlike the phrase apparent weight built on the established name weight. Table II, item 4 indicates that eight textbooks frequently used a descriptive phrase as opposed to special names like apparent weight or effective weight, a sign of moving away from the polysemous term weight while keeping the discussion the same and reducing semantic difficulties.

Clearly, differing name or phrase usages for the same physical concept will cause confusion and learning difficulties for students, and this may even be exacerbated if they consult several textbooks to increase their knowledge. Even students using a single textbook could face ambiguities and inconsistencies in the use of the term weight and related terms within that book. Some textbooks that gave the gravitational definition of weight introduced the term "weightlessness" and later on adopted the term "apparent weightlessness" [e.g., [58]]. Such textbooks cautioned readers that the term "weightlessness" is a misnomer. Textbooks which had either the scale force or the ISO definition of the term "weight" used the term weightlessness to describe the state of free fall. Similarly, for the *state of free fall* we also observed variations in textbook treatments. Table II, item 5 indicates that there are several differences among textbooks regarding naming of the status of free fall, just as there are variations in naming the gravitational and scale forces.

Even with the ISO definition of weight, troublesome terminological, as well as conceptual issues can arise when discussing the state of free fall, as, for example, experienced by astronauts in an orbiting spaceship. Denker [59], using a similar definition, argues that weight should really be discussed as reference-frame dependent, in which case it could make sense to say that astronauts are weightless with respect to the spaceship frame even if not with respect to an outside observer in a nonaccelerating frame. Note that many less than precise discussions of spaceship-type situations implicitly adopt the spaceship (accelerated) frame of reference in their phrasing, and this introduces further conceptual and language issues. Some experts have noted that there could be a problem with the ISO definition for not specifying the frame of reference within which *free fall acceleration* is to be measured or weightlessness described [21]. Consequently, as far as the ISO definition is concerned, the question of whether astronauts in a spaceship are weightless or not depends not only on the definition of weight adopted, but also on the frame of reference of the observer. This takes us back to the language issue which is now closely related to a conceptual issue. Clearly, it is, in principle, possible to avoid such confusions if terms such as weight and weightlessness are simply eliminated in the discussion of the physical concepts. In our textbook analysis, we did not code the textbooks based on whether they discussed this terminological issue or not, but it was clear that this issue was rarely addressed in textbooks, probably partly because textbooks did not use the ISO definition of weight which might reveal these subtle aspects. The main point is that these confusions are based mostly on language. When people talk about weightlessness in a spaceship, they often talk in terms of the *experiences* of the astronauts within the frame of reference of the spaceship. In doing so, whether they are right or wrong is a terminological and framing question involving some subjective preferences. However, the question of what kind of observations or measurements different observers in different frames can infer or make on the astronauts is entirely conceptual and objective, and could easily be understood and agreed upon by physicists without employing the ambiguous terms weight or weightlessness.

#### *4. Semantic ambiguities (item 6 and 7)*

Ambiguities came in different forms, one of which was defining the term weight one way and using it in the text in another (Table II, item 6). For example, Serway, Faughn, Vuille, and Bennet [60] ask "What weight does the scale read if the elevator accelerates upward at $2.00\ \mathrm{m/s^2}$?" (p. 98). In this case, weight is referred to as a scale force but earlier they defined weight as the gravitational force. The textbook by Kirkpatrick and Wheeler [61] defines and uses the term weight inconsistently in different textbook passages. Another form of ambiguity was exemplified by Hewitt [50], who inconsistently defined the term, stating that he was providing a broader definition while he was actually providing a conceptually different definition. Our analysis of the language issues indicated various definitional, terminological, and semantic issues within and across the textbooks. This raises the important question of whether or not textbooks explicitly mention the language issues and possible confusions regarding the term weight, i.e., its polysemous nature. Indeed, Touger [5] notes that students should be explicitly informed of any language in textbooks that impedes clear conceptualization. We also believe that textbooks have the responsibility of making students aware of the issues and teachers could do the same in their classrooms. Recall that only the Knight [51] textbook *explicitly* noted ambiguities associated with the definition of the term weight (Tables II and III, item 7). Certainly, some textbooks implicitly acknowledged the ambiguities in various ways. For example, Nolan [62] pointed out that it is misleading to say that objects in free fall are weightless because such objects still have weight. However, such textbooks did not tie these implicit statements to the inherent polysemous nature of the term weight.

