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Textbook Presentation of Circular Motion Dynamics: Centrifugal Force Controversy & Implications for Teaching

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ABSTRACT

To explain experiences of riders of rotating systems, such as a merry-go-round, some physics educators have employed the concept of 'centrifugal force.' However, others have suggested that the term is unnecessary in explaining experiences in rotating systems and that it encourages misconceptions surrounding circular motion dynamics. Owing to this tension, this project employs Gestalt theory and content analysis to explore whether introductory and general physics textbooks employ or mention the term centrifugal force in their discussion of experiences of objects within rotating systems. The project also explored related ideas such as (1) whether textbooks discuss real vs. fictitious forces, and (2) whether or not textbooks remind students when to use Newton's Laws of motion. Twenty textbooks were analyzed, and the results were tabulated. Findings of this project indicate that about half of the textbooks analyzed did not use or mention the term centrifugal force when discussing the physical perceptions of humans in rotating systems. Thirty-five percent of the textbooks examined discussed real vs. pseudo forces clearly. About half of the textbooks did not remind students that Newton's laws are valid only for inertial observers when discussing physical perceptions in non-rotating systems. About twenty-five percent of the textbooks modified, or said that there is a way to modify, Newton's second law to be applicable in a non-inertial frame of reference. Ten percent of the textbooks explicitly warned or suggested that students not to use the term 'centrifugal force'. The results of this study, coupled with the study's theoretical lens and our teaching philosophy led us to propose an approach to teaching circular motion dynamics that explicitly acknowledges (1) the controversy rather than shunning away from it, (2) the perceptions within rotating frames, and (3) the interdisciplinary use the concept of centrifugal force.

Keywords: Centrifugal Force, Fictitious Forces, Circular Motion Dynamics, Physics Education, Textbook Analysis

Introduction

The phrase "centripetal and centrifugal forces" appears in several academic circles as a metaphor (e.g., Graham et al., 2017; Krzysztofik, 2016) to imply cause vs. effect or connectedness/unitary vs. decentralization, the tension between competing views, or dichotomous views of a concept or some philosophical position. Several academics have used the metaphor as a framework to shape their studies. The term centrifugal force was coined by the famous Dutch physicist, Christiaan Huygens (1629–1695), while the term "centrifugal force" was coined by Sir Isaac Newton (1642–1727) to understand dynamics of circular motion (Roche, 2001). In classical mechanics, centripetal force is the net force that acts on an object undergoing circular motion while centrifugal force is a force that appears to act on all objects when viewed in a rotating frame of reference. It is directed radially outward from the circular path. The concept of centrifugal force can be applied in rotating devices/systems, such as merry-go-rounds, centrifuges, and banked curves, when they are analyzed in rotating reference frames. Considering the two perspectives of circular motion dynamics (inertial vs. non-inertial) and the associated student misconceptions, this study investigates how introductory and general physics textbooks present circular motion dynamics.

Students face a lot of challenges in understanding the dynamics of circular motion. One of the difficulties relates to the inclusion of centrifugal force in force diagrams when solving dynamics problems for inertial observers. This is arguably because students have firsthand physical experiences of what it is like to be in circular motion. Applying Newton's Second law requires one to be able to accurately identify all forces acting on an object so that they can, in turn, determine the net force, which can then be used to find the acceleration of an object. Any mistake in force diagrams leads to incorrect solutions. Centrifugal force is a term often used in physics to describe the apparent force that acts on an object moving in a circular path. It is not a *real* force in the sense that it doesn't originate from an interaction between two objects but rather is an inertial force that arises from the object's tendency to move in a straight line (Küchemann et al., 2020). Centrifugal force can be observed in various everyday situations. For instance, when driving around a curve in a car, one feels being pushed to the side of the car away from the center of the curve. Similarly, when a person (who is in an inertial frame of reference) spins a bucket of water in a circular motion, the water stays inside the bucket due to the centripetal force acting on it (and an object's tendency to move in a straight line), but to an observer on the spinning bucket, it appears as if there's a force pushing the water outward (centrifugal force).

Kirkpatrick and Francis (2010) argue that "the word centripetal is rarely used in our everyday language. The word centrifugal is much more common and often mistakenly substituted for centripetal" (p. 60). Likewise, Fishbane et. al. (1993) stated that "the use of the notion of centrifugal force is commonplace" (p. 149). Physicists (e.g., Küchemann et al., 2020) argue that the reason centrifugal force and similar forces are called *fictitious forces* is because Newton's third law of motion (action and reaction) does not hold for them. Thus, centripetal force and centrifugal forces are not the result of an interaction between two bodies but the consequence of the motion of the rotating frame of reference. On the other hand, *inertial forces*, are called so because the forces are caused by the inertia of the moving object. It has been argued that real forces are *accelerating forces* while inertial forces "restrict the growth of the acceleration, balancing the action of the accelerating forces at a strictly definite acceleration" (Emelyanov, 2015, p. 52).

