Context Dependence of Newton's Second Law in Introductory Physics Topics

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INTRODUCTION

After a topic has been covered in a course, the assumption made by many instructors is that the students understand the topic that was taught at least well enough to apply that concept during the rest of the course. This assumption shows itself in tasks presented later in the course that presume an understanding of the topic and in later courses where the subject matter is considered a pre-requisite to enrollment. The assumption that a student has learned the material is largely based on the student's performance on course assessment tasks. Much research has shown that just because a student has earned a passing score in a course, or even a very high score, he or she does not have a good conceptual understanding of the topics that were covered [11, 24, 31]. Bagno, Eylon and Ganiel (2000, p. S17) more clearly articulate this assumption: The Word

> "It is often assumed that the strong resemblance between several examples of a general concept is readily identified by learners. Furthermore, it is also assumed that when comparing examples of a single general concept, learners will easily differentiate between the critical attributes that characterize the general concept and the noncritical attributes unique to each example."

This 'Assumption of Transference' between topics in a given physics course is the inspiration for this study. The overarching goal of the present study is to investigate conceptual student understanding as it develops during a physics course, and then to explore how students apply a concept throughout the course (transfer the knowledge).

The conceptual area of mechanics is by far the most thoroughly researched topic in physics education. In 1994 Wandersee, Mintzes and Novak reported (1994, p. 181):

> "Of some 700 studies within the school subject of physics about 300 have been devoted to concepts in mechanics (including force and motion, gravity, velocity and acceleration), about 159 to electricity, and about 70 each to concepts of heat, optics and the particulate nature of matter and energy. The earth and space sciences have sparked some 35 studies and 'modern physics' (physics based on relativity and quantum theory) about 10."

This focus on mechanics is somewhat understandable. Above all, mechanics is taught at all levels of education providing both opportunity for research and an audience for its outcomes. Mechanics is the area where students have the most obvious and explicit personal experience and therefore have formed their own concepts before entering the classroom.

From a constructivist point of view, mechanics forms the basis on which all other physics understanding is built placing it in a crucial foundational stance. This notion is best articulated by Galili (1995, p. 371):

> "The importance of mechanics is more than just being one of these domains. It determines the 'rules of the game', defines the main tools in physics, presents the most universal laws of nature. It actually describes the method of the discipline of physics which is then applied in all other domains in this discipline."

Newton's Second Law, F=ma, was chosen as the concept to follow throughout the calculus-based introductory course. This choice was governed by a number of factors:

1. It is taught early in the course, which maximizes opportunity to investigate student understanding and transfer later in the course.
2. Its teaching and learning well-researched. Misconceptions are already classified for this topic.
3. For many other topics taught an introductory course, students need to apply Newton's Second law.
4. It is not a complex concept. Thus, the evaluation as to whether it was used by the student is simplified.

The calculus-based course was chosen over other introductory physics courses because it covers the largest variety of conceptual topics. Also, the topics are covered in more depth providing a richer basis to harvest data on student understanding.

Integration with Existing Research

Much of physics education research in the last 25 years has focused on identifying student misconceptions concerning a particular topic. Many of these studies focused on Newton's laws in mechanics [32]. Frequently, research in this and other content areas has been on the pre-existing mental models that a student brings to the classroom [10, 20, 29, 32, 45]. These mental models have been called preconceptions, alternative conceptions, common sense concepts and misconceptions [14]. Most studies have shown that people of all ages hold some type of misconception [27]. And, students at all achievement levels have these misconceptions, l [36, 42]. In addition, misconceptions have also been reported to be rather persistent. Even after thorough and innovative teaching methods, these misconceptions have remained or re-emerged [45]. The findings reporting the persistence of misconceptions alone is enough to question the assumptions of transfer of knowledge mentioned above.

A large portion of these studies shared a similar research design: 1) Test students on a concept, 2) instruct students in the topics covering that concept, 3) retest students on that concept. This design is effective at determining the prevalence and persistence of student misconceptions in a particular topic. However, in general only one type of problem context or conceptual area is employed by the instrument and typically the instruction in those types of designs.

Studies have investigated student understanding of Newton's laws in conceptual areas other than the one in which it is taught [16, 20, 34]. These studies have focused primarily on Newton's first law and have reported misconceptions continuing into or emerging in these other areas. They typically did not investigate more than two differing conceptual areas.

The goal of this study is to investigate the contextual dependence of student's use and/or understanding of Newton's Second Law in a diversity of task situations. The research aims to find contextual scenarios that hamper or enhance student's application of Newton's Second Law. Moreover, the aim is to determine what factors cause the student to choose other reasoning. Accounting for these factors could improve instruction on these other topics.

Contextual Appreciation

From the constructivist perspective, the process of learning is deemed conceptual change. Many theories exist to explain how this change occurs based on the theorist's particular view of knowledge structure. The theories of conceptual change differ in terms of the grain size of information that is processed: The smallest pieces of knowledge are re-organized [41]; Parts of concepts are modified and/or built upon [37]; Whole concepts are replaced [8] or re-categorized [9]. None of the referenced researchers addressed context in their theories of conceptual change. To address this issue, an additional dimension for mental constructs to conceptual change has been proposed:

> "Clearly the appropriate application of scientific theories and concepts requires an appreciation of context - forging an appropriate relationship with the context. Consequently it would seem reasonable to argue that it is inadequate to depict meaningful learning in terms of a changing of conceptions in the sense of simply generating a new or altered cognitive structure" ([25], p. 5).