The text analysis shows that many are seemingly either unaware of the language or conceptual problem, or are trying to avoid the issue by omitting it rather than clarifying. This may be done with the intent of not confusing students, but it thereby ensures confusion at some point, as soon as accelerating situations come into play. To deal with this, authors and teachers may ''hedge''

TABLE III. Overall results of the textbook analysis.

| Text and item | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bauer and Westfall (2011) | E | A | C | B | D | A | B | C | D | A | D | D | D | C | A |
| Cassidy *et al.* (2002) | A | C | B | D | B | A | B | B | B | D | D | C | A | D | D |
| Cutnell and Johnson (2009) | A | A | B | B | B | A | B | A | B | C | D | A | A | A | D |
| Giancoli (2000) | A | B | B | B | B | B | B | A | B | A | C | A | A | C | A |
| Halliday *et al.* (2005) | C | A | C | B | A | D | B | A | A | A | A | A | C | D | A |
| Hecht (1998) | A | C | B | C | C | A | B | A | A | D | C | C | A | A | A |
| Hewitt (2006) | C | C | C | A | A | C | B | B | A | B | A | B | B | A | B |
| Hobson (2007) | B | B | A | D | B | A | B | A | B | D | D | C | A | D | D |
| Jones and Childers (1999) | D | C | C | B | A | C | B | B | B | A | A | A | C | A | B |
| Kirkpatrick and Wheeler (2001) | A | B | B | D | B | B | B | B | A | D | C | C | C | A | B |
| Kirkpatrick and Francis(2010) | A | B | B | B | B | B | B | A | B | C | D | C | C | A | C |
| Knight (2013) | C | A | C | A | A | A | A | A | A | A | A | A | A | C | A |
| Nolan (1995) | A | A | A | D | D | A | B | B | B | C | C | A | D | C | B |
| Ostdiek *et al.* (2005) | A | C | A | D | A | B | B | A | D | A | D | D | D | A | D |
| Serway (2010) | E | A | C | D | B | A | B | A | B | A | D | A | D | C | C |
| Serway *et al.* (2006) | E | A | C | D | A | B | B | A | B | A | B | A | D | A | C |
| Trefil and Hazen (2004) | A | A | A | B | B | B | B | B | B | D | D | C | C | D | D |
| Walker (2002) | A | B | B | B | A | A | B | A | B | A | C | A | A | D | C |
| Wilson and Bufa (1997) | A | C | B | B | B | B | B | A | B | C | C | A | A | A | A |
| Young and Geller (2007) | B | A | B | D | B | A | B | A | B | A | C | A | B | C | B |

by attaching various modifying adjectives, thus introducing terms such as apparent weight, effective weight, true weight, real weight, etc. These names can themselves cause further confusion.

### B. Physics concepts and principles (items 8–15)

Results for items 8–15 of the coding scheme relate to how gravitational and scale force weight constructs for objects in nonaccelerating and accelerating situations were conceptualized and contrasted in the textbooks. Discussions of the gravitational and scale force constructs and how they relate to each other in nonaccelerating and accelerating cases can reveal a great deal of physics besides the semantic ambiguities, and it can also be argued that once the physics is clear, students can more easily be made aware of the language issues and will consequently be aware and careful when interpreting and using the term. With these arguments in mind, we discuss each physics item of the coding scheme using the results presented in Table II. Table IV illustrates the percentage of textbooks in each of the four categories (A, B, C, and D) of the physics items of the coding scheme.