Problem Statement

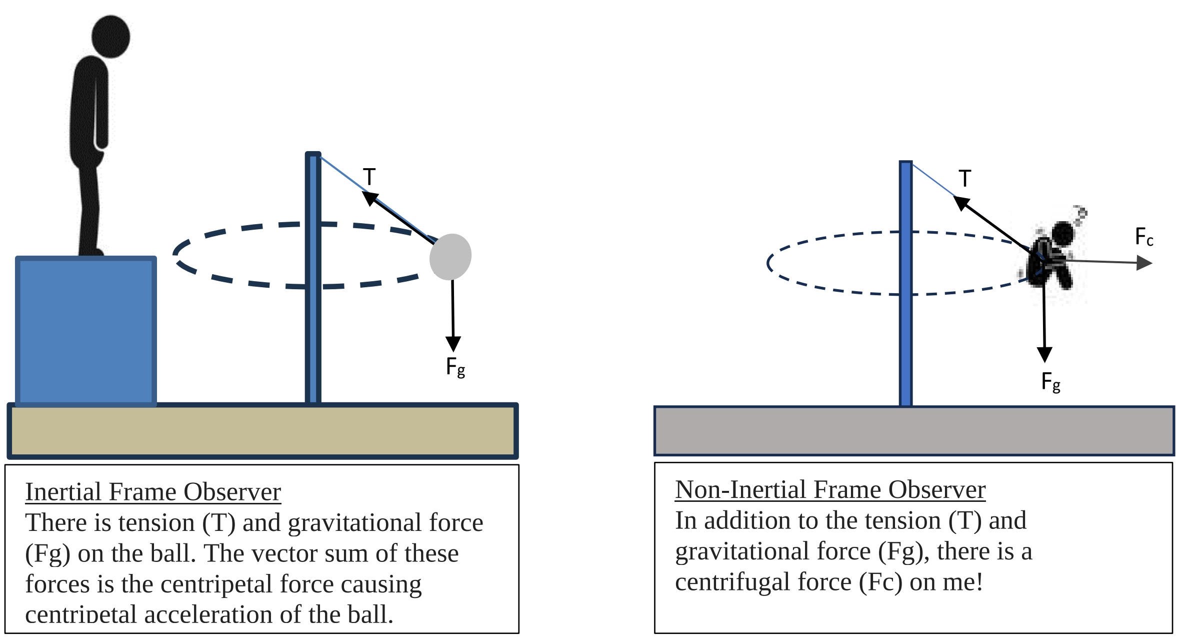
Physics teachers/faculty have a role in selecting books that thoroughly deal with controversial concepts such as the centrifugal force. Textbook analysis is a good method to critically analyze these books. Therefore, in the current project, we conducted a textbook analysis to investigate how textbooks present circular motion dynamics considering the highly controversial centrifugal force idea. The above section indicates that students continue to have difficulties in dealing with circular motion dynamics and that physics educators do not quite agree on how to present circular motion dynamics considering the common misconception regarding centrifugal force. Therefore, this study built on the study by Hahn et al. (2010) regarding textbook analysis of the issue. However, our emphasis will be on physics textbooks only unlike the other study which looked at Earth Science textbooks in addition to physics textbooks. The current paper not only asked whether centrifugal force is employed in circular motion dynamics, but it also explored i) approaches that textbooks employ to dislodge the centrifugal force misconception for inertial frame observers, and ii) whether textbooks discuss real versus fictitious forces. This study answers the research question: Considering the two perspectives of circular motion dynamics (inertial vs. non-inertial) and the associated student misconceptions, how do textbooks present circular motion dynamics?

Theoretical and Conceptual Framework

The theoretical and conceptual frameworks of this study delve into the intricate dynamics of circular motion, as described above. We examine two contrasting perspectives: one from an inertial observer's standpoint and the other from within a rotating system. Both perspectives are crucial for understanding the associated physics. These viewpoints not only highlight the complexities inherent in circular motion but also the influence of the frame of reference on our comprehension of dynamic systems. To unravel these complexities and provide a robust theoretical foundation, we draw upon Gestalt theory, a seminal framework in the psychology of perception (Guberman, 2015). Gestalt theory was selected because it deals with perceptions, moods, cognition, emotions, and complex feelings (Smith, 1988). In the case of perception, Gestalt theory encourages a holistic approach to understanding phenomena (Smith, 1988). In this theory, one's perception can help in the understanding of a complex phenomenon. Therefore, by exploring these theoretical underpinnings, this study aims to illuminate pedagogical approaches that foster a comprehensive understanding of circular motion dynamics. Consider the two diagrams shown in Figure 1. The diagram on the left shows a ball in uniform circular motion.

Figure 1

The Two Perspectives of Uniform Circular Motion Dynamics



Only two forces act on the ball: tension force and gravitational force (from the perspective of an inertial observer). The net force points towards the center of the circle (i.e., the horizontal component of tension force). The vertical component of tension force balances the gravitational force.

The tension force in the horizontal direction provides the centripetal force. The observer is watching from an inertial frame, and they say that the ball is accelerating. From this inertial frame perspective, it is incorrect to say that there is a radially outward force on the ball. It is incorrect because *nothing* is pulling the ball radially outward.

Also, consideration of such a force contradicts the observation (by an inertial observer) that the ball is accelerating. Indeed, from an inertial frame point of view, it is also incorrect to say that there is a radially outward force acting on the ball because it leads to inconsistent results when solving circular motion dynamics problems. A lot of misconception-based research in circular motion dynamics is related to this *centrifugal force* idea (e.g., Mclaughlin, 2006; Pendrill, 2020). A real force such as a push on a wagon involves one object (a hand) interacting with another object (wagon). An apple falls to the ground because the Earth pulls it downward. We cannot make the same case with centrifugal force, which bears several other names such inertial force, fictitious force, and pseudo force among others.

For the diagram on the right, the observer is right in the rotating system. Let's assume that this observer is not able to see the ground (the case of being right in the rotating system such as the carousel container or assume that the observer closes their eyes so that they are not distracted by seeing the ground). In this case, the observer's acceleration with respect to the rotating system is zero. The observer says that in addition to the tension and gravitational force, there is also a radially outward force (centrifugal force). The vector sum of the three forces is zero since there is no acceleration. From this non-inertial frame perspective, it is correct to say that there is a radially outward force on the ball (the centrifugal force).

To better help a student understand the above ideas, we apply the Gestalt theory developed in 1912 by Max Wertheimer. Max Wertheimer published a seminal paper entitled "Experimental Studies of the perception of Movement" in 1912 (Wertheimer, 1912); a paper which laid the foundation for Gestalt theory. In his experiment, when two nearby light sources are turned on and off at the proper alternation rate, the distant observer sees a single light moving back and forth providing the illusion of movement. This experiment places the idea of perception in human sensation (Guberman, 2015). Gestalt theory asserts that our perceptions are influenced by several factors such as our own experiences and "a frame of reference with respect to which other objects are perceived" (Rock & Palmer, 1990, p.85). This is a similar case regarding the centrifugal force controversy. The centrifugal force idea is a misconception in one frame of reference but not in another.