> "Instead of depicting meaningful learning in terms of conceptual change we should consider depicting it in terms of conceptual appreciation - an appreciation that is delimited by context" ([25], p. 295 original emphasis).

Also, studies on problems solving in physics [7, 23] indicate knowledge organization as "one of the factors in the preeminence of the expert over the novice. Such organization facilitates transfer between different domains and helps in dealing with novel situations" [1], p. S16). Contextual appreciation could be a factor in affecting transitions in the stages of understanding: Novice to expert or concrete operations to formal operations. Thus, determination of when this contextual appreciation occurs (or does not as the case may be) is the focus of this study.

The term context possesses many different meanings depending on the, ahem, context of its use. Its coverage spans from the overall social culture to the wording in an arithmetic problem. Similarly, the term 'domain' has also been used just as generally. The ambiguity begs clarification.

Definitions

The investigation at hand focuses on concepts used in homework tasks assigned in an introductory course. Context only needs to be clarified for problems and therefore does not include the scope of classroom, institution or overall social cultures.

A hierarchy of problem or task classification is defined for this study: Domain, Context, Scenario, and Feature. This hierarchy is from the general to the specific. See Table 1 for definitions and examples.

TABLE I: Classification of Problem Context

Term	**Definition**	**Example**
Domain	An overarching theme of concepts.	Mechanics, Oscillations, Electromagnetism.
Context	A specific area of the concept domain.	Electromagnetism has several contexts: Electrical Charges; Electric Fields; Magnetic Fields; Magnetic Poles
Scenario	The specific situation within a context. A description of what is happening in the task.	Electric charges are moving, fixed, released from rest, etc.
Feature	Objects that make up the scenario or characteristics of them.	The charge is positive or negative. The amount of charge, amount of mass. Number of charges, etc.

Other research has studied student understanding across these boundaries. The work of Engel Clough and Driver (1986) investigated consistency of student responses across more than two domains (as defined here). Palmer (1997) and Zollman (1987) investigated only scenario changes.

Bao, Hogg, and Zollman (2002) and Rebello, Itza-Ortiz and Zollman (2003) used responses to certain feature changes by students to determine their mental models for the given context. Similarly, this investigation will vary all of these parameters to some extent and study the contextual dependence of student mental models of Newton's Second Law.

Other researchers have applied different mechanical contexts to Newtonian problems. Halloun and Hestenes (1985) found some inconsistencies in student reasoning between linear and projectile motion scenarios. Galili and Bar (1992) discovered that students were more likely to use alternative mental models as the questions increased in difficulty from constant velocity to changing acceleration. Palmer (1997) investigated linear motion in several scenarios with different features. He found different features to be a factor in students use of non-Newtonian mental models: speed of the moving object or weight of the object. He also found a difference in scenario to be a factor: e.g. direction of the motion (vertical or horizontal).

With respect to content areas other than mechanics, Rebello, Itza-Ortiz and Zollman (2003) reported non-Newtonian student mental models of motion were used to describe particles moving in electric fields. Törnkvist, Pettersson, and Tranströmer (1993) suggest that student difficulties with field concepts and particle motion are from confusion of representations between field lines arrows, velocity arrows, and acceleration/force arrows. Where Galili (1995) viewed results in the electric field context from another perspective: "It appears problematic for students to include the concept 'field' in the mechanics framework previously acquired in physics courses (p. 382)." The referenced framework was Newton's third law and energy-work relations.

The research of Rebello, Itza-Ortiz and Zollman (2003) most closely follows this investigation. They investigated student mental models in both mechanics contexts and electromagnetic contexts. Their study primarily probed Newton's first and third laws. The interview protocols and research instruments employed changed contextual features that created changes in force but did not change the mass feature which is a key in investigating Newton's Second Law. Their results showed that students did use non-Newtonian reasoning when asked about object motion in electromagnetism. However, the design of the study was not thorough enough to find which particular scenarios or features within the domain caused students to revert to these non-Newtonian mental models.

In addition to mechanics and electromagnetism domains, the rotation and torque conceptual area is associated with the mechanics domain by some practitioners in the field of physics. However, rotation and torque have been largely neglected in the research pertaining to the learning of mechanics. Neither the Force Concept Inventory [21] nor the Force and Motion Conceptual Evaluation [43] include a single question directly regarding torque or rotation. In addition, little research which investigated torque in particular has been carried out. Barowy and Lockheed (1980) found student difficulties regarding torque. Ortiz (2001) found student misconceptions as well. Both of these studies had the student applying Newton's laws in one context only. Contextual dependency of Newtonian reasoning was not determined.

Simple Harmonic Motion is also a relatively neglected topic as far as research in learning is concerned. Of the research which included simple harmonic motion [6, 15, 39], none sought Newtonian mental models specifically in their applications. Simple harmonic motion was used in this study as a scenario in which to pursue a separate research goal.

RESEARCH DESIGN

The intent of the investigation was to investigate how Newton's Second Law is or is not used and/or understood in as many content contextual areas as possible. Qualitative methods provide the highest resolution of data for such an endeavor using a phenomenological approach [4, 5].