TABLE IV. Percentage of textbooks in each category.

| | Item (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Category | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | Average |
| A | 65 | 25 | 50 | 20 | 55 | 40 | 45 | 30 | 41.25 |
| B | 25 | 65 | 5 | 5 | 5 | 10 | 0 | 25 | 17.5 |
| C | 10 | 0 | 20 | 35 | 30 | 25 | 30 | 20 | 21.25 |
| D | 0 | 10 | 25 | 40 | 10 | 25 | 25 | 25 | 20 |

#### *1. Characteristics of weight (item 8)*

Sixty-five percent of the textbooks (Tables II and IV, item 7) clearly noted that, unlike an object's mass, weight is not an inherent property of an object. Serway [63] states

> *We are familiar with the everyday phrase, the "weight of an object." Weight however, is not an inherent property of an object; rather, it is a measure of the gravitational force between the object and the Earth (or other planet). Therefore, weight is a property of a system of items: the object and the Earth (p. 109).*

Many books further clarified by stating that weight on the moon would be smaller than on Earth, while noting that mass, by contrast, remains unchanged. Some textbooks (mostly those associating weight with gravitational force) justified this aspect with the universal law of gravitation formula. For example, Cutnell [64] provides the universal gravitation formula $W = GM_E m/r^2$ to relate the magnitude of weight, $W$, mass of the object ($m$), mass of Earth ($M_E$), and the distance between $m$ and $M_E$ (p. 97). Some textbooks that gave the scale force definition (see Table II and IV, item 1) stated that weight also depends on whether an object is accelerating or not, e.g., Ref. [50]. Although some textbooks noted the changing values of weight in different locations, and used the law of universal gravitation to explain this, they did not emphasize that mass is an intrinsic property of an object, unlike weight. Lack of attention to this distinction is a missed opportunity to clarify the physics involved. Indeed, Brown [22] contends that, “the use of the words ‘weight’ and ‘mass’ become essentially interchangeable in so many people’s minds because they seem to both be identifying the same property of the objects themselves” (p. 241).

#### *2. Treatment of the basic nonaccelerating case (item 9)*

The majority of the textbooks (65%) treated the basic static cases of weight by using a figure of an object resting on the ground or table with a force diagram showing as vectors the gravitational and scale forces (equal and opposite) acting on it (Tables II and IV, item 8). However, only 25% of the textbooks reminded readers that although Earth is being considered a nonaccelerating frame, this is only an approximation due to its rotation. On the other hand, some textbooks noted this explicitly, fully meeting the requirements of this coding item. For instance, Halliday, Resnick, and Walker [52]: “Consider a body that has an acceleration $\vec{a}$ of zero relative to the ground, *which we again assume to be an inertial frame*” (p. 96) (italics ours). A few textbooks simply mentioned that weight is the gravitational force, without appropriate illustration (e.g., [65]) and could not meet all requirements of this coding, since the scale force construct can best be demonstrated by suitable illustrations and not mere text statements. Others only showed one force in action (due to Earth’s gravity) for an object in the static case [54].

#### *3. Treatment of buoyancy effects (item 10)*

Discussions of Archimedes’ principle and buoyancy have the potential to clarify the relationship between gravitational and scale force constructs in the static case, and explicate the seeming lightness of submerged objects. While half of the textbooks took advantage of this phenomenon to enhance understanding of gravitational forces, scale forces, and equilibrium, others did not (Tables II and IV, item 10). Yet even lay people have an experiential intuitive notion that submerged bodies feel lighter. One of the textbooks that satisfied the requirements of this item, apart from illustrating gravitational and buoyant forces, indicated that scale reading = weight-buoyant force [65]. Some textbooks, e.g., Ref. [66], discussed Archimedes’ principle without consideration of how the scale force changes for submerged objects and the way this relationship explains lightness of submerged or floating objects.

#### *4. General idea of accelerating situations and weight (item 11)*

The central idea that the scale force (operational definition of weight) depends on whether or not the object and measurement frame are accelerating is crucial to understanding the topic in an introductory college-level physics course. Unfortunately, few introductory college textbooks (20%) stated this central idea explicitly, thereby treating the weight concept in a manner similar to lower levels of schooling (Tables II and IV, item 11). Only three textbooks stated the general idea; for example, Knight [51] wrote, “weight, in N [Newton], depends on the object’s mass, but it also depends on the situation—the strength of gravity and, as we will see, whether or not the object is accelerating” (p. 146). In the textbook by Serway, Faughn, Vuille, and Bennet [60], this idea is put as, “accelerations can increase or decrease the apparent weight of an object” (p. 99). However, this was implicitly presented with reference to a specific and limited case of the elevator problem. We argue that some of the complexities associated with the weight concept are due to not explicitly noting whether an object is accelerating or not in considering forces acting on it. This study indicates that there are relatively few problematic textbook presentations related to weight for ordinary everyday situations, i.e., nonaccelerating situations where the gravitational and scale forces have equal magnitudes. However, significant conceptual and language problems arise regarding the weight of an accelerating object, and particular cases of this are discussed below.