The other view in Gestalt theory/psychology is holism (i.e., the whole is greater than the sum of its parts). Gestalt theorists argue that "an individual perceives the whole as a meaningful and organized whole, not through separating the whole into parts" (Çeliköz et al., 2019, p .25). This idea has been interpreted in different ways. In this study, we focused on the fact that students need to have an entire picture (both inertial and non-initial perspectives) of circular motion dynamics to better understand the underlying concepts. Indeed, the psychology behind Gestalt learning theory states that we use our senses and previous experiences to gain knowledge about the world around us (Burns, 1995). While Newton's laws of motion are applicable in inertial frames, as humans we often find ourselves in rotating frames such as those situations at amusement parks. Those experiences shape our thinking and learning. The teaching of circular motion dynamics should place the observer both in inertial and then non-initial frames of reference and let them use their experiences to develop new learning.

Thus, this study analyzed textbooks based on whether they provide a holistic view of circular motion dynamics or not (considering the controversial centrifugal force idea). Using content analysis (Neuendorf, 2002) the use of the terms *centrifugal force*, *real forces*, and *fictitious forces* and example problems relating to circular motion dynamics and textbooks' view of centrifugal force idea will be investigated. This will involve searching relevant terms within the textbook's index and table of contents and investigating presentations of circular motion dynamics in relevant sections of the textbook (Krippendorff, 2004; Stemler, 2001; Weber, 1990). Coding and categorization of data will help answer the research question.

Literature Review

Approaches to Teaching Dynamics of Circular Motion

Teaching for effective understanding involves an integrated consideration of the scientific concepts, awareness of common student misconceptions, and the implementation of effective instructional strategies (Etkina, 2005). Our suggestion is that educators must emphasize the distinction between centripetal force and centrifugal force. Further, to facilitate conceptual clarity, teachers should employ clear definitions, contextual examples, and visual aids. Hands-on activities and interactive simulations can help students visualize and comprehend these forces in action. This is encapsulated by several studies described in this section. First, a study by Aoude (2015) used PHET simulations to teach students uniform circular motion dynamics. Although results indicated a positive impact on students' understanding, the study only focused on inertial frame of reference with no discussion of centrifugal forces.

Addressing misconceptions through formative assessments and discussions is crucial, as is connecting these concepts to broader physics principles and real-world applications. An article by (Pendrill, 2020) analyzed several students' responses to a variety of circular motion dynamics problems, focusing on their force diagrams for various physical situations. This analysis revealed several difficulties students encounter in understanding circular motion dynamics. Pendrill (2020) argues that the diverse examples provided to students effectively highlighted different aspects of their thinking. This author suggests that a collection of these common force diagrams, both correct and incorrect, could help teachers identify student conceptual problems. The varied examples were intended to probe differences in student strategies and clarify their conceptual understanding.

Pendrill (2020) further connects this approach to variation learning theory. This is supported by prominent educators such as Arons(1981), who delves into Pedagogical Content Knowledge (PCK) concerning circular motion dynamics but appears to suggest a different explanation of the physical perceptions in rotating frames that involves Newton's Third Law and not centrifugal force. For instance, Arons (1981) writes:

> In our work on amusement park physics, we try to make students focus on the forces acting on their own bodies as they accelerate in carousels and roller coasters: if they feel like they are pushed into the seat of a carousel, it is because the seat pushes on them—Newton's third law in action! (p. 3)

In some instances, she refers to centrifugal force as a non-existent force without addressing the controversy associated with different perspectives (inertial vs. non-inertial observers). In this article, within the section titled "Implications for Teaching," we further explore the intricacies surrounding the use of Newton's Third Law to explain physical perceptions in rotating systems.

Mclaughlin (2006) advised that the introduction of circular motion should employ a real object, such as a hover puck tied to a string and set into uniform circular motion. Similar to Pendrill (2020), she further recommends encouraging students to draw free body diagrams of objects in circular motion. Mclaughlin (2006) suggested using everyday language at the beginning of discussions on circular motion, introducing technical terms like "centripetal force" only after students have grasped the fundamental physics. When labeling forces in free body diagrams, Mclaughlin (2006) advised making it clear which object is exerting the force on the object in uniform circular motion. For example, the force on the puck by the string should be labeled as (Ft(p, s)). She calls this the "on, by" notation. The author argues that this method helps students understand that there is no outward force (centrifugal force) by highlighting that they cannot identify an object exerting this supposed force. Mclaughlin (2006) also suggested using an accelerometer on a rotating turntable to demonstrate that acceleration in uniform circular motion is directed towards the center.

The above approach (Mclaughlin, 2006) to teaching circular motion is strictly limited to an inertial frame of reference. The author encourages thought-provoking questions and scaffolding throughout the inquiry process. However, it is not clear whether the author encourages or anticipates student questions regarding perspective (rest vs. accelerating perspective). From the article, it is also unclear how an instructor should respond to questions like, "What if the observer is in the rotating system?"

Considering problems associated with the centrifugal force misconception, Savage & Williams (1989) suggested that when solving dynamics problems, it is important, among other things, to follow the Newtonian strategy. This strategy requires that force diagrams should include only Newtonian forces (i.e. forces caused by other bodies), where Newtonian forces are those recognized by "an observer who is at rest asking the question 'which Newtonian forces are acting on the body?" (Savage & Williams, 1989,p. 135). The author further notes that "these Newtonian forces constitute the F in Newton's second law, F = ma, and a is the acceleration seen by the observer" (p 135).

Research on Understanding of the Dynamics of Circular Motion

Circular motion is experienced by people in a lot of instances such as during the circus, children on a merry-go-round, or passengers in vehicles travelling in a curved path. People in these rotating systems report that they feel as if they are being tossed radially outward. There is a great interest in understanding how people (both students and lay people) view circular motion, etc. For example, Volfson et al. (2020) showed adults an activity in which two bowls were filled with water, connected to a rope, and rotated. The observers were asked to explain their observations. Results indicated that only about 2% of the participants provided a correct explanation for why the water stayed in the container when the container was swung. The centrifugal force idea was the most often expressed (~40%), especially among the adult participants. Fifty-six percent of the participants predicted that, when released, the rotating container will fly in a radial direction, outside the circle trajectory of motion, while 5% said that the container will go outside in a diagonal direction. The centrifugal force misconception has been reported among university students in their responses to problems regarding circular motion (Canlas, 2016).