Given the nature of the research questions, semi-structured interviews with a developed and ordered interview guide, referred heretofore as the protocol, was deemed the best option for data collection. In addition, the investigation is to cover several content or contextual areas so a series of interviews was planned. Ideally, the same students would be interviewed a number of times throughout a physics course.

Participants

From the calculus-based introductory course, volunteers were sought originally from one studio section to minimize the variance in the shared experience of the interviewees. As time progressed, the number of interviewees dwindled, and so more volunteers were sought from addition studio sections. A small payment was offered as an incentive for participation.

Overall 22 students participated. Each student was interviewed from one to six times. The frequency of interviewing is listed in Table 2.

Demographically, 14 participants were male and 8 female. Four were physics majors while the remaining 18 were engineering majors (in eight different areas). Two participants did not take the first semester course at the time of the interviews. Overall performance levels varied for the first semester interviews. Performance varied less for the second semester interviews, probably due to the requirement of passing the first semester course. Since Students 13 and 22 had only 1 interview, their responses were dropped from consideration since no comparisons could be made.

Participant sampling was limited to students who had volunteered. This method is deemed "convenience" sampling [35, 40]. However, the participants had varied interests and varied performance levels in the course, and both genders were adequately represented. This range of participants was similar to the larger population and was more akin to "maximum variation" sampling [35, 40]. Such a sample allows for the most probable transferability to other populations.

Additionally, the student participant final course scores were compared statistically to determine if the student participants were representative of the class as a whole with respect to the course performance variable. The student course scores were separated into 10 point bins and normalized. A Chi-Squared goodness-of-fit test calculated a χ^2 value of 25.3 for the first semester and 94.5 for the second semester. Both of these values are well above the critical value of 9.488. The student participant scores were not representative of the population of students enrolled in the course.

The average score in the first semester course was 77.2 while the student participant average was 81.0. In the second semester, the course average was 64.8 where the participant average was 83.3. The student participants were better performers than their peers on average especially in the second semester. Any misapplication of mental models would be even less likely in this group of students as compared to rest of the students enrolled in the course.

Interviews

Six interviews were scheduled throughout the two-semester course. Interviews 1 through 4 were approximately 30 minutes in duration and were scheduled during the first semester of the course. Interviews 5 and 6 were approximately 60 minutes in duration and were scheduled during the second semester of the course.

TABLE II: Participants Interview Frequency

Student Number	**Interview 1**	**Interview 2**	**Interview 3**	**Interview 4**	**Interview 5**	**Interview 6**	**Total Interview**
1	1	1	1	1	1	1	6
2	1	1	1	1	1	1	6
3	1	1	1	1			4
4	1	1	1	1			4
5	1	1	1	1			4
6	1	1	1	1			4
7	1	1	1	1	1	1	6
8	1		1	1			3
9			1	1	1	1	4
10			1	1			2
11			1	1			2
12			1	1	1	1	4
13			1				1
14			1	1	1	1	4
15			1	1	1	1	4
16					1	1	2
17					1	1	2
18					1	1	2
19					1	1	2
20					1	1	2
21					1	1	2
22	1						1
Participants per Interview	9	7	15	14	13	13	

The protocols utilized a conceptual question to narrow the range of possibilities as well as ensuring the students would have some familiarity with the concepts involved. Despite this restriction, the interview protocols were designed to target as many contextual categories as possible.

The conceptual questions were always based upon concepts that were related to an assigned homework problem. Each scenario had a series of questions associated with it. As defined earlier, a scenario is the specific situation within a context, what is happening. Each question in the series changed a feature in the scenario and asked the student to compare the result to the first question. The following is an example from Interview 3. The scenario of applying a constant force to a wrench clamped to a well greased pin was presented to the student as Figure 1.

The student was asked to describe what would happen. That description was probed for clarity with follow up questions. Subsequently, the force was doubled in the second question. This question was included to confirm the students understanding of the situation. Then the third question was posed where the original force placement was changed.

The interviews covered several interesting content contextual areas. Each of these has its particular misconceptions. The focus of the interviews was the concepts required to do the assigned homework problems and Newton's Second Law. At times, forgoing information regarding the content misconceptions and/or depth to remain on the path of investigating Newton's Second Law was necessary. For example, in Interview 5, the content area was electric fields. Whether or not the participant applies electric field theory has little applicability to the goal this investigation. Asking follow up questions regarding field theory was tempting, but would not have been fruitful for the above stated goals. In addition, the participants are not to be dismissed either. If all of the interview questions had been strictly about force, mass and acceleration, they would have figured that out as well. To combat this impediment to validity, the interviews included questions that were not directly related to Newton's Second Law. These have been deemed distracter questions due to their intent to distract the participant from the true agenda of the interviews.

Data Acquisition and Quality

A single researcher conducted all of the interviews which were recorded on audiotape. Additional notes were taken on a copy of the interview protocol. The interviewer transcribed each interview. The transcriptions were not verbatim. Only student responses that were relevant to the protocol questions were transcribed carefully. Discussions that did not pertain to physics in any way were not transcribed. As part of their answers, students may have also written or drawn on paper. These papers were also consulted during transcription and analysis. When questions arose during analysis, the interview tapes were consulted directly.