#### *5. Elevator example (item 12)*

One of the special cases of accelerating situations is the elevator example (Tables II and IV, item 12). Fifty-five percent of the textbooks showed the relationship between the gravitational and scale forces for various states of elevator motion through the use of Newton’s second law, and relevant illustrations and force diagrams such as those in Fig. 2. Some textbooks, however, employed descriptive statements without going into physics principles. For example, Hobson [49]: “Suppose you are in an elevator and the elevator cable breaks. The elevator cable is then in free fall, and so are you. After the cable breaks, your feet no longer press down against the floor” (p. 96). Other textbooks omitted the elevator case (see, e.g., Ref. [54]). This made it difficult to deal with the two constructs involved, without an explicit example and one that people may have experienced in real life.

#### *6. Spaceship example (item 13)*

Another special case involving an accelerating situation that is commonly discussed is that of astronauts in an orbiting spaceship. It has physics similarities to the case of an elevator where the cable breaks so that it is in *free fall* under the influence of gravity, except that the space ship also has transverse orbital motion. Tural, Akdeniz, and Alev [38] argue that students have problems in conceptualizing orbital “free fall” in that they do not recognize an orbiting spaceship to be in free fall, which is not surprising since using this term clearly has semantic issues. The word “fall” has the common implication of falling downwards (closer toward Earth), and appropriation of the term to orbiting situations is probably not particularly helpful. A related result is given by Galili and Lehavi [37], who reported students' difficulties in recognizing that both the moon and Earth are in free fall with respect to each other, in agreement with findings by DiSessa [67]. We found that 40% of sample textbooks treated the spaceship problem with a discussion of orbital free fall as it relates to dropping free fall (Tables II and IV, item 13). For example, Cassidy, Holton, and Rutherford [68] argued

> *But astronauts orbiting the Earth seem to be weightless, floating in their spaceship. Does this mean that they are beyond the Earth's pull of gravity and therefore really weightless? The answer is NO they are still being pulled by gravity, so they do have weight. But they cannot experience this weight because, while they orbit the Earth or the Moon, they are in free fall! (We will come to explain this curious phenomenon in Section 3.11) (p. 139).*

Some textbooks treated this item without noting possible student conceptual difficulties with orbital motion, or only by saying that astronauts are in free fall; e.g., Hewitt [50] says "astronauts in orbit are in a state of continual free fall" (p. 166). Others did not mention this at all (e.g., Ref. [63]), although some clarified the situation in another section of the book. Most textbooks extended the discussions of free fall in an elevator to the spaceship case, and then made the required clarifications of orbital motion, though not all mentioned the general idea of accelerations and weight. While some textbooks explained weightlessness by stating that both astronauts and spacecraft are in continual free fall [49], others [52] reasoned that both astronauts and spacecraft are in (nearly) circular motion. The first reasoning is an extension of the elevator case, while the second may pose its own conceptual difficulties if not clarified, since not all objects in circular motion experience weightlessness. For example, a person in a car going in a circle cannot be weightless although they might be moving in circular motion with the car. Some textbooks (e.g., Ref. [69]) employed both types of reasoning (i.e., astronauts are in free fall and that they are moving in orbital motion with the spaceship). Twenty-five percent of the textbooks omitted the spaceship situation.