In addition to the centrifugal force misconceptions, misconceptions regarding the kinematics of circular motion have been reported in Canlas's (2016) study. These misconceptions include an object in circular motion does not accelerate, speed and velocity are the same thing, and that there is a force along the tangential velocity for an object in uniform circular motion. Küchemann et al., (2020) tested physics students' understanding of the motion of a rolling sphere on a rotating disc as seen from different frames of reference. Results indicated that the students had significant difficulties in predicting and observing the correct trajectory of a sphere rolling over a rotating disc. Specifically, students had challenges understanding that both the Coriolis force and the centrifugal force are necessary to correctly make sense of the motion of a rolling ball on a rotating disc as viewed by an observer in the non-inertial frame of reference. The study also found that students exemplified a preconception that centrifugal force acts on an object only when the object is fixed to the rotating disc and that centrifugal force, and centripetal forces, are Newton's action-reaction force pairs.

Physics textbooks play a major role in how teachers approach both pedagogy and concepts. A study by Fan and Kaeley (2000) found a relationship between textbook selection and teaching strategies. Another study by Knight (2015) found that educators still believe that textbooks are reliable in providing credible information for teaching. Further, a study by Pavesic and Cankar (2022) found that students who learned using different textbooks acquired different knowledge and attitudes. Therefore, it is important to examine how textbooks present controversial concepts such as centrifugal force. Hahn et al. (2010) examined physics textbooks that were widely used in high schools and colleges in Korea. These researchers asked two questions: i) Is the centrifugal force used in the textbook? and ii) How is the centrifugal force explained? Results of the study indicated that all the high school textbooks mentioned the centrifugal force, whereas 75 % of the college introductory physics textbooks either did not use the term or recommended not using the term.

Methods

Our focus was on introductory and general physics textbooks known to be in fairly wide use over the last two decades. We used a convenience sample (Niaz et al., 2010) of 20 textbooks from the authors' and colleagues' bookshelves as well as OpenStack. We employed content analysis methods to answer the research questions. According to Weber (1990), a key aspect of content analysis is its capacity to condense numerous words from the text into a smaller number of content categories. This technique involves categorizing and coding relevant text data (Stemler, 2001). For example, Taibu et al. (2015) applied content analysis to examine how physics textbooks present the concepts of weight and weightlessness, highlighting the method's flexibility in allowing researchers to focus on content of interest. Additionally, content analysis methods have been used in various other textbook studies (Niaz et al., 2010; Ramos & Ibanez, 2004).

In accordance with the requirements of content analysis methods (Weber, 1990), in this study, the two investigators identified research goals, relevant theories (theoretical framework), previous research, and the texts to be analyzed and classified, developed a coding scheme and applied it to the sampled text material. Initially, the second author's understanding and skills in content analysis were limited, but he improved through inquiring from the first author and reading relevant materials (Krippendorff, 1990, 2004; Neuendorf, 2002; Stemler, 2001; Weber, 1990). When it comes to content analysis, the unit of analysis helps researchers clearly outline the scope of their study, it shapes data collection and interpretation, and ultimately determines the validity and applicability of research findings (Krippendorff, 2004). In this study, the unit of analysis included the following sections of the book: (1) sections that discussed centrifugal force and centripetal force, and (2) sections that discussed inertial and non-inertial frames of reference within classical mechanics. These sections were chosen because they are the most likely places to peruse if one wanted to learn more about circular motion dynamics. We used the index and table of contents to get to the targeted sections of the book.

We utilized the following procedure to create a coding scheme for textbook presentations of circular motion dynamics and related concepts: The two authors discussed issues surrounding the centrifugal force in the context of circular motion dynamics and explored several textbooks to understand how the subject of circular motion dynamics is presented. This initial exploration revealed a variety of approaches: some textbooks use the term centrifugal force, while others do not. Additionally, some textbooks discussed circular motion dynamics exclusively from the perspective of inertial frame observers, while others included both inertial and non-inertial perspectives. Furthermore, some textbooks addressed common student misconceptions related to circular motion dynamics, whereas others did not. These observations helped refine the research question, leading to the following: Considering the two perspectives of circular motion dynamics (inertial vs. non-inertial) and the associated student misconceptions, how do textbooks present circular motion dynamics?

With the research question in mind, the first author conducted an exploration of ten textbooks to come up with a coding scheme. During this process, he took relevant notes and quotes for each book based on the research questions. These notes were shared with the second author for further discussion, which led to the improvement of the coding scheme. Later, each author employed the coding scheme to analyze a sample of five textbooks (representing 20% of the sample textbooks). The choice of a 20% subsample size was in agreement with social science research methods (Wimmer & Dominick, 1994). There was 90% interrater reliability, with minor differences arising from issues such as varying interpretations of item descriptions. For instance, initially, we had an item: "The textbook modifies Newton's second law to be applicable in non-inertial frames of reference." We then realized that some textbooks do not actually modify Newton's second law but merely state that it can be modified. Also, there were some scenarios where categorization was unclear. For example, gauging whether a textbook distinguishes real vs. fictitious forces was unclear in some instances, such as situations where the book does not explicitly mention fictitious force or apparent force or non-inertial forces but instead mentions about real forces. Such cases were coded as unclear This realization led to the refinement of the items and resolution of differences in categorization. leading to Table 1 as a final coding scheme. Table 2 lists textbooks along with their respective categories for each item. Table 3 presents notable quotes for selected items in the coding scheme.