Time was allotted at the end of the interview for each participant to ask questions. No limits were set for these questions, and typically, the students asked about the content of the interview. This process alleviated participant stress and was also an aid to them since they were in the midst of a course where grades were to be assigned. By addressing students deficiencies related to the content, error may have been introduced into later data collected. However, the ethics of diagnosing a problem and then not treating it was considered of greater neglect.

This "tutoring" was part of the benefit of being a participant. However, it was also a possible source of bias on the part of the students. Once they had been "tutored" on Newton's Second Law in one content contextual area, then the probability of increasing their understanding of Newton's Second Law from participation in the interview rather than the course activities would have been increased. This potential bias was combated somewhat by adding participants as the process continued. These additional participants did not participate in earlier interview "tutoring" sessions.

The interviewer is the instrument of data collection. This approach has both advantages and disadvantages with regards to bias in the data. First, because the interviewer had experience with the subject, she could direct the interview towards the objectives and remain on the focus topic. However, she may also have had anticipated responses based upon her own experience. This possible bias was addressed by eliciting open-ended responses to the interview questions. Thus, the participant was able to choose the answer and its direction.

DATA ANALYSIS

These transcribed interviews were reviewed along with the written responses and notes. The student final responses were collected by question into an electronic spreadsheet. One may ask why final responses? Several students waffled on answers, adopting ideas and then rejecting them and/or changing answers to previous questions after a subsequent question had been asked and/or answered. These final responses were the ones settled on, sometimes checked for consistency and appeared to be believed most fully by the students.

As with many investigations, much data were collected, but only a small portion was relevant. Nine question scenarios provided information regarding student's use and understanding of Newton's Second Law. These questions and scenarios are listed in Table 3. Some of the questions are for comparison purposes and are included here for completeness. The last column in the table is an abbreviation that will be used throughout the rest of the article. Only the responses to questions listed in Table 3 were placed into categories.

Data Categorization

The student responses were categorized in a two-level approach. First, the responses were listed as either Congruent with Newton's Second Law or not. Second, those responses that were deemed Incongruent with Newton's Second Law were categorized to represent the student's mental models where possible.

Obviously, if clear connections between mass, acceleration and force were made by a student, then the response was classified as Congruent with Newton's Second Law. However, several student responses were not demonstrating explicitly correct uses of Newton's Second Law reasoning, but were along the correct path. As an example, compare the statement, "I would say slower than that one because it's bigger." (Student 14) to "So it has twice the mass, it will have half the acceleration because it will have the same force because it has the same charge" (Student 17). The latter statement is a clear and complete application of Newton's Second Law. Both responses were supported by drawn trajectories of particle paths. The response given by Student 14 does not show clearly if he sees the same force with a larger mass therefore the acceleration must be less so the motion is affected. However, the student could be, and likely is, thinking in this manner. These types of responses were categorized as Congruent with Newton's Second Law.

Some of the responses that were deemed Congruent with Newton's Second Law were fully written out problem solutions. A student response was also classified in this manner if the student mentioned Newton's Second Law

TABLE III: Questions pertinent to Student's use and understanding of Newton's Second Law: Listed by Interview number.

	Contextual Scenario	Question	
2	Modified Atwood Machine with identical blocks: One on table and one hanging.	If this is released from rest, what happens? Describe the motion.	MA1
	Modified Atwood Machine with identical blocks: One on table and two hanging.	If this is released from rest, what happens? Compare to above case.	MA2
3	Person on Sled Throwing off a Block every 10 seconds.	What happens? Describe the motion of the sled.	SLD1
		(If velocity increases) Does that mean there is a force on the sled?	SLD2
4	Applying a Constant Force to Turn a Wrench	What is happens? Describe the motion.	WR1
	Block on a Spring in Simple Harmonic Motion	Does the Force Vary?	SHM1
		(If so) Does the Acceleration Vary?	SHM2
5	Equal charges: one fixed and one released from rest.	What happens? Describe the motion.	CH1
	Unequal charges: one fixed and one with larger mass released from rest.	What happens? Compare to above case.	CH2
	Equal charges: one fixed and one traveling at velocity v.	What happens? Describe the motion.	CHV1
	Unequal charges: one fixed and one with larger mass traveling at velocity v.	What happens? Compare to above case.	CHV2
	Charge placed in E-field zone and released from rest.	What happens? Describe the motion.	EF1
	Charge with larger mass placed in E-field zone and released from rest.	What happens? Compare to above case.	EF2
	Charge traveling with velocity v towards E-field zone.	What happens? Describe the motion.	EFV1
	Charge with larger mass traveling with velocity v towards E-field zone.	What happens? Compare to above case.	EFV2
6	Charge traveling with velocity v towards B-field zone.	What happens? Describe the motion.	BFV1
	Charge with larger mass traveling with velocity v towards B-field zone.	What happens? Compare to above case.	BFV2

correctly in their response

> If you want to find the acceleration then ma would equal -kx because of the two forces, so therefore a would be -kx over m - and if you're changing x, the spring constant and the mass are the same then the acceleration will vary. (Student 12)

These question scenarios changed the applied force and requested the student to compare situations. When a student correctly associated the applied force with the acceleration, the response was classified in the Congruent with Newton's Second Law Category.

The responses deemed Incongruent with Newton's Second Law were then scrutinized further. Any response that was duplicated by more than one student was noted and a category created. Some responses were unique and therefore were not placed into any category besides Incongruent with Newton's Second Law reasoning. The results of both the first second level of classification are listed in Table 4.
Legend:

TABLE IV: Categorization and Percentage of Newtonian Student Responses

	First Semester Questions				Second Semester Questions					
St#	MA2	SLD2	WR1	SHM2	CH2	CHV2	EF2	EFV2	BFV1	%N
3	N	N	N	N						100
6	N	N	N	N						100
17					N	N	N	N	N	100
18					N	N	N	N, Imp	N	100
20					N	N	N	N	N	100
21					N	N	N	N	n	100
2	N		N	N	N	N	N	N	N	89
9		N	N	N	N	N	N	N	M,E	88
4	N		N	N						75
10			N	N						67
14		N	A		M, G	N	N	N	A	57
1	N	N	N	N	M,E	M,E	M,E	M,E	N	56
5	N									50
15			N		N	N	M	M.G	N	50
19					N	M	N	M	M	40
7	N		A	N	M,E	N	Sz	Sz,Imp	M,E	33
8		N	A							33
12			A	N			Sz	Sz,Imp	Sz	13
11			A							0
16					M	M,A	M	M,A	M,E	0
%N	100	43	57	64	62	69	62	54	54	

A	Aristotelian
Imp	Impetus
M	Mass does not matter
E	Mass not in equations
G	Gauss's Law
Sz	Size Matters
N	Congruent with Newton's Second Law
	Student was not asked this question

Second Level Categories

As is apparent from inspection of Table 4 and its legend, a number of secondary categories exist. Some student responses fell into more than one category. The classification criteria for each of these categories and its coded name are explained in the next sections.

- *Aristotelian Category - A*

Aristotle preceded Newton in theorizing about the motion of objects due to an applied force. His famous work stated that motion implies force: If no force is acting, the object is at rest. Also, that the velocity of a body is proportional to the force acting on it. These statements are very simplified version of a thorough and complex set of works that were accepted for hundreds of years [12, 22].

Some student responses clearly had Aristotelian reasoning patterns as their basis. These responses, such as "If it's a constant force, I'm assuming a constant speed." (Student 11) and "If the force is greater, then the velocity would have to be greater." (Student 12) are associating force with velocity. These types of responses were classified as belonging to the Aristotelian second level category.

In addition to the transcriptions, the written responses were also reviewed. One student drew a force vector along the direction of particle initial velocity. See Figure 3.

The transcript for this student's response reads: "If it's got a force pushing that direction [draws arrow along left-right axis] a force moving in that direction [labels the left-right arrow with F] and then I guess there's a force also moving in this direction [draws an arrow along velocity vector and labels it F] we've a velocity in that direction. So I would say that it would draw this vector here [draws diagonal arrow]. The force here [to the right away from fixed charge] and the force here [along v] will give it a net force here [along diagonal]" (Student 16). Student 16 clearly associates a force with the velocity as in an Aristotelian style of reasoning. The response given by Student 16 and others similar to it were categorized as Aristotelian.

- *Impetus Category - Imp* The impetus theory of object motion dates to the 14th century. It defines the 'imprinting from a body onto a moved (projectile)' as impetus, 'a permanent quality which is acquired and possessed by any moving body? [18], p. 232-233).

The student responses that were classified as the Impetus category gave the object some sort of memory such that it returned to its initial velocity complete with direction after interacting with a force. This memory of the initial state was most apparent in the written responses. See Figure 4.

The transcript for the student whose drawing appears in Figure 4 reads: "I would say it moves straight on as well and then it will go at more of an angle and then go straight as well. And then it will move at more of an angle because it since it's bigger will also would encounter more of the electric field as it passes." (Student 7)

Student 7 has the particle retaining something from its original state and returning to it. This 'memory' placed this student response and another similar to it into the Impetus second level category.

- *Mass Does Not Matter Category - M*

This category included student responses that imply or state that mass does not matter with respect to an object's motion. Usually this statement was explicit: "The mass I mean is not gonna matter because it's still going the same velocity so I would say it's going to do the same thing." (Student 19) It was also reflected in comparing sets of the written responses. See Figures 5.a and 5.b

The transcript for the student whose drawing appears in Figure 5.a reads: "I figured it would just go [Draws an arc away from fixed charge] something like that. This one is moving this way - this is still going to give it some component there [away] but it has this one initially so just combine the two." (Student 1)

The transcript for the student whose drawing appears in Figure 5.b reads: "This one will do the same exact one as #1. [Interviewer: Why?] Well, like just in any equation we use the size the mass hasn't really come to play." (Student 1)

Student 1 explicitly showed that mass did not matter by drawing the trajectory of the particles identically even though the masses were different. In addition, reasons were given for that statement. Those reasons were also categorized further leading to multiple categories for student responses.

- *Equation Category - E*

The statement by Student 1 "like just in any equation we use the size the mass hasn't really come to play" was reiterated by a number of students as their reason for mass not affecting the motion in the charge and field question scenarios. Another student stated: "Since it's q v cross B [writing] so this will - there is no m over here so it doesn't matter on the mass." (Student 9) This theme was common. The popular equations to reference were for Coulomb forces, electric fields or magnetic forces. All student responses referring to mass as absent from an equation were classified into this category.

- *Gauss's Law Category - G*

Another reason students cited for mass not affecting the motion was Gauss's law. The responses included statements like "If it has the same charge, I think you can assume it's a point charge ... and assume that since the charge encl ... make it a Gaussian surface whatever, the charge enclosed is identical." (Student 15) Only 2 student responses were classified as belonging in the Gauss's Law Category.

- *Size Category - Sz*

In the field question scenarios, the increase in physical size as opposed to the mass was cited by two students as the mechanism for changing the motion. This increase in size provided a greater interaction with the field and thus a greater force. "Here the radius is 2 times the radius from before so that one has a bigger area that can be affected so then more field lines can affect the particle, the charged particle so it should, it should move probably faster than the original." (Student 12) This statement demonstrates a misunderstanding of field theory. However, if the student tacitly included mass into the reasoning as well as the size, the effects of Newton's Second Law and the increased force from the greater field interaction would counter each other. Thus, different discussions and drawings would have occurred. These student responses were classified as belonging to the Size category.

Verification of Categorization

Since the researcher was directly involved with both the data collection and manipulation, verification of the categorization was prudent. A second researcher not involved in the study in any way was given the Interview 6 transcripts of 4 disparate students. This independent researcher performed a primary level categorization of the student responses to the relevant questions. The results were identical to the classification by the study researcher.

In addition, the independent researcher also checked a random sample of student responses from the other question scenarios. Differences in first level categorization occurred with only 1 student response.

Overall, 11 out of 115 student responses were checked. Of these, only one response was not in agreement. This constitutes a 91% agreement rate of the nearly 10% of responses checked.

Overall Trends

From inspection of Table 4 some trends emerge. Of the five students who were asked eight of the nine question scenarios, none gave Newtonian responses to every question. In viewing student responses per semester, four students gave consistently Newtonian responses in the first semester and a different five students did so in the second semester interviews. Comparisons between these sets of students are questionable because some of the students in the second semester were not interviewed during the first semester and vice versa. Still, between 30 and 38 percent overall was a rather small rate of use of Newton's Second Law reasoning.

Questions that were asked during the time that students were receiving direct instruction about Newt's Laws not surprisingly had a 100% rate of using Newton's Laws. This scenario will not be considered further. Another scenario with high Newtonian performance, spring with an attached block - SHM, with 64% Newtonian response was also in the first semester. The Simple Harmonic Motion of a spring and a block was emphasized in the course. This particular instructor chose to spend more time on simple harmonic motion and forego gravitation.

Contextual Dependence of Newton's Second Law

The results of data categorization presented in Table 4 were reviewed both from a contextual domain perspective and a student longitudinal perspective. From these perspectives some themes emerged.

- *Sled Scenario Question*

The Sled scenario question (SLD2) had the least percentage of Newtonian responses. Six of the 14 students gave non-Newtonian responses. Students 2, 4 and 10 had this scenario as their only non-Newtonian response. This scenario used concepts which were employed in only one assigned homework question. And the homework question was labeled as an exercise versus a problem in the textbook [19]. This exercise label means that students merely had to determine the correct formula and the values required to correctly answer the question. Thus conceptually, this scenario was fairly unfamiliar to the students. Also, the current topic of instruction was center of mass which was mentioned by several students. Few students providing Newtonian reasoning were not surprising.

In addition, the phrasing of question SLD2 was less than optimal. Since the scenario dealt with both a sled and blocks being thrown from it, question SLD2 which asked about the sled alone caused some confusion.

- *Wrench Scenario Question*

From the first semester questions, the only question scenario that elicited clear non-Newtonian reasoning was the scenario with a force applied to a wrench (WR1). The student responses were either Newtonian or Aristotelian in nature. The students understood the question scenario and seemed familiar with it. The students clearly used non-Newtonian reasoning in this question scenario.

Questions WR1 and SHM2 regarding simple harmonic motion were asked during the same interview session. Students 7 and 12 gave Newtonian responses to SHM2 minutes after giving non-Newtonian responses to WR1.

- *Electric Charge Scenario Questions*

In these scenarios, two charges are present: one is fixed, and one is free to move. In the charge at rest questions (CH), the free charge is released from rest. In the moving charge questions (CHV) the free charge is moving with a velocity perpendicular to the direction of the force created by the fixed charge. In both of these scenarios, the mass of the free charge is greater in question two than in question one.

Many students gave Newtonian answers for this question scenario. Interestingly, in the responses that were non-Newtonian, all but one student provided 'mass does not matter' as a reason with some responses clarified further.

The one student that did not agree with 'mass does not matter' had a very unique response that described the free charge in a sort of equilibrium. This response did not fall into any category.

Students 7, 14 and 19 had different reasoning for the charge starting from rest and the one starting with an initial velocity. The addition of velocity in this question scenario triggered two of these students to invoke reasoning congruent with Newton's Second Law. Conversely, student 19 did just the opposite. The addition of an initial velocity triggered that student to abandon the Newtonian reasoning used when the charge had started from rest.

- *Electric Field Scenario Questions*

These question scenarios involved a zone of uniform electric field. In the charge at rest (EF) questions, a charged particle is released from rest in the center of the electric field. In the moving charge (EFV) questions, the charged particle is traveling with a velocity toward and perpendicular to the electric field. Once again, the mass of the charged particle is greater in question two than question one.

Again focusing on the non-Newtonian responses, all students indicated or implied that mass does not matter. Recall that the Size category grouped the responses that stated the size of the charged particle caused a greater force from the field with no mention of the mass increase countering that effect. In addition, a field is required for the reasoning pattern classified as the Size category to be employed. So EF and EFV scenarios were the first to have Size as a category of student responses.

Also, EFV was the only question scenario where responses were classified as belonging to the Impetus category. This Impetus classification was in conjunction with the categorization of the responses as either Newtonian or non-Newtonian.

- *Magnetic Field Scenario Question*

The question scenario involving moving charges in a magnetic field (BFV) was nearly identical to the moving charge in an electric field (EFV) scenario. The notable difference being that the student chose which direction the B-Field zone should point with respect to the initial velocity of the charged particle in order to draw the trajectory of the particle's motion.

Again, the non-Newtonian response that includes or implies mass does not matter was the most common. Student 14 indicated that mass mattered but used clear Aristotelian-based reasoning. This response was the only occurrence of this type of reasoning in the second semester questions.

Longitudinal Themes

Several longitudinal themes emerged from a review of Table 4. Students 2, 3, 6, 9, 17, 18, 20 and 21 fairly consistently gave Newtonian responses throughout the interviews. Similarly, Students 11, 12 and 16 fairly consistently responded in a non-Newtonian manner.

Student 1 abandoned Newton's Second Law in his responses starting with the second semester questions. Student 9 abandoned Newton's Second Law later in response to the magnetic field question scenario, BFV.

Students 7, 14, 15 and 19 toggled in and out of Newtonian reasoning patterns as the questions were asked. Student 14 had an early Aristotelian response, changed to Newtonian responses and then returned to Aristotelian reasoning in the final interview.

As mentioned previously, the introduction of an initial velocity in the moving charge scenario (CHV) caused Students 7, 14 and 19 to change their reasoning. But only Student 19 changed reasoning when velocity was introduced in the electric field scenario (EFV) as well, and kept to that reasoning base in responding to the moving charge in a magnetic field scenario (BFV) in the next interview session.

Students 7 and 12 employed the Size reasoning for electric field question scenarios. However, only Student 12 continued this reasoning into the moving charge in a magnetic field question scenario (BFV).

RESULTS AND CONCLUSIONS

Since this study did not involve hundreds of students, the data cannot be generalized to a entire population of physics students. And, from the Chi-Squared goodness-of-fit-test performed on the students' final course scores, the participants did not fully represent the population of students enrolled in the calculus-based introductory course at Kansas State University. However, the student participants were better performers on average than their peers. Thus, their responses of an 'incorrect' nature hold more value. From these responses, trends and themes emerged.

These results show that students also do not use Newton's Second Law reasoning in the full range of course topics. The mental models used by students and classified into the Aristotelian or Impetus category are similar to the results of other researchers [10, 27, 38]. However, the present study indicates strongly that the students' use of these alternative mental models is dependent upon the context of the physical situation. A student who uses the scientifically accepted model in analyzing one scenario may choose an alternative model in another.

As Table 4 indicates, many of the students stopped using a Newtonian model as the year progressed. However, this conclusion is not universal. One student reverted from consistently using Newtonian-based mental models for only the moving charge in a magnetic field (BFV) scenario questions out of eight questions asked of him. Every indicator implies that this should not have occurred. The moving charge in an electric field (EFV) and magnetic field (BFV) scenarios are rather similar in nature. This student answered the electric field questions using a Newtonian-based mental model but not the magnetic field questions. Tutoring occurred between the two interview sessions as well which should have re-enforced the Newtonian-based mental model employed consistently up to that point by this student. It did not. Clearly for this student, the moving charge in a magnetic field (BFV) scenario caused some consternation.

Likewise, all of the student responses for the force applied to a wrench (WR) scenario questions were categorized as either Aristotelian or Newtonian in nature. This either-or situation was not repeated in any other scenario. Additionally, the wrench scenario questions were followed by the simple harmonic motion (SHM) scenario question in the same interview session. Tutoring occurred at the end of the interview and so could not have come into play. Three student responses to the SHM scenario questions were categorized differently than the responses to the wrench (WR) scenario questions asked only minutes previously. These contextual scenarios definitely affected the student's choice in using Newton's Second Law.

Similarly, the moving charge (CHV) questions followed the charge from rest (CH) scenario questions in the same interview session. Three student responses changed category between these two scenarios when an initial velocity was incorporated. However, only one of these students remained consistent with this adjustment when the velocity was added between the charge from rest in an electric field (EF) and moving charge in an electric field (EFV) scenarios. So the addition of an initial velocity triggered some students to change mental models.

Three students responded differently to the charge context (CH and CHV scenarios) than to the field context (EF, EFV and BFV scenarios) with respect to Newton's Second Law reasoning. This result is further clarified by the categorization of the non-Newtonian responses. The Size and Impetus categories only appeared in the field context.