### *7. Artificial gravity (item 14)*

Another rather different accelerating case relevant to the discussion of weight is that of a space station rotating to provide artificial gravity. The underlying physics of this situation is the same as for the other accelerating cases considered, but the two space cases differ in that, for the orbiting astronaut, we say that gravity constitutes the centripetal force, while in the rotating space station the normal force by the inner wall provides the centripetal force. (We note as an aside that use of the term *centripetal force* itself can lead to conceptual difficulties if students think it is a special type of force like gravitational force or electric force). The physics of artificial gravity is interesting in that it explains how a person who would otherwise be weightless in space may experience *gravitationlike effects* if the space station is spinning. Nine out of the twenty textbooks devoted adequate attention to this item, with relevant diagrams (Tables II and IV, item 14). Such textbooks tied the physics of artificial gravity to the notion of weight. For example, Cutnell [64] says "The normal force applied to the astronaut's feet by the floor is the centripetal force and has magnitude equal to the astronaut's earth-weight" (p. 149). Several textbooks left the discussion as an exercise or problem or omitted it (Table II).

### *8. Effect of Earth's rotation on weight (item 15)*

The final notable case of an accelerating situation is the rotating Earth. Only six of the twenty textbooks fully treated this aspect using physics concepts like centripetal force (Table II, item 15). Several textbooks did not compare and contrast gravitational and scale forces on an object taking Earth's rotation into consideration. Yet this case provides a good distinction between the actual measured value of the acceleration due to gravity on Earth and the value that is obtained theoretically from the universal law of gravitation, where rotation is not taken into account, and can highlight the scale force construct, often called apparent weight. In their discussion of a crate on a scale at the equator, Halliday, Resnick, and Walker [52] treat this aspect clearly and note that "the measured weight is less than the magnitude of the gravitational force on the crate, because of the Earth's rotation" (p. 336). This is done with the application of Newton's second law to the circular motion involved. The discussion (p. 336) also provides a distinction between free fall acceleration due to gravity ($g$), gravitational acceleration ($a_g$), and centripetal acceleration ($\omega^2 R$), namely $g = a_g - \omega^2 R$, for the illustrative case of an object on the equator, where $\omega$ is the Earth's angular speed and $R$ is the approximate radius of the earth. The situation is more complicated at other latitudes but centripetal acceleration is greatest on the equator [51,52]. This explains the latitude dependency of the effect of Earth's rotation on scale contact force. The distinction between free fall acceleration and measured "acceleration due to gravity" has also been suggested by Bartlett [19] as a way of better conceptualizing weight on a rotating Earth. Several textbooks simply mentioned the effect, some left it as an exercise and others omitted it.

## C. Sequencing

Topic sequencing in textbooks sometimes affected the way weight was introduced and treated. Circular motion and centripetal acceleration may or may not be in the same chapter as discussion of weight in the orbiting spaceship case, for example, and chapter orders varied somewhat.

In static situations the potential for confusion about weight is less, since both gravitational and scale force definitions, though conceptually different, give the same value for weight, and are not directly at odds with everyday usage. However, if the two physical constructs and terminology issues are avoided at this stage for "simplicity," then the issues only surface again later in the more general accelerating cases. Further, discussing weight in multiple cases can potentially strengthen student understanding of all the concepts involved. Several [4–6] stress the need to employ multiple diverse instances to reinforce both conceptual understanding and word usage.

## VII. CONCLUSIONS

Our study indicates that introductory physics textbooks differ in how they conceptualize, define, and describe weight, and in whether they help students appreciate and understand the distinct ways in which the polysemous term "weight" is used by physicists. The most prevalent definition in textbooks is that weight is the gravitational force on an object by Earth. The scale force definition of weight was relatively rare (about 20%) in our sample, despite cogent arguments for it by advocates. These findings pertaining to textbook definitions of weight are similar to previous studies (i.e., Refs. [37,38]). Other possible definitions were less often found: the net gravitational force, and the ISO definition of weight. As noted, it is useful to categorize these definitions as either gravitational or operational, similar to Galili [15]. The first category includes the gravitational force on an object by Earth or by another planet or moon, or the net gravitational force, or the magnitude of the gravitational force. Both the scale force and the ISO definition may be considered operational definitions. About half of the textbook sample treated the ideas behind the weight concept before introducing the name, a strategy known to be more effective for student learning of concepts [7,8]. Others gave a name and definition first. Regarding terminology, we encountered a variety of practices, usually in a somewhat forced semantic effort to differentiate the two major physical constructs associated with the term weight in accelerating situations where the gravitational and scale forces are not of equal magnitude. While the gravitational force was mostly called weight, we found the idea of scale force labeled in various descriptive ways, including weight, apparent weight, effective weight, and sometimes no special name.