Table 1

Overall Results of the Textbook Analysis (Items 1 through 5 Relate to the Research Question)

Item	Item Description	Classification/ Observables	# of Books
1	The term 'centrifugal force' is available in the index/table of contents and the idea is discussed/mentioned within the book.	A. Yes	11
		B. No	8
		C. Unclear	1
2	Within circular motion/centripetal force discussions, the textbook distinguishes real vs. fictitious forces.	A. Yes	7
		B. No	9
		A. Unclear	4
3	Within circular motion/centripetal force discussions, the textbook mentions that Newton's laws of motion are valid only for inertial observers.	A. Yes	9
		B. No	10
		C. Unclear	1
4	The textbook modifies or says there is a way to modify Newton's second law to be applicable in non-inertial frame of reference.	A. Yes	4
		B. No	14
		C. Unclear	2
5	Within circular motion/centripetal force discussions, the textbook frames at least one circular motion dynamics example problem in a way that explicitly specifies the frame of reference of the observer	A. Yes	3
		B. No	17
		C. Unclear	0
6	Within circular motion/centripetal force discussions, the textbook discusses physical perceptions in rotated bodies.	A. Yes	15
		B. No	2
		C. Unclear	3
7	The textbook warns not to use the term 'centrifugal force'.	A. Yes	2
		B. No	18
		C. Unclear	0

Table 2

Textbook Classification

	Research Question/Category						
Textbook	1	2	3	4	5	6	7
1. (Coletta, 2010).	A	A	A	A	A	A	B
2. (Cutnell & Johnson, 1998).	B	B	B	B	B	C	B
3. (Fishbane et al., 1993).	A	A	C	C	B	A	B
4. (Giambattista, 2020).	B	B	A	B	B	C	B
5. (Giancoli, 2014).	A	C	B	B	B	A	B
6. (Griffith & Brosing, 2015).	A	A	A	A	B	A	B
7. (Hecht et al. 1996).	B	B	B	B	B	A	B

Textbook	Research Question/Category						
	1	2	3	4	5	6	7
8. (Hewitt, 2015).	A	A	A	B	A	A	B
9. (Hobson, 2007).	B	B	B	B	B	B	B
10. (Jones & Childers, 1999).	C	C	B	B	B	A	B
11. (Kirkpatrick & Francis, 2010).	A	A	A	C	B	A	B
12. (Knight et al., 2013).	A	C	B	B	B	A	B
13. (Krauskopf & Beiser, 2020).	B	B	B	B	B	B	B
14. (Rex & Wolfson, 2010).	B	B	A	B	B	C	B
15. (Serway & Jewett, 2010).	A	A	A	A	A	A	B
16. (Serway & Faughn, 1999).	A	C	B	B	B	A	A
17. (Trefil & Hazen, 2004).	B	B	B	B	B	A	B
18. (Urone & Hinrichs, 2022).	A	A	A	A	B	A	B
19. (Walker et al., 2014).	B	B	B	B	B	A	B
20. (Young & Freedman, 2020).	A	B	A	B	B	A	A

Table 3

Notable Quotes

Item Description	Exemplar Quote (s) Textbook, & Page Number	Percent
The term centrifugal force is available in the index/table of contents and the idea is discussed or mentioned within the book.	*"to observers who are in rotating system, centrifugal force feels like, and is interpreted to be, a very real force"* (Hewitt, 2015, p. 160).	55%
Within circular motion/frames of reference/centripetal force discussions, the textbook distinguishes real vs. fictitious forces.	*"Real forces are those that have some physical origin, such as the gravitational pull. Contrastingly, fictitious forces are those that arise simply because an observer is in an accelerating frame of reference, such as one that rotates (like a merry-go-round) or undergoes linear acceleration (like a car slowing down*)"(Urone & Hinrichs, 2022, p. 169).	35%
Within circular motion/centripetal force discussions, the textbook mentions that Newton's laws are valid only for inertial observers.	*"In Chapter 4 we formulated Newton's laws of motion and found that they, as well as other laws of physics, are valid only in inertial reference frames"* (Coletta, 2010, p. 147).	45%
The textbook modifies or says there is a way to modify Newton's second law to be applicable in non-inertial frame of reference.	*"If we want to apply Newton's Second Law in these situations, we have to modify the law by adding imaginary or inertial forces that arise as a result of the acceleration of the frame of reference"* (Griffith 2015, p. 440).	20%
Within circular motion/centripetal force discussions, the textbook frames at least one circular motion dynamics example problem in a way that explicitly specifies the frame of reference of the observer.	*"A car rounds a curve of radius 100 m at the speed of 20.0 m/s as viewed from the car, what are the real forces and pseudo forces acting on the 80.0 kg driver, who is stationary relative to the car?"* (Coletta, 2010, p. 149).	15%
Within circular motion/centripetal force discussions, the textbook discusses physical perceptions in rotated bodies.	*"Inside the non-inertial frame of the car rounding the curve, the driver may actually believe she experiences an outward force that pushes her against the car door. In reality, however, it is the car seat and door that press inward on the driver, causing her to move in a circular path"* (Jones & Childers, 1999, p. 154).	75%
The textbook warns not to use the term centrifugal force	*In an inertial frame of reference there is no such thing as "centrifugal force". We won't mention this term again, and we strongly advise you to avoid it" (Young & Freedman, 2020, p. 150).*	10%

Item Description	Exemplar Quote (s) Textbook, & Page Number	Percent
	"This is sometimes called the centrifugal force, but that term often creates confusion, so it is not used in this book" (Serway & Faughn, 1999, p. 262).	

Results

Item 1: Use of the Term "Centrifugal Force"

Eleven out of 20 textbooks employed or mentioned the term centrifugal force within circular motion dynamics sections of the book. For example, Jones and Childers (1999) write "the words centripetal and centrifugal were used in their present-day context in the Principia" (p. 155).

Item 2: Discussion of Real vs. Fictitious Forces

Seven out of the 20 textbooks discussed real vs. pseudo forces clearly. Twenty percent of the textbooks seemed to have discussed real vs. pseudo forces but it was unclear. Thus, close to half of the textbook did not discuss the difference between real vs. fictitious forces.

Item 3: Validity of Newton's Laws of Motion

Oftentimes, textbooks remind students of the validity of Newton's Laws when these laws are introduced for the first time. This study was interested in seeing the percentage of textbooks that remind students that Newton's laws are applicable for observers in an inertial frame of reference when discussing circular motion dynamics. About 50% of the textbooks reminded readers of the applicability of Newton's laws of motion. Interestingly, those that reminded students had differences in the way they presented this idea. Some textbooks said Newton's laws are applicable in inertial frames, while others pinpointed only the third law being applicable in inertial frames. Yet others indicated that it is only the first law that is applicable in inertial frames.

Item 4: Modification of Newton's Second Law

Owing to the debate regarding the scope of introductory and general physics courses, this project sought to explore the percentage of textbooks that attempt or say there is a way to modify the second law to be applicable in non-inertial frames of reference. Only 20% of the textbooks fell in this category, indicating that most authors either feel it is unnecessary or beyond the scope of the books to discuss Newton's second law for observers in rotating frames of reference.

Item 5: Example Problem that Explicitly Specifies the Frame of Reference of the Observer.

This project was interested in the framing of questions within circular motion dynamics. If Newton's laws of motion are applicable for observers in inertial frames of reference, shouldn't the problems be framed in a way that helps students know the frame of reference of the observer? Interestingly, only 15% of the textbooks had an example that specified the frame of reference of the observer (see Table 3 for an exemplar quote). It appears that, if the frame of reference is not specified, readers are supposed to assume an inertial frame of reference. In the discussion section, we will argue that saying that students have a centrifugal force misconception without asking their placement of the observer is problematic.

Item 6: Physical Perceptions in Rotated Bodies.

Seventy-five percent of the textbooks clearly discussed the physical perceptions of objects or humans in rotating vehicles, using various examples such as a passenger in a car rounding a curve, artificial gravity scenarios, and amusement park experiences. Although about half of the textbooks did not use the terms "centrifugal force" or "apparent force," they still explained these physical perceptions in their own preferred ways. For instance, one explanation without using the term centrifugal force is: "The passenger feels as if she is being thrown toward the outside of the car, but that is due to her inertia resisting the force pushing her toward the inside" (Trefil & Hazen, 2004, p. 104). Conversely, an example that employs the concept of centrifugal force states: "The car represents a noninertial reference frame that has a centripetal acceleration toward the center of its circular path. As a result, the passenger feels an apparent force which is outward from the center of the circular path" (Serway & Jewett, 2010, p. 148). Although we did not include the textbook by Serway et al. (2006) in our content analysis, it provides an interesting definition of centrifugal force and describes physical perceptions in rotating frames: "A so-called centrifugal force is most often just the absence of an adequate centripetal force arising from measuring phenomena from a non-inertial (accelerating) frame of reference such as a merry-go-round" (Serway et al., 2006, p. 206).

Item 7: Warning on Use of 'Centrifugal Force'

Ten percent of the textbooks warned not to use the term although they described the concept briefly. "In an inertial frame of reference there is no such thing as centrifugal force. We won't mention this term again, and we strongly advise you to avoid it" (Young & Freedma, 2020, p. 150); "This is sometimes called the centrifugal force, but that term often creates confusion, so it is not used in this book"(Serway & Faughn, 1999, p. 262). These quotes indicate a strong desire for these authors to get rid of the term centrifugal force in physics vocabulary although it is often used in other STEM fields (see the discussion and conclusion sections). Tables 1 and 2 show the overall results of the textbook analysis while Table 3 shares some notable quotes from the textbook analysis.

Discussion

The results of this textbook analysis indicate a wide disagreement among experts regarding how to treat circular motion dynamics. Amid this disagreement, one is left with no choice but to pick a side and present the relevant physics to students. However, picking a side comes with being well-informed about the subject matter itself, and knowing the kind of students we teach and their aspirations (majors and non-majors, engineers to be, or earth-scientists to be, etc.). In this section, we will discuss the results of this study considering all these aspects.

This study has shown that about half of the textbooks prefer not to use centrifugal force in their discussion of circular motion dynamics. Amongst the textbooks that used the term, some warned that this is a confusing concept/term and should not be used (e.g., Young & Freedman, 2020), while others (e.g., Hewitt, 2015) adopted the concept wholeheartedly. One would think that the textbooks that adopt centrifugal force should be the more advanced ones such as Young and Freedman (2020) (University Physics), but we see here that a conceptual textbook by Hewitt (2015) delved into the concept without the use of mathematics. Thus, the choice of whether to teach or not to teach centrifugal force is not based on the level of the course.

This study found that close to half of the textbooks did not discuss the difference between real vs. fictitious forces, and only about 50% of the textbooks reminded readers on the applicability of Newton's laws of motion. This is even though as humans; we find ourselves not only in inertial frames but also in non-inertial frames of reference such as linearly accelerating vehicles and rotating vehicles such as a merry-go-round. The study found that only 20% of the textbooks attempted or mentioned that there is a way to modify Newton's second law to be applicable in non-inertial frames of reference. Further, only 15% of the textbooks had a teaching problem/example that specified the frame of reference of the observer. We argue here that saying that students have a centrifugal force misconception without asking their placement of the observer is problematic. The observation that most physics textbooks usually indicate the applicability of Newton's laws, only when introducing these laws, without reminding students of this important point when dealing with circular motion dynamics is a cause for concern.

The presentation of classical mechanics usually is divided into kinematics and dynamics. When discussing kinematics, we discuss terms such as speed and acceleration. Students are told that these quantities are measured relative to an approximately inertial frame. Similarly, Newton's laws are valid for inertial observers. We argue here that textbooks need to keep reminding students that Newton's laws of motion are valid when the observer is making observations while in an inertial frame of reference. This also goes to the way physics educators share teaching/example problems; students may interpret questions with reference to an observer in non-inertial situations when what we want is for them to respond based on an observer in the inertial frame of reference. Giancoli (2014) observed that "there is a common misconception that an object moving in a circle has an outward force acting on it, a so-called centrifugal (center-fleeing) force. This is incorrect: *there is no outward force* on the revolving object" (p. 113). Arguably this could be the right time to explicitly remind students about the applicability of Newton's laws of Motion.

Implicitly, some textbooks, even those that shun the term centrifugal force, are careful when they explain circular motion kinematics and dynamics in terms of properly placing the observer. For the common example in which a mass is swung in circular motion on the end of a string and then one cuts the string, for one to conclude that the mass flies off tangentially (immediately after escaping the circular path), and not radially outward, they must observe the motion in an inertial frame. For this reason, the latter example is usually represented with the aid of a diagram, but then most authors are *very careful* to state that the observer is in the inertial frame of reference. Often, textbooks state "as viewed from above" or "looking down from above" (Giancoli, 2014, p. 113). One of the questions on the famous Force Concept Inventory (Hake, 1998) relates to the latter and the developers of the question also were careful to mention that the motion needs be interpreted in an inertial frame. At this point, students have a legitimate question to ask What about as viewed from the rotating frame? If a textbook shuns away from the idea of centrifugal force, then what's next? We believe that the explanation of the principle of operation of a centrifuge machine, engineering designs, and the explanation of the movement of tornadoes in earth science can be simplified if the centrifugal force is adopted; after all, a force is commonly introduced to students as a "push' or "pull". Furthermore, it is true that people in rotating frames feel like they are being pulled radially outside the circular path. In his attempt to dislodge the centrifugal force misconception, Knight et al. (2013) argued that riders in rotating systems feel as if they are being pushed outward but "feelings are not forces" (p. 179). This is an interesting sentiment that probably deserves another separate discussion. However, for now, we note that the riders are the ones in the rotating frame and have the legitimacy to associate their feelings with force, in this case, a fictitious one having the same feeling as real force.

Implications for Teaching

It appears that neglecting a discussion of the centrifugal force is an unfortunate situation since the concept has historical roots and is widely used in several practical applications in engineering or everyday language. Further, we believe that this concept cannot be a misconception if we appreciate the point of view of the observer. Therefore, we disagree with experts who advocate for "let's stop the centrifugal force" (e.g., Wörner, 2023, p. 425) and those who argue that "it can be highly confusing" (Roche, 2001, p. 403). In his recent article, Wörner (2023) argued that discussing fictitious forces distracts students from the main purpose of elementary mechanics and that these should be left for upper-level courses. We note that a good fraction of college students taking elementary mechanics plan to join the engineering field. Therefore, physics educators should start to seriously think about addressing centrifugal force head-on instead of ignoring it. Hewitt (2015) noted that "to observers who are in rotating systems, centrifugal force feels like, and is interpreted to be, a very real force" (p .160). If it feels real to people in familiar situations, if it has practical applications, if Newton's laws can be modified to be applicable in non-inertial frames, why should physics educators completely shun it? Is it because of the complexity of the math that surrounds it and the level of education of our students? If so, what happened to this is beyond the scope of this textbook Or what about the conceptual approach adopted by textbooks such as Hewitt (2015)? Is it because it is considered a misconception for observers in inertial frames of reference? If yes, we should remember that it is not a misconception for an observer in non-inertial frames. In fact, several previous misconceptions in physics such as the 'impetus' theory, are taught to students so they know where we are coming from to better understand the present and consequently the future. In fact, Volfson et al. (2020) argued that "the concept of centrifugal force is not "criminal"" (p. 3). They also stated that "it is pretty attractive to use the idea of centrifugal force when dealing with uniform circular motion problems." (p. 3).

When instructors teach dynamics of circular motion, they often encounter situations where students include a radially outward force on an object in a circular motion. For example, consider the following case: Put water in a small bucket, about one-quarter full. Tie the bucket handle to an inelastic cord. Spin the bucket in a vertical orientation (plane). An experiment like this shows that even when the bucket is upside down, the water does not spill off the bucket. When instructors ask students to draw a force diagram for water in the bucket at the maximum height, students often recognize gravitational force and sometimes they also correctly recognize the contact force exerted by the bottom of the pail on the water. Some students also include a force that points vertically upward opposite to gravitational force; a force often called centrifugal force. At this point, educators say that it is a misconception to include this radially outward force considering that there is nothing that pulls the rotating water radially outward, and it leads to inconsistent conclusions for circular motion dynamics problem solutions for inertial observers. For example, the effect of gravitational force can be explained by the pulling of the earth; the contact force can be attributed to the bottom of the base of the bucket, but there is nothing that can be attributed to the alleged radially outward force There are several reasons students find it hard not to include centrifugal force. Here are some:

1) Things get confusing when we consider our physical perceptions in rotating frames of reference such as those at amusement parks, or our physical perceptions in a car that negotiates a curve. We feel like there is a force pulling us radially outward while in a circular path. Convincing students that they should not include centrifugal force when dealing with the dynamics of circular motion becomes a difficult task. Students have personal experiences of what it is like to be in rotating frames. When students include a centrifugal force, in force diagrams, do they place themselves in inertial frames or rotating frames? Could it be that instructors wrongly label students as having misconceptions when they are describing the situation from a different and familiar point of view? It could be that students seem to forget that Newton's laws of motion (as introduced in their classes) are applicable only in an inertial frame of reference. That is, the one making observations must be in an inertial frame of reference while the object that is being observed could be in inertial frames or accelerating (linearly or curved frames).

2) Educators need to be very careful regarding what they call a misconception. This study's theoretical framework, the Gestalt theory, reminds us to consider the idea of perceptiveness

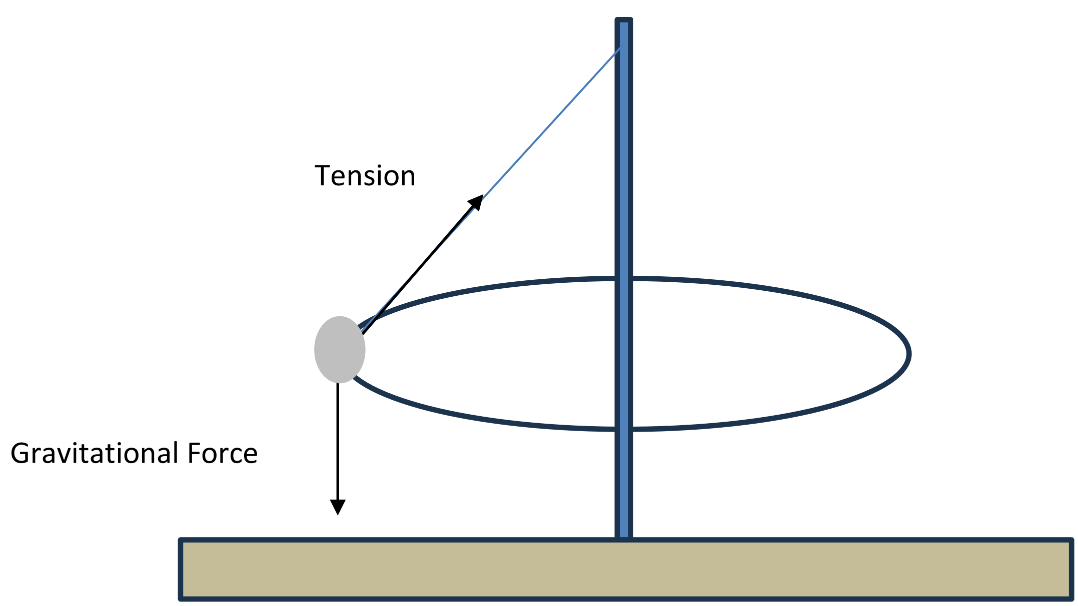
before we jump to conclusions. “Is this 'experience’ of centrifugal force simply another example of a common misconception that students have about physics? The answer is 'No'. There is a legitimate and scientific basis for the concept of inertial force and one which is not inconsistent with Newtonian theory” (Savage & Williams, 1989, p. 136). Thus Savage and Williams (1989) note that for an observer in a rotating frame, it is not a misconception to say that a centrifugal force acts on them.

3) When students are asked to draw a force diagram of a conical pendulum, the correct answer (according to an inertial observer) requires that they only include tension and gravitational force. Most textbooks emphasize that the centripetal force is the net force acting on an object in circular motion. However, in examples such as the conical pendulum (Figure 2), students wonder why an object finds itself in a uniform circular motion at fixed radii if not for the centrifugal force. Similarly, students may think that the Earth’s attraction to the Moon is balanced by a centrifugal force for an inertial frame observer.

   Instructors may help students by applying Gestalt theory and demonstrating the two perspectives as shown in Figure 1 under Theoretical and Conceptual Framework. Also, students should be aware that objects in orbit around the Earth are not kept in orbit only because of the gravitational force but also the right amount of speed. If not for the right amount of speed, the spaceship will plummet into the Earth or deviate away from the Earth.

Figure 2

Analyzing Forces on the Bob of a Conical Pendulum

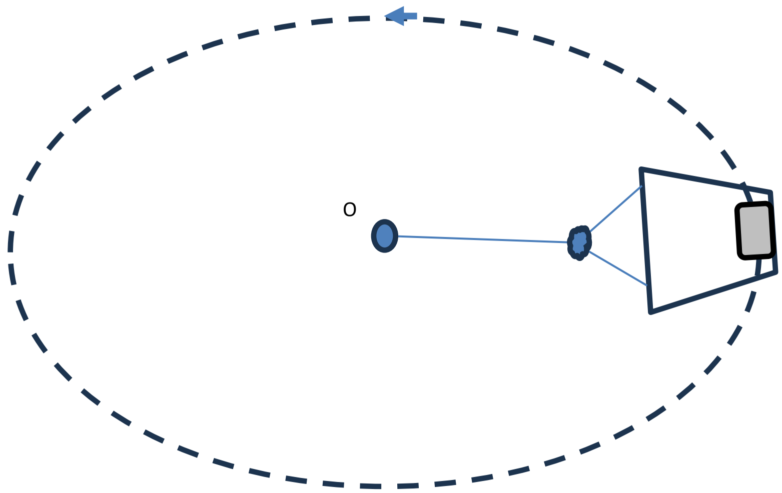


4) Sometimes, it is the way students apply Newton’s third law for rotating objects. Consider a cube in a pail rotated about Point O. According to Newtonian mechanics, neglecting gravitational force, the only force acting on the cube is the force due to the base of the pail on the cube. It is true that by the third law, the cube also exerts force on the base of the pail. Students sometimes confuse this with the centrifugal force although this is just one of the

action reaction forces. Students need to be reminded that action and reaction forces act on different objects, not the same. For example, the force by the cube on the pail as shown in Figure 3, although it acts radially outward, is not a centrifugal force but action-reaction force.

Figure 3

The Pail Exerts a Force on the Cube and the Cube Exerts a Force on the Pail



5) Related to point 3 above, it is true, according to Newtonian mechanics that there is a radially outward force on the pail (due to the cube) but there is also a force by the string on the pail. The net force on the pail (according to an inertial observer) should be radially inward and that's the centripetal force. The emphasis is that the centripetal force is not necessarily a single force but a net force that is directed radially inward on an object in circular motion.

Conclusions

This study has shown that about half of the textbooks analyzed prefer not to use centrifugal force in their discussion of circular motion dynamics. This study found that close to half of the textbooks did not discuss the difference between real vs. fictitious forces, and only about 50% of the textbooks reminded readers of the applicability of Newton's laws of motion. Only 20% of the textbooks attempted or mentioned that there is a way to modify Newton's second law to be applicable in non-inertial frames of reference. Further, only 15% of the textbooks had a teaching problem/example that specified the frame of reference of the observer. Ten percent of the textbooks warned not to use the term, although they described the concept briefly. It is true that in an inertial frame of reference, there is no such thing as "centrifugal force". However, we have argued that saying that students have a centrifugal force misconception without asking their placement of the observer is problematic. We have suggested that textbooks need to keep reminding students that Newton's laws of motion (as introduced in elementary mechanics) are valid when the observer is making observations while in an inertial frame of reference and that they can be twisted for an observer in non-inertial frames of reference. Our position is that the centrifugal force should not be shunned but discussed in the same way we discuss controversial issues in science, such as how to define weight (Taibu et al., 2015), and in the same way we acknowledge the role of perspective (Gestalt theory) (Köhler, 1975) in our physical sensation. We can't erase history, and we can't run away from the reality that as humans we find ourselves in both inertial and rotating frames (e.g., at an amusement park). Indeed, the conflict between physicists and engineers regarding how to approach centrifugal force (Roche, 2001) can be resolved if Gestalt theory is adopted in teaching of circular motion dynamics. We should acknowledge the simplicity that the centrifugal force vocabulary provides in discussing perceptions in rotating frames, especially for experts in other STEM disciplines such as engineering and earth sciences.

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