The above evidence clearly shows that question context does cause students to use various mental models in responding to differing scenario questions. Yet, all students were able to apply a Newtonian model immediately after instruction on this topic. Thus, this issue does not seem to be a failure to learn the appropriate physics.

With the exception of the first interviews, nearly all of the question contexts had both Newtonian and non-Newtonian student responses. What triggers one student to use a Non-Newtonian model may trigger another to use a Newtonian model. A clear indication that a certain context will cause more or less use of Newtonian-based mental models did not emerge from the data.

The evidence does not indicate that once a student changes from being congruent with Newton's Second Law he or she will remain incongruent for the remainder of the course. Instead, some students switched back-and-forth between Newtonian and non-Newtonian mental models in responding to different scenario questions. The data provide few clues to understand what details of the scenarios that might have caused these switches.

Strong evidence indicates that rather small changes in a scenario can trigger a rather large change in the mental model that students are using. This change is most apparent in the differences in mental models between the CH and CHV and the EF and EFV scenarios. Here, a difference that a physicist would consider relatively small - initially at rest versus moving - caused major shifts in some students' application of mental models.

This study, thus, emphasizes the scenario in which a physics problem is presented is very important in determining the mental model which students apply. The data are not sufficient to discover any underlying reason for the effect of scenario on mental model.

Implications for Instruction

Research [7, 23] has shown that when novices and experts are presented with the same problem to solve, their responses differ because experts organize the needed information better than novices. To help students along the path towards mastery, inclusion of Newton's Second Law by explicitly showing how and where it is useful in other course topics would help delineate the boundary conditions of its use which are clear to experts but only to some novices. This clarification of boundary conditions may help expand students' contextual appreciation.

The student participants in this study were exposed to Newton's Second Law in other contexts via the interview questions. During the tutoring sessions that followed each interview, many students had 'aha' moments demonstrating a connection or clarification previously missed on their curricular path. These connections increased the students' awareness of the boundary conditions moving them towards mastery. Some of these questions could be posed to the students in class as part of the instructional process which would require little additional time. They may even be appropriate for use with an electronic response system.

The entire second semester had many variations in student's use of Newtonian-based mental models. The charge and field contexts triggered non-Newtonian models from students who otherwise provided consistent Newtonian responses. These scenario questions required the student to include Newton's second Law in ways that no other task in that portion of the course elicited. The introduction of mass into these problem scenarios troubled many students. They relied on equations since they had no first hand intuition regarding the subject. According to some students' logic, the equation of force in electricity and magnetism had no explicit mass component as Newton's Second Law does. Therefore, mass does not affect the motion in charge problems.

The student participants were not the only ones to have trouble with mass in the charge context. When testing a protocol, several graduate students and faculty members neglected gravity in response to a modified Millikan experiment scenario question until triggered with the fact the particle has mass. The boundary condition of including mass for delineating the choice to use Newton's Second Law or not then became clear. Exposing this boundary condition during instruction would benefit student learning and unify understanding

In addition to mass, the introduction of an initial velocity in charge and field scenarios caused some students to give non-Newtonian responses to questions. This velocity triggered both Aristotelian and Impetus type of mental models. Thus, velocity appears as a boundary condition to novices and not to experts. This initial velocity of a charge needs to be addressed separately and clearly in the second semester contexts.

The assumption of transference is most apparent in these findings from the wrench contextual scenario question. The assumption that a student will map the linear context easily to the rotational context is also reflected in textbooks. The textbook used by the students in this study offered only 17 homework problems that require Newton's Second Law in a rotational context as compared to 94 homework problems listed for a linear context [19]. For three recent instructors of this course at Kansas State University, the assigned problem ratio has been about four linear context problems for every rotational context, following the textbook's lead. That ratio reflects about four homework assignments in a linear context and one in rotational context. With respect to time, that means two weeks versus three days for a student to absorb these concepts.

Addressing rotational contexts as a separate domain instead of a tacit subset of mechanics would help the situation. Demonstrations and conceptual questions typically included with the introduction of a new concept would then be applied.

Final Discussion

The explicit or implicit assumption made by many instructors is that once a student has learned and understood a concept in one situation, she or he will then be able to apply it to another situation when required. This assumption of transference has been exposed as a poor one to make. Concept transfer to other contexts has been described as a process of learning called contextual appreciation. From the constructivist perspective learning takes effort. The student must construct the knowledge. In this case, the student must construct connections between concepts and contexts and vice versa.

This longitudinal investigation found that students do employ Newton's Second Law in contexts other than those used during the instruction of Newton's laws, but they are not consistent in doing so. The context and scenario affect students' choice of mental models when responding to questions that require Newton's Second Law. Each scenario investigated (rotation, simple harmonic motion, electric charges, electric and magnetic fields) was troublesome for some portion of the student participants. These results show that students are in different stages with respect to contextual appreciation of Newton's Second Law.

Students may increase their contextual appreciation with inclusion of Newton's Second Law topics throughout the course topics. The rotational, electric charge and field contexts appear to have especially weak connections to students' use of Newton's Second Law. Instruction including Newton's Second Law in these areas may help students expand their understanding of the boundary conditions for using this and other concepts in harmony.

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