Varied terminologies were also encountered in the description of free fall situations, e.g., weightlessness and apparent weightlessness. in line with results from a study by Galili and Lehavi [37]. We rarely encountered discussions of the status of free fall in relation to reference frames, most probably because textbooks did not employ the ISO definition of weight, which makes weightlessness in a spaceship frame dependent. Semantic ambiguities were found *across* textbooks, with the same term weight attached to different physical constructs, and surprisingly the problem was also observed *within* some textbooks, as semantic and conceptual issues became confused. Half of the textbooks studied were found to be inconsistent in how they used the term weight. Only one textbook explicitly acknowledged the language issues associated with the term weight by discussing both possible usages. Most textbooks simply presented their own approach to weight without mentioning the alternatives or the semantic issues. They then tried to deal with semantic and conceptual confusions by attaching various adjectives to the term weight, such as true or real (gravitational), and apparent or effective (scale), and they struggled to explain the conceptual and semantic status of weightlessness. It was interesting that textbooks using the operational definition usually said why, while those using the gravitational definition usually defined it without much discussion.

Our analysis of how textbooks treat weight conceptually indicated several inadequacies. In terms of the distinction between weight and mass, most textbooks carefully addressed student difficulties in differentiating the two, usually by contrasting their properties. Nevertheless, books did not often explicitly state that weight is not an intrinsic property of an object. Only half of the textbooks in the sample treated the weight concept adequately in buoyancy situations. Several textbooks did not mention the fact that scale force as measured on Earth is affected by Earth's rotation. Most textbooks introduced the term weight only with reference to nonaccelerating situations (e.g., an object at rest on the ground). Discussions of weight-related physics concepts and semantic issues for accelerating objects were meager or absent in many textbooks, despite the fact that student conceptual difficulties are known to be prevalent for such situations [23,24]. The elevator example was sometimes treated fairly satisfactorily, but treatments of the orbiting spaceship and the issue of weightlessness were generally less than satisfactory and sometimes exacerbated conceptual and semantic confusions rather than clarifying. Textbooks tended to relate the free fall case for an elevator to the space ship situation, but using the phrase free fall in the orbiting situation risked more confusion. Both the words free and fall, when used in the orbiting case, can be seen as somewhat misleading misnomers, probably hindering learning more than helping. This suggests that the conceptual and language issue around free fall should be explicated fully, or perhaps the term could be used sparingly if at all.

## VIII. IMPLICATIONS FOR INSTRUCTION

The broader goal, beyond concept definition, is surely conceptual understanding of all the physics principles involved and the ability to apply them in various situations. This suggests an instructional approach that emphasizes ideas first before scientific terminology, especially for terms that pose language difficulties [25], plus explicit discussion of terminology issues. This approach may also help students learn to interpret the words in context. Thus teaching the two weight-related constructs as "partner concepts" in all these situations and tackling the related naming issues head-on is a way to minimize confusion and achieve the desired broad conceptual understanding, along with an appreciation for language as it relates to learning.

Most existing work has argued in favor of either one or the other definition of weight as the correct or best definition, suggesting that this be prescribed in instruction in the hopes of eliminating confusion. Textbooks likewise adopt one or the other definition, and introduce various adjectives such as true and apparent for describing accelerating situations. However, our view is that the issue is not likely be resolved this way; it is ultimately not an issue of physics but of language and usage. Indeed, two perfectly good physical constructs have been given the same name weight, so that the term is polysemous even among scientists.

Understanding how the conceptual and language difficulties arise and manifest themselves should enable one to design an instructional approach that recognizes the issues explicitly, instead of trying (possibly in vain) to decide and prescribe one or the other. It may have some effect, but agreement is not likely to happen any time soon. It is best to recognize that as long as two important constructs go by the same name, there are bound to be terminological issues and confusions, and that scientists and students alike will need to be aware of this and infer meaning from the context of usage. This is unfortunate perhaps for a scientific term, but contextual interpretation is a characteristic of much of language. Thus scientists, teachers, and students all have to be aware of and work with, rather than against, the polysemous nature of weight and weightlessness. Indeed, since intriguing issues such as weightlessness in orbital motion have the potential to promote understanding of physics principles [11,36] ignoring or avoiding complexities associated with weight are not advisable. One can certainly teach one's own students one way only, but they will encounter it the other way elsewhere, and should be prepared for it. All this trouble is stirred up by a term, which scientifically speaking is not even essential in describing the physical phenomena; the physical constructs are clear enough without it. Given that understanding can ultimately only be in terms of the physical picture, we focus on that from the start. Nevertheless, although we ourselves prefer not to use the term weight at all in initial teaching, it is virtually impossible to avoid it thereafter, nor should we of course. Based on our knowledge of the arguments for and against each definition, we make clear our strong preference for the operational definition, in line with Galili, when we do use the term. This is despite the fact that a majority of textbooks use the gravitational definition, which we argue leads to more confusion and the semantic gymnastics of introducing modifying words in various situations. We also note that the operational meaning of weight corresponds nicely to the everyday experiential notion from which the term originally arose, that of perceived heaviness. There was no need to appropriate the existing word weight as a name for gravitational force, and that has led to all the trouble. Furthermore, when intuitive and scientific ideas are at odds with each other, misunderstandings and misconceptions are likely. Thus although we understand both options, we are far from being complete relativists on the issue.

To summarize our instructional ideas, our approach is to first introduce the two physical constructs, each of which is clear and unambiguous, and refer to them simply as gravitational force and scale force. Then we discuss each of them and their relationship in various nonaccelerating and accelerating cases, as a firm basis for clarifying and learning the physics involved in such situations. The term weight and the conceptual and language issues associated with it can preferably be brought in after the physics treatment.

A more radical solution to the difficulties might be to eschew the word weight altogether, at least in instruction. There is merit to this suggestion since the name is not essential and we could, in principle, do without it since the physics can be discussed without the term. However, the reality is that the word is ingrained in both scientific and everyday usage. Nevertheless, in support of elimination, we point out that if we are actually going to do the physics for a given case of motion, we do not worry about the term weight one way or the other; we identify the specific forces acting for that motion. That being the case, it is not clear why we would want to subject students to terminological convolutions that are not going to go anywhere. Furthermore, in support of elimination, one could note that besides the polysemous nature of the term, the way it is used grammatically in sentences may actually engender misconceptions. We talk of "the weight *of* an object," falsely implying that weight is an intrinsic property *of* the object. The grammatical structure misleads us into thinking of weight as something that the object *has*, rather than being an interaction force with another object, usually Earth. By contrast, for the concept of *mass*, when we say "the mass of an object," the grammatical structure fits the nature of the concept, suggesting a correct sense of mass as an attribute of the object. It would not be surprising if the grammatical similarity in the two cases may suggest to students that weight and mass are ontologically of the same kind, although they are not, and the shared grammatical structure may also contribute to the common confusion between weight and mass. The ways that we name, talk, and write about things tends to shape how we think about them. Thus, in our preferred approach we recognize the polysemous nature of weight-related terminology and convey this explicitly, aiming at the root of the confusion, at the same time enlightening students about language and science. This can only stand them in good stead in the future. Note that similar language and conceptual difficulties arise for the term heat, which has multiple usages, both scientific and everyday, and is polysemous as both a noun and a verb.

Recapitulating, the important feature of our preferred approach is to talk about the physics first, and about names and definitions afterwards. When we do talk about weight we make clear our preference for the operational meaning but also tell students that they will find more textbooks using the gravitational. The physics textbooks in our sample do not adopt the approach we advocate, but define weight as either one or the other of the two constructs, and introduce various qualifying adjectives to distinguish meanings in various situations. Hardly any textbooks address the language issue explicitly or sufficiently. Paraphrasing Braithwaite's earlier quote (1932), we tend to become prisoners of the words we invent ourselves [27]. One simple escape measure would be to talk wherever possible about gravitational force and scale force, freeing us to focus on physics fundamentals.

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