Spring 5-14-2016

Inconsistent Conceptions of Acceleration Contributing to Formative Assessment Limitations

Gregory D. Kranich
University of Maine - Main, gregory.kranich@maine.edu

INCONSISTENT CONCEPTIONS OF ACCELERATION CONTRIBUTING TO FORMATIVE ASSESSMENT LIMITATIONS

By

Gregory Douglas Kranich

B.S. University of Maine, 2009

A THESIS

Submitted in Partial Fulfilment of the

Requirements for the Degree of

Master of Science in Teaching

The Graduate School

The University of Maine

May 2016

Advisory Committee:

Michael Wittmann, Professor of Physics, Cooperating Professor of Education; Advisor

Eric Pandiscio, Associate Professor of Education

MacKenzie R. Stetzer, Assistant Professor of Physics, Cooperating Assistant Professor of Education

THESIS ACCEPTANCE STATEMENT

On behalf of the Graduate Committee for Gregory Douglas Kranich I affirm that this manuscript is the final and accepted thesis. Signatures of all committee members are on file with the Graduate School at the University of Maine, 42 Stodder Hall, Orono, Maine.

Michael Wittmann, Ph.D. April 5, 2016

LIBRARY RIGHTS STATEMENT

INCONSISTENT CONCEPTIONS OF ACCELERATION CONTRIBUTING TO FORMATIVE ASSESSMENT LIMITATIONS

By Gregory Douglas Kranich

Thesis advisor: Dr. Michael C. Wittmann

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Teaching
May 2016

Science, technology, engineering, and mathematics (STEM) education has become a national priority in light of measures indicating marginal student interest and success in the United States. Just as evidence is integral to policy decisions, so too do teachers depend on evidence to inform instructional choices. Classroom assessment remains a touchstone means of gathering such evidence as indicators of students' progress, and increasingly, teachers are designing, implementing, and interpreting assessments in collaboration with one another.

In rural Maine, the work of the Maine Physical Sciences Partnership (MainePSP) has enabled science educators to come together as a supportive professional community. We focused on a team of MainePSP teachers as they developed common assessments for a unit on force and motion concepts. During group discussions individual members vetted their own ideas about acceleration comprising the following perspectives: a) terminology used to describe acceleration, b) the sign of acceleration as an indicator of speeding up or slowing

down, and c) the sign of acceleration as an indicator of direction, dependent on the change in both the magnitude and direction of velocity. The latter two ideas could be in agreement (when motion is in the positive direction) or conflict (when motion is in the negative direction). With objectives to accomplish and limited time, the team opted to only include an item about motion in the positive direction, leaving the inconsistencies of their ideas unresolved. As a result, the assessment lacked the ability to provide sufficient evidence of which idea students might hold.

We examined the group's interactions as captured by video recording and employed basic qualitative methods to analyze the event as a case study. Our findings suggest that an incomplete understanding of acceleration limited the teachers' ability to resolve their initial conflict. Further, the item's susceptibility for students to provide correct answers for the wrong reasons was not recognized at the time. We consider the item's implications on teachers interpreting student assessment responses, masking a potential need for adjusted instruction by teachers and conceptual refinement by students. Finally, we discuss the pedagogical implications and limitations of this study.

DEDICATION

To Haley, whose inspiration keeps me listening, growing, and pushing forward with humility.

I know how to be brought low, and I know how to abound. In any and every circumstance, I have learned the secret of facing plenty and hunger, abundance and need. I can do all things through him who strengthens me. (Philippians 4:12–13)

ACKNOWLEDGEMENTS

Firstly, my sincere gratitude goes to my thesis advisor and mentor Dr. Michael Wittmann. Such genuine trust, encouragement, and compassion are elusive by today's standards. It was his unwavering confidence in this project that sustained its trajectory. I would also like to thank my post-doc mentor Dr. Carolina Alvarado, whose drive, enthusiasm, and effervescence are unequivocally contagious. Gracias por sus muchas horas de ayuda y orientación, y por su gracia interminable mi buen amiga. Under the tutelage of these extraordinary individuals, I was able to evolve from someone conducting a research project to recognizing myself as an educational researcher.

Besides my mentors, I would like to express my appreciation for the rest of my thesis committee: Dr. Eric Pandiscio, and Dr. MacKenzie Stetzer, for their feedback and support during the process.

Dr. John R. Thompson and Dr. MacKenzie Stetzer played an integral role in making this study possible. Thank you for the various opportunities that led to the culmination of this project.

Thank you to the many faculty, staff, students, and teachers involved with the RiSE center for the tremendous support and collegiality.

I would like to recognize the incredible team of teachers involved in this study. We would be remiss not to situate the events described as only a very small fraction of the tremendous work and accomplishments made by this group. Five individuals conducting a curriculum overhaul in two weeks, and doing a good job at it in light of self-admitted content area discomfort, was not a trivial feat. Furthermore, this group inherently assumed ownership of the outcomes, good or bad, which were to be scrutinized by a larger cohort of their peers, already dissatisfied with the pre-existing curriculum. With open minds and determination, the group delivered. The results of their work have since motivated professional development efforts, continued research, and ongoing curriculum refinement, now in its second iteration. Preliminary data suggest increased student performance after instruction compared to the previous version according to work in progress by the MainePSP group. Perhaps the most important outcome that may not often be presented as a statistic, is the sense that students are having fun, where there had previously been widespread boredom and frustration according to informal conversations with teachers. The opportunities that these teachers took to grow professionally, and the continued lasting impact that their efforts have on students is certainly worthy of celebration.

Finally, my profound love and thanks goes to my family: my daughter, my parents, and to my sisters for your prayers and support throughout writing this thesis and life in general.

This project was supported in part by NSF grants MSP-0962805 and DRL-1222580.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1. The Complexity of Teaching

Any teacher will attest to the fact that good teaching is not so simple as transferring one's knowledge of a particular subject to a classroom of receptive students, and a large body of research evidence stands to support this position. However, quantifying what a teacher is to know to ensure effectiveness has proved an arduous task yielding little consensus. Defining what a teacher should know about the subject he or she is teaching is highly debated. Studies suggest that these domains of knowledge are actually interrelated and simultaneously independent, which is to say that a teacher's knowledge in an academic discipline informs his or her knowledge of the most appropriate methods of supporting student learning of said discipline, and vice versa (H. C. Hill, Schilling, & Ball, 2004; Magnusson, Krajcik, & Borko, 2002). Yet, we lack a complete understanding of the mechanism that employs these domains to lead teachers to make the best pedagogical choices.

Given the complexities of teaching, the role of teacher educators is particularly challenging, both in support of in-service teachers in improving their practice, as well as providing sufficient preparation for new teachers entering the field. In teaching, there is an expectation of learning on the job. Unfortunately, the extent of what must be learned upon entering the classroom is proving to be a formidable barrier to teacher retention and fostering high levels of student achievement in the United States (Kaiser & Cross, 2011).

Results of student achievement are summarized by the Congressional Research Service (Kuenzi, 2008), which recently reported marginal student success in K-12 science, technology, engineering, and mathematics (STEM) disciplines. Similar findings were described in the executive report to President Barack Obama, *Prepare and Inspire: K-12 education in Science, Technology, Engineering, and Math (STEM) Education for America's Future*, stating that work must be done to better support and prepare students and teachers in STEM (President's Council of Advisors on Science and Technology, 2010). Thus, a precedent has been set demanding higher quality teacher training and classroom instruction in these fields.

1.2. Context of the Study

Large-scale efforts have been undertaken to address problems thought to be contributing to our students' marginal success. One such effort has been fervently implemented in rural regions of the state of Maine over the past five years. The Maine Physical Sciences Partnership (MainePSP), an NSF funded project affiliated with the Maine Center for Research in STEM Education (RiSE Center), has sought to bring science teachers together to create a supportive professional network. With the lowest population density east of the Mississippi River (43.0/sq. mi) (US Census Bureau, 2010), Maine is home to individuals who may be the sole middle school science teacher within a 50-mile radius. The MainePSP has addressed some of the challenges of teaching in isolation by providing the infrastructure for teachers to develop meaningful and sustained relationships. As a result, the community of educators is supporting one another in a multitude of ways. The program aims to provide Maine students with a comparable experience in science regardless of their school's location or available resources.

One particular arm of the MainePSP has been selecting common instructional resources for use amongst participating districts. By creating a mutual experience and knowledge base centered on a single set of resources, members engage in a shared conversation regarding classroom materials, instruction, and assessment. The eighth grade science curriculum includes instruction in the areas of energy, chemistry, and forces and motion. The broad spectrum of topics addressed presents challenges to instruction in terms of science content knowledge and content-specific best practices for a population of teachers typically lacking expertise in science.

1.3. Assessment: How Do We Know What Students Are Thinking?

To support learners, teachers need the ability to recognize where an individual student is at relative to a specific learning target. We refer to any means of obtaining this information as assessment. For the purpose of this study, we focus on classroom formative assessment, defined by Black and Wiliam (1998) as any activity used to elicit student understanding, which is interpreted by a teacher in order to give feedback and adjust instruction. Through classroom formative assessment, teachers are able to use student responses to provide descriptive feedback to a student regarding his or her in-the-moment progress, and adjust subsequent instruction to best meet the needs of a group of diverse learners. However, in practice there is little consistency on the meaning of, purpose of, and implementation of formative assessment.

1.4. Understanding the Relationship Between Teachers' Content Knowledge and Assessment Knowledge

In our research, we had the opportunity to study a small team of eighth grade science teachers working together to decide the goals for student learning, and how to assess understanding. The collaborative nature of their work provided us insight into the individuals' content knowledge of accelerated motion and the ways this knowledge was utilized in group discourse. During the team's work to design an assessment item on acceleration, we observed a point of group inconsistency regarding ideas about the sign of acceleration. Our research aim was to better understand what happened when the group reached a point of conflict, the nature of their disagreement, and finally, how the disagreement influenced the efficacy of the assessment item created.

1.5. Overview of This Thesis

The next several sections situate our study within existing research literature, describe the methods used to design and implement the study, present the results observed, and finally discuss the analysis of those results.

1.5.1. Existing Literature

Past research has devoted attention to the topics of knowledge for teaching, assessment, teacher collaboration, and physics education, but seldom in concert with one another. We explore past studies in these areas and identify gaps in the literature where our work makes a contribution.

1.5.2. Research Methods

In Chapter 3, we discuss the design of the study involving a team of teachers from the MainePSP. We used basic qualitative methods to examine a single assessment item designed by the team and the conversations and decisions involved in the development process. The research is presented in a case study format. I discuss my role in the group as well as the methods utilized in collecting and analyzing video recordings from the team's working sessions in further detail in this section.

1.5.3. Results

During the process of designing the item in question, we observed the decisions being made by the group and the nature of their consensus as it worked to complete the task. These findings will be discussed in detail in Chapter 4.

1.5.4. Discussion

The team of teachers came to a point of contention regarding a certain content idea. Chapter 5 offers an analysis of our findings used to address the following research questions:

- What happens when the group becomes aware of inconsistencies among the conceptual models they hold as individuals?
- What is the nature of these inconsistencies, both among the models themselves, and with those that are scientifically accurate?
- What is the nature of the group consensus, and how does it influence decisions for and the efficacy of the assessment item produced?

1.5.5. Implications

In the final chapter, we reflect on the research process described in this thesis and offer suggestions for instruction of acceleration and future research. Additionally, we take time to acknowledge the far larger body of work accomplished by the teachers, though it is not the focus of the following account.

CHAPTER 2

REVIEW OF THE LITERATURE

In this section, we situate our study within the existing literature on knowledge for teaching, assessment, teacher collaboration, and conceptual difficulties of acceleration. While research has contributed to each of the respective domains, efforts in one often lack explicit inclusion of the others. We identify where we broaden these domains and demonstrate their interrelatedness.

2.1. Modeling Teaching is Complex

The act of teaching involves complex and in-the-moment interactions between an individual's knowledge, goals, and beliefs towards teaching and learning. While there is agreement on the synergistic nature of these components (Magnusson et al., 2002), the interactions amongst them and exactly how they contribute to effective teaching are not well understood (H. C. Hill, Ball, & Schilling, 2008; McCrory, Floden, Ferrini-Mundy, Reckase, & Senk, 2012; Speer & Wagner, 2009).

Since Shulman's (1986) delineation of subject matter knowledge and pedagogical content knowledge (PCK), researchers have continued to refine and categorize the types of knowledge that teachers have and how they use them. In science education, Magnusson and colleagues (2002) have developed the "components of pedagogical content knowledge for teaching science," while in the mathematics literature, Ball's research group (2008) has devised "domains of mathematical knowledge for teaching." Though the disciplines vary, the emphasis on the importance of teachers' understanding of subject matter in addition to practice-oriented knowledge for teaching remains consistent.

Studies on teachers' PCK have shown that, while the components act as part of a whole, development focused on one does not insure growth in others (Heron, Michelini, & Stefanel, 2008). Understanding teachers' knowledge has become a moving target as researchers attempt to simultaneously define and measure PCK (Alonzo, 2007). For the purposes of this study, we focus on the interplay between two components of this system, content knowledge and knowledge for assessment.

2.2. Modeling Knowledge is Complex

Teachers' ways of knowing can be described from many perspectives. Expanding on the frameworks mentioned in the previous section, components of pedagogical knowledge for teaching science (Magnusson et al., 2002, p. 97) include:

- orientations toward science teaching,
- knowledge of student ideas,
- knowledge of curriculum,
- knowledge of assessment, and
- knowledge of instructional strategies.

The domains of mathematical knowledge for teaching (Hill et al., 2008) are divided into two subcategories, subject matter knowledge and pedagogical content knowledge. The former comprises:

- common content knowledge (CCK),
- mathematical horizon knowledge, and
- specialized content knowledge (SCK),

while pedagogical content knowledge includes:

- knowledge of content and teaching (KCT),
- knowledge of content and student (KCS), and
- knowledge of curriculum.

While we acknowledge the multifaceted landscape of teachers' understanding, we narrow our focus to only knowledge for assessment and subject matter knowledge, also referred to as common content knowledge (CCK).

Described by Ball and Bass (2000), CCK is the formal knowledge developed by professionals in a particular discipline, such as the knowledge a mathematician has of mathematics. While content knowledge alone has proven insufficient for effective teaching (Speer & Wagner, 2009), research also suggests that it can act as a limiting factor regarding other aspects of teaching, such as assessment (Stein, Baxter, & Leinhardt, 1990). Although effective instruction requires teachers to know at least the level of content that he or she will be teaching, studies show that teachers need to know subject knowledge in ways that are uniquely specialized compared to other experts (Ball, Lubienski, & Mewborn, 2001). What is most useful for teachers to know beyond that falls into contention (McCrory et al., 2012).

In an effort to explore the effects of utilizing multiple dimensions of knowledge for teaching, Schneider and Krajcik (2002) observed three eighth grade science teachers' knowledge development in a force and motion unit through the use of educative curriculum materials. Grounded in a PCK framework, results suggested that teacher materials focused on aspects of PCK could promote both science content knowledge and pedagogical knowledge. Features such as focus on student ideas and asking questions to discern student understanding proved effective for furthering teachers' individual conceptions of concepts like velocity and speed. In light of this research, though a very small sample, there is a need to explore teachers' subject matter knowledge itself, and its relationship to components of PCK such as assessment knowledge.

2.3. Modeling Knowledge for Assessment is Complex

Teachers' knowledge of assessment in science includes knowledge of what topics and skills are important to assess, and the many different methods of measuring student understanding to choose what is most appropriate for a group of students (Magnusson et al., 2002). While knowledge of the various methods of assessment is essential to the practice of teaching, effective assessment of students' ideas places further demands on a teachers' knowledge.

Knowledge for effective assessment requires a teacher to select or design and evaluate the efficacy of a task as a means to elicit a best representation of students' understanding in a particular domain. Furthermore, teachers must be adept at accurately interpreting and appropriately responding to individual student ideas in light of those data obtained from the task (Black, Harrison, Lee, Marshall, & Wiliam, 2004; Black & Wiliam, 1998; Coffey, Hammer, Levin, & Grant, 2011; Cowie & Bell, 1999; Otero, 2006; Ruiz-Primo & Furtak, 2007; Sadler, 1989).

The focus of our study is on an example of knowledge for effective assessment in conjunction with subject matter knowledge, as exhibited by a small collaboration of teachers. More specifically, we explore how both domains of knowledge influence the group's capacity to diagnose and resolve potential student difficulties.

2.3.1. Formative Assessment

While the realm of classroom assessment is diverse, we center our attention on knowledge used by teachers to design and implement formative assessment. For the purpose of this study, we use the definition of formative assessment developed by Black and Wiliam (1998) as any activity used to elicit student understanding, which is interpreted by a teacher in order to give feedback and adjust instruction. For the sake of clarity, we identify the type of assessment studied as planned or formal formative assessment as described by Cowie and Bell (1999).

Since its original conception by Scriven (1967) as a method of evaluating curricula, and Bloom's (1969) proposal as a means of assessing student understanding throughout the learning process, the intent has been for formative evaluations to motivate adjustment by practitioners (as cited in Wiliam, 2006). The instrument itself is used to promote a feedback loop between teachers and students during the learning process such as the one shown below in Figure 2.1.

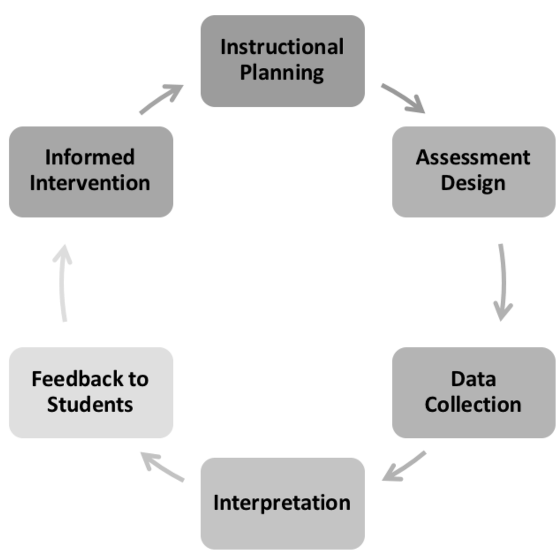


Figure 2.1. A teacher/student feedback loop throughout the learning process.

Formative assessment as a practice requires teachers to employ specific tasks in order to further this feedback loop in the interest of student learning. Specifically, teachers are required to elicit, interpret, and respond (Cowie & Bell, 1999) to student ideas throughout the learning process as a means of answering the questions (Black & Wiliam, 1998):

- Where are my students now?
- Where do they need to go?
- How do I help them get there?

The need to answer these questions speaks to the import of both the selection of an effective instrument and the teacher's actions following students' completion of the assessment task.

2.3.2. Formative Assessment Criticism

While formative assessment is becoming increasingly popular as a practice that embodies good teaching, it has received criticism as being void of a particular theory of learning (Otero, 2006) and lacking attention to conceptual detail (Coffey et al., 2011). These studies have evaluated teachers' implementation of assessment items, but do not provide insight into the decision-making processes by teachers, and how those processes influence the implementation and quality of an assessment task.

Therefore, there exists a need to better understand the relationship between the design and implementation of formative assessments by teachers, and the content knowledge utilized during the process. Uncovering these interactions requires explicit attention to how teachers employ their content knowledge during the process of assessment design and decision-making (Avargil, Herscovitz, & Dori, 2011).

As an example, a recent study of elementary school teachers' content knowledge and assessment practices found only indirect associations between the two, speaking to difficulty of measuring these qualities (Herman, Osmundson, Dai, Ringstaff, & Timms, 2011). Given the complexity of these knowledge domains, we focus on the basic assumption that they inform each other, and that teachers move back and forth between them as they create assessments.

2.4. Teacher Collaboration

Many of those being asked to teach science are not well-prepared with respect to content knowledge, as a recent survey showed that many middle school science teachers held a degree or certification in a field unrelated to science (J. G. Hill, 2011). As a result of this systemic gap in preparedness and other barriers to accessing quality professional development opportunities (Darling-Hammond, 2005), the teacher learning paradigm has shifted to one of peer collaboration. These professional learning communities (PLCs) can promote a better sense of community and shared knowledge amongst colleagues (DuFour, Eaker, Association for Supervision and Curriculum Development VA, & National Educational Service IN, 1998). In relation to our work, teams of teachers who are not content experts in science can benefit on a supportive professional network drawing from a shared body of knowledge, namely CCK and knowledge for effective assessment.

One way teachers collaborate is through the creation of common assessments–those developed cooperatively by teachers of the same grade and subject area–across multiple classrooms as a means of comparison and evidence of curricular and instructional effectiveness (Stiggins & DuFour, 2009). Communication is integral to successful assessment creation as a team, as the group's collective knowledge and experience can inform assessment and instructional decisions. Common assessment design requires teams to arrive at consensus regarding the decisions to be made about what is important to assess, what constitutes acceptable evidence of student success, and how to measure student understanding. Furthermore, the process lends itself to facilitating discourse amongst members, increasing clarity of student learning objectives and overall assessment quality (Stiggins & DuFour, 2009).

We describe a study in which we observe a team of teachers developing an assessment and the role that content knowledge plays in completing the task. This process has traditionally been unobserved due to the individual nature of teachers' classroom preparation. Our opportunity to observe teachers in a professional group lends itself to gaining a better understanding of how teachers use subject matter knowledge during assessment generation by analyzing decisions that are made by the group, and the conversations surrounding them.

2.5. Instruction in Accelerated Motion

The previous sections spoke to the complex system of knowledge required for teaching with content knowledge as one subset of this system. This section explores the subset of content knowledge within the context of accelerated motion in light of past research in physics education. Studies described in the following sections imply that a deep conceptual understanding of acceleration, though considered to be an elementary and foundational concept, requires a great deal of cognitive demand, proving difficult for students and experts alike.

A review of the literature is presented regarding this content topic and its difficulties. We explore the scientific meaning of concepts that are foundational to acceleration as well as the intuitive ideas and everyday notions that have been found to cause dissonance in the minds of learners.

Acceleration is recognized as fertile ground for witnessing individuals vetting their scientific conceptions with their everyday, intuitive notion of a concept. Reif and Allen (1992) considered acceleration as representative of other fundamental concepts in the physical sciences. Through pre- and post-tests and interviews of college physics students and professional physicists, the pair found the development of a deep conceptual understanding of acceleration to be cognitively demanding, requiring learners to delineate the scientific domain from that of everyday life. Like other studies on students' preconceptions in physics (Clement, 1982; Halloun & Hestenes, 1985; Smith, III, DiSessa, & Roschelle, 1993), Reif and Allen found learners' incoherent conceptions persisting even after instruction.

2.5.1. Colloquial Confusion

During the development of a conceptual understanding of motion, students encounter difficulties not only related to the ideas, but to the use of language as well. Contrary to colloquial usage, words like acceleration, positive, and negative have specific meanings when used to describe motion.

The term acceleration is used to describe increasing speed in everyday language. However, in a scientific context acceleration generalizes to any change in the speed and/or direction of an object, or simply, any change in velocity. Acceleration describes objects when they are speeding up, when they are slowing down, and even when they are traveling at constant speed and changing direction (circular motion). Referring to a chosen coordinate system, to be explored later, the modifiers positive and negative are used to describe the direction of changes in velocity. Thus positive acceleration can be used to describe objects speeding up, as one might intuitively expect, but can also be used to describe objects slowing down, which may seem counter-intuitive. Similarly, studies by Reif and Allen (1992) and Trowbridge and McDermott (1981) found the everyday usage of "acceleration" to interfere with conceptual coherence. Further work has expanded on these results, as described below.

2.5.2. Middle School as an Opportunity for Conceptual Mechanics

Introductory mechanics has long been identified as being particularly difficult at all levels of instruction for both students and teachers alike (Hake, 1998; Hammer & Elby, 2003; Hestenes, Wells, & Swackhamer, 1992; Trowbridge & McDermott, 1981).

It is important to note that these studies reflect measures of conceptual understanding, rather than the algorithmic proficiencies traditionally taught and practiced using mathematical descriptions of forces and motion. The studies cited have generally focused on postsecondary physics students, juxtaposing previous academic success and a persisting lack of thorough conceptual understanding. Relevant to our study of teacher knowledge and assessment, findings suggest that the type of knowledge associated with traditional learning in physics is required, but not sufficient for deep conceptual understanding.

We study accelerated motion at the middle school level. Typical middle school science classrooms are heterogeneous, as not all are taking/have taken algebra, constraining teachers from using an algebra-based approach to instruction. The Next Generation Science Standards (NGSS) (Lead States, 2013) have set the following performance expectation for middle school: “Students who demonstrate understanding can: Plan an investigation to provide evidence that the change in an object’s motion depends on the sum of the forces on the object and the mass of the object” (p. 56). To provide greater detail about the aims for such a student task, the following statement is included: “Clarification Statement: Emphasis is on balanced (Newton’s First Law) and unbalanced forces in a system, qualitative comparisons of forces, mass and changes in motion (Newton’s Second Law), frame of reference, and specification of units” (p. 56). Though acceleration is not motioned explicitly, it is referenced by “the change in an object’s motion”. The case of non-zero acceleration, however, is made explicit as students are to investigate and compare instances of both balanced (a=0) and unbalanced (a≠0) forces. Stated, perhaps subtly, is a need for students to be able to provide “qualitative” and physically meaningful descriptions of acceleration at the middle school level.

2.6. Conceptual Resources Available at the Middle School Level

In the sections that follow, we present some resources that require development in order to construct a more complete understanding of acceleration at the middle school level. We are not suggesting the extent to which they need to be covered, but we consider all of them necessary to correctly interpret the concept of acceleration.

2.6.1. Defining a Coordinate System: Necessary and Arbitrary

In order to communicate the nature of motion to someone else, it is required that a contextual orientation is described, essentially letting an audience know which ways are up, down, left, and right. Though the orientation chosen is arbitrary, the defined coordinate system dictates all subsequent descriptions of motion. Beginning with a basic one-dimensional number line, positive and negative are used to describe directions of travel with reference to some defined origin.

Unlike the everyday notion of the word, positive is not indicative of an increase in amount or magnitude. Likewise, negative is not indicative of a decrease in amount or magnitude. Instead, these terms are used to describe a particular direction in reference to a pre-defined coordinate system.

While solving problems in mechanics, students in twelfth grade (Bowden et al., 1992), as well as at the college level (Hayes & Wittmann, 2009; Sayre & Wittmann, 2008) have demonstrated a limited ability to choose the coordinate system in a way that avoided unnecessary effort in arriving at a solution. These studies illustrate students' persistent difficulties attaining fundamental proficiencies in physics, such as coordinate systems, despite multiple experiences throughout a student's academic career. Observations of these learning gaps at the college level motivate the need to better understand students' ideas about coordinate systems in physical contexts in earlier grade levels, where there is a shortage of literature.

2.6.2. Vectors: Magnitude and Direction

Once a coordinate system has been defined, one can describe motion accordingly. An understanding of what constitutes the positive and negative directions is required in light of the coordinate system choice. Describing relative motion necessitates the identification of a particle's direction of motion and how quickly it is moving within a given frame of reference. The use of vectors offers a convenient means of describing both components simultaneously, as they indicate the direction and magnitude of a specified rate.

In a study on introductory physics students' understanding of vectors, Flores, Kanim, and Kautz (2004) found the majority of students hesitated to use vectors when reasoning about forces and motion. The group suggested substantive changes to the ways vectors are emphasized in introductory physics courses in order to improve students understanding.

Shaffer and McDermott (2005) developed and implemented research-based instructional materials in introductory physics with a greater emphasis on using vectors. Though students demonstrated larger gains after instruction with the new curriculum, difficulties persisted in students' ability to delineate vectors representing velocity and acceleration. Though, like Flores, *et al.* (2004), attention is directed to student understanding at the college level, both studies call for instructional shifts earlier in the school sequence.

2.6.3. Velocity: A Ratio

One rate described by magnitude and direction is velocity. This quantity communicates a ratio of a change in position along the number line relative to an increase during each standardized unit of time. Where speed only describes how much position is changing each second, velocity also indicates the direction of said change.

Studies by Bowden et al. (1992) and Trowbridge and McDermott (1980) reveal college students' difficulties with he concept of velocity in introductory physics courses. Not unlike those focused on other concepts, these studies suggest that students experience problems when distinguishing between various quantities (e.g. velocity and position).

A previously mentioned study by Schneider and Krajcik (2002) suggests that middle school teachers also demonstrate limited understanding of velocity, notable in the case of relating velocity and speed when velocity is in the negative direction. Our work attempts to build on these findings and to establish a better understanding of teachers' conceptions at the middle school level.

2.7. Common Threads in the Literature

While the studies described in the previous sections vary slightly in conceptual focus, their findings exhibit many parallels. We offer brief descriptions of the most noticeable patterns, and how they relate to our work.

2.7.1. Conceptual Understanding

As previously indicated, the central focus of physics education research has been on students' ability to apply knowledge of a concept across multiple contexts and representations, and to explain their reasoning in a consistent and correct manner. Emphasis has been placed on the need for students to provide physically meaningful descriptions not only of concepts, but also of the procedural steps necessary for correct interpretation, or operational definitions (Arons, 1997; Flores et al., 2004; Shaffer & McDermott, 2005; Trowbridge & McDermott, 1980; 1981).

2.7.2. Internal Coherence in Mechanics

In light of the challenges associated with the direction of acceleration, the predictive and explanatory power of an analysis of the forces on an object becomes an especially valuable tool. This and other concepts that provide a coherent framework within mechanics have been cited as means for students to make sense as they transition from one concept to another (Bowden et al., 1992; Shaffer & McDermott, 2005; Trowbridge & McDermott, 1980; 1981).

2.7.3. Assessment Practices

The implications of previous research efforts most clearly call for more careful methods of assessment as learners move within the conceptually demanding domains of physics. Though recommendations are not referred to as "formative assessment," they clearly describe practices consistent with our definition of the term. Bowden et al. (1992) suggest that, "…[T]eachers can better assist conceptual change in students if they are clearer about what the current student conceptions are and in which direction they intend student understanding to develop" (p.267). Likewise, Trowbridge and McDermott (1980) found that, "The results of our investigations are consistent with our experience as instructors that for many students some form of active intervention is necessary for overcoming confusion between related but different concepts" (p. 1028). Reif and Allen (1992) speak to the role of the student in assessment in their suggestion to, "…[A]sk them to detect mistakes of concept interpretation, to diagnose the likely reasons for them, and to correct them" (p. 38).

Given the importance of a conceptual understanding of acceleration as the change in both the magnitude and direction of velocity, it is germane to explore the design of a formative assessment item that aims to address it. The evaluation and interpretation of students' current conceptual understanding then relies on the item to generate sufficient and reliable evidence to inform teachers' subsequent pedagogical decisions. This study demonstrates the challenges teachers face while making assessment decisions and grappling with their own conceptions in a content area that has been shown to be difficult.

CHAPTER 3

METHODOLOGY

Given the literature regarding teachers' formative assessment practices and the conceptual difficulty of accelerated motion described in the previous chapter, there exists a need to observe teachers during the process of designing assessment. Typically, we, as researchers, do not witness this process due to its nature as an individual practice that occurs outside of the classroom. This project presented us the rare opportunity to work with a small group of teachers working collaboratively to create formative assessment items for use as part of an eighth grade unit on force and motion.

3.1. Research Design

The following section describes the choices involved in the design of this study.

3.1.1. Basic Qualitative

My inquiry featured a single group of teachers engaged in assessment development. The complex nature of the interactions amongst group members in reaching consensus warranted a basic qualitative approach grounded in social constructivism consistent with the depiction given by Creswell (1998). A basic qualitative study was an appropriate choice in meeting my general research goals. I sought to understand the process of teacher-developed assessment and how they expressed subject matter while deliberating with one another. The collaborative nature of the study allowed access to underlying cognitive rationale that is typically hidden by convention, as classroom assessment creation is primarily an individual act.

3.1.2. Case Study

The teacher activity being studied happened over four months with a single team of participants. Thus, the interactions analyzed were inextricably tied to the contextual aspects of the study, deeming it a distinctive case requiring rich description, similar to Merriam's (2009) definition of a case study. More specifically, my focus is on episodes of one meeting within the overall work of the group, resembling the features of a particularistic case study (Merriam, 2009). Given this framework, the case of interest can be defined as a group of four teachers working collaboratively to solve a problem during a meeting in November of 2014.

3.2. Context and Setting

Providing the primary organizational link amongst the participants of this study, the MainePSP served as a community of science educators dedicated to improving K-12 science education in Maine. Affiliation with the MainePSP offered teachers the opportunity to engage in an intensive effort to modify a unit of instruction being used in his or her eighth grade science classroom. Over the span of two weeks in August of 2014, a self-selected group of four teachers and myself as a facilitator produced a sequence of instructional activities that its teacher members would begin piloting in September and October of the upcoming school year. The focus of this study centers on the team's continuation of this curriculum project, creating assessments to accompany each of the four modules that had been developed.

The group and I conducted our work on the University of Maine campus, which also served as the hub for the community and events of the MainePSP. This location provided the most central and convenient place to meet, though our commutes ranged anywhere from 20 to 60 minutes, placing a constraint on our time together. A small conference room was a natural choice as our primary base camp, where we had conducted our work at the end of the summer, giving it the unspoken brand of "our space." The group gathered around a rectangular cluster of tables in the center of the room, where each member had ample space for his or her laptop and binder of curriculum materials and notes. Pairs of teachers faced one another from opposite sides of the cluster, and I sat on one of the sides adjacent to them. The empty side, opposite me, served as our obligatory coffee station and the location of a portable whiteboard or chart paper, as needed.

As previously described, the group comprised four in-service teachers and, on occasion, my four-year-old daughter, Haley. The teacher members of the group had been self-selected, continuing work on the aforementioned modified curriculum materials, including piloting the materials in his or her classroom. Similarly, I acted as the group facilitator and organizer as an extension of our previous work together.

As a group, we had been granted extended time to continue our work related to the curriculum modification effort. Maintaining my assignment as the group facilitator, I made the decision to focus our efforts on the creation of assessment instruments for each module of the curriculum. Assessments were chosen in light of a list of unfinished tasks that we had compiled at the conclusion of our summer work. As another deciding factor, these assessments would be able to be administered by the four teachers, who were concurrently piloting the revised materials, lending themselves as a measurement of not only student performance, but also a means of the group evaluating the piloted curriculum. Feedback provided by the assessments would allow us to make focused revisions of the materials based on emergent areas of need per the results. Prior to the emergence of refined research questions, the study centered on the creation of said assessments.

The group met approximately once a month from October 2014 through January 2015 with the primary objective of creating common formative assessment instruments to be included as part of the curriculum materials we had developed on the concepts of force and motion. We typically gathered in the evening, midweek, for approximately two hours per session.

3.3. Population Studied

We describe the teachers (pseudonyms) involved in the study disclosing their experience teaching science at the middle school level as well as their personal education background. In the interest of clarity, we wish to point out that participant selection was not a facet of our research design and group membership was self-selected.

3.3.1. Lisa

Lisa had been teaching middle school life science for nine years and had been assigned physical science classes for the first time in the past year. Her academic background was in education with a focus on biology. As a second year member of the MainePSP, Lisa had also become a participant in the MainePSP Leadership Academy (LA), a K-12 initiative for active members of the MainePSP to increase their capacity as leaders and advocates for change in their respective school districts.

3.3.2. Kristina

Kristina had been teaching for four years, three of those in physical science. She earned her B.S. in biology and had taken courses as part of a graduate program for teacher certification. Additionally, Kristina was a member of the second cohort of LA and a third year participant of the MainePSP.

3.3.3. John

John had been teaching for more than 20 years in physical science, and due to his experience, was considered the nominal “expert” of the group. He earned his B.S. in elementary education. In his second year of participation, John had become deeply involved in the MainePSP as a member of the second cohort of LA and the Leadership Team.

3.3.4. Derrick

Derrick was in his second year of teaching life science and mathematics. His background was in earth science, and like Kristina, he had become certified to teach as part of a Masters of Science in Teaching (MST) program. Like the MainePSP, the MST program is affiliated with the Maine Center for Research in STEM Education (RiSE Center). Derrick had been conducting research in teaching and learning forces and motion within the MainePSP as the focus of his thesis. Though not an official member of the MainePSP due to his teaching assignments outside of physical science, he had arranged to pilot the modified curriculum that he, as a co-facilitator, and the team had developed during the past summer. Derrick had also been involved as a facilitator for MainePSP teacher professional development in forces and motion.

3.3.5. Participant Observer

My background in teaching middle and high school physics informed my perspective as the facilitator of our group. I had been involved in physics education research (PER) during both my undergraduate and graduate student experiences. More specifically, in the summer of 2012, I acted as a co-facilitator a week-long MainePSP teacher professional development program for eighth grade science teachers. The program centered on kinematics and dynamics concepts and utilized research-based curriculum materials (McDermott & Physics Education Group, University of Washington, 1995) designed for physics teacher education.

In addition to my role as the organizer and facilitator of the group, I spent time in introspection before our work began to delineate my responsibility as a researcher to avoid a potential conflict of interest. While I knew that my participation would inherently influence the group, I wanted to allow the teachers as much autonomy as possible when it came to making decisions for assessment items. My selected role was to ensure the scientific accuracy of the group whilst remaining as unbiased as possible to specific assessment choices, save the express solicitation of my input. This relationship was akin to Gold's (1958) depiction of participant as observer. My discretion served as an effort to maintain a reasonably unclouded picture of the teachers' interactions and decisions regarding their conceptual understanding of and assessment goals for the topics being addressed.

My position as a researcher was disclosed to the group, and I shared the fact that I would be documenting and studying our process of developing assessments. The teachers took this information in stride, as they had conducted and/or participated in MainePSP studies in the past. As a participant observer, I employed a hermeneutic style of listening as to inform my level of participation, intervention, and ultimately, my interpretation of the events of the meetings (Davis, 1997). My interactions with the group resembled an interview at times, as I tried to elucidate individual's thinking, rather than merely evaluating its level of correctness or relying on my own interpretation.

Operating from an enactivist perspective of cognition (Varela, Thompson, & Rosch, 1991) enabled my recognition of the inherent complexity of the interactions amongst the group and relationship to the larger social, environmental, and historical systems (Davis, 1997). My participatory role served to maintain the rapport that I had previously established during our summer work and offered value to my presence as a resource available to the group in a content area that was self-reportedly tenuous for the four teachers. Having prior knowledge of the shared conceptual discomfort afforded me an increased sensitivity and empathy for the teachers as individuals whose lives involved much more than making sure that his or her students uncovered all the subtleties of Newtonian mechanics. However, the need for scientific accuracy created a tension with my empathy for the teachers. Finally, as part of the group, I was able to allow myself to become engaged in the spirit of a community and the task at hand, leaving the duty of documenting every nuanced happening to the video camera.

3.4. Data Collection

I gathered observational data from group meetings as a participant observer led by things I noticed, intuition, *in situ* interpretation, and *post hoc* reflections through a reflexive private research blog and journal. My evolving thoughts and ideas from one meeting to the next were captured in nearly 40 blog posts and 80 pages of handwritten notes, scribbles, and diagrams. In addition, I recorded nearly nine hours of audio/video data, photographs of team-generated whiteboards and chart paper, and kept track of 25 assessment items developed from the work that took place over the four assessment meetings. The collection of video as a primary source of data was informed by the work of Derry et al. (2010). Lauded for its ability to capture and archive detailed social interactions, video data lends itself to increased validity in that it can be reviewed and reanalyzed by multiple researchers.

3.5. Data Analysis

Analysis of the video and audio recordings took an iterative approach consistent with general inductive analysis (Thomas, 2006). Inductive analysis allowed major thematic patterns to emerge from the raw data through repeated studies of the video recordings, and eventual transcripts. The raw data, characterized as naturalistic observations (Creswell, 1998), were further distilled into events (Derry et al., 2010) for further analyses.

3.5.1. Video Episodes

From my direct observations, I reflected on my thoughts and reactions from each meeting via my research journal. The outcome of the second meeting struck me as being unusual in regards to the interactions of the group. It was clear that there were different ideas about acceleration, but the fact that certain concessions were made in resolving individual differences persisted in my mind. The concept of acceleration emerged as what is described by Star and Griesemer (1989) as a boundary object, namely the thing about which the group members had divergent views of its particulars, but agreed on its common identity. Once the assessment item was constructed in the follow-up meeting, it became clear that the events leading up to that moment warranted closer examination.

I managed the corpus of video data by adopting Erickson's manifest content approach (as cited in, Derry et al., 2010), guided by the subject of acceleration. The iterative progression of decreasing grain size began with pure observation of the video, followed by identifying time-indexed events, and ultimately resulting in transcriptions of the salient episodes.

3.5.2. Patterns Emerge

Emerging from these focused events, patterns of interactions became characterized as:

- discussion of acceleration as a concept for assessment,
- discussion of the scope of goals for student understanding of acceleration,
- and explanation of one's conceptual understanding of acceleration.

Research questions arose from careful study of the complex exchanges amongst the group. As previously noted, there were various ideas held by the individuals ranging from differences in how acceleration was talked about to the explicit descriptions of individual conceptions of the topic. The inconsistencies existing between the postures of the group members, and their eventual resolution became the focus of my inquiry.

Primarily, I was interested in the question of, "What happens when the group becomes aware of inconsistencies among the conceptual models they hold as individuals?"

Furthermore, I sought answers to the questions of, “What is the nature of these inconsistencies, both among the models themselves, and also with those that are scientifically accurate,” and “What is the nature of the group consensus, and how does it influence decisions for and the efficacy of the assessment item produced?”

3.6. Data Sample

Shaped by research question refinement, the sampled data were distilled to six transcribed episodes comprising approximately 13 minutes of video from a single meeting that lead to the creation of the one assessment item that I considered in this study. Said episodes featured group member elaborations of acceleration as a valued topic for assessment, ideas about potential student misunderstandings of acceleration, clarification of terminology use in the classroom, notions of acceleration held by individuals, and an episode in which I intervened in order to clarify the limitations of a particular conceptual model.

3.7. Credibility

Given the limitations of qualitative case studies, particularly with attention to my role as a participant observer, I was careful in employing methods that would support the validity of my research. Consistent with Erlandson, Harris, Skipper, and Allen (1993), I engaged in reflexive journaling, frequent peer debriefing, and persistent observation of recorded video and transcripts. My research blog was shared with my advisor, Michael Wittmann, and post-doctoral mentor, Carolina Alvarado, providing an additional forum for us to discuss my work outside of regularly scheduled meetings. Collaboration with these research colleagues also included viewing and discussing the video data together as a means of receiving feedback on my own interpretations.

Finally, my engagement with the group of teachers occurred over the span of several months after already establishing a rapport with them during our summer work, contributing to the trust and authenticity of our interactions.

Figure 3.1. Methods used to support credibility of the study.

CHAPTER 4

RESULTS

The methods described in the previous chapter provided us a perspective from which to observe the interactions and outcomes of the group's work. We now share these observations comprising transcript excerpts and detailed portrayals of the events surrounding the group design of an assessment item for use across eighth grade science classrooms.

4.1. Individual Postures Regarding Acceleration

In the next several sections, we present ideas expressed by the individual teachers about acceleration and how to assess it. Group discourse progressed from overall topics for assessment to specific details of acceleration as student learning goals.

4.1.1. How Do We Talk About Acceleration?

A recurrent theme in our discussion of acceleration was the language used in reference to acceleration. Conversation varied from specific word use to the same words generalizing to different meanings. Much of the debate reflected tension between individuals' everyday conceptions and scientific conceptions.

4.1.2. Topics for Assessment

To begin the meeting, the group came up with a list of topics to assess. Kristina read from a list of ideas that she had made in preparation for the meeting:

Kristina: …I said graphs, one with uniform motion and one with non-uniform motion; "describe how the motion of the two objects differs." I said something about a dot car map. I don't know if that's what you call it, but "what if it looked like it was *speeding up, slowing down, or maintaining uniform?" Um, I had average versus instantaneous [speed], and then I said the difference between speed and velocity, but then I put a note that I thought that might be too deep right now, but eventually we might want to go there. And then I put a note that acceleration can be positive or negative, because right now, they are having a hard time with the idea that acceleration must just mean that you are speeding up, and they don't think that it's both.*

Kristina's list included assessment goals that inherently focused on the concept of acceleration; however, explicit use of the term only came as a note at the end of her list in that "acceleration can be positive or negative" without reference a coordinate system. The other items in the list seemed to emphasize a contrast with uniform motion, instead of motivating the specifics of describing the nature of non-uniform motion.

4.1.3. Student Expectations

Discussion shifted to a closer focus on what students should know about positive and negative acceleration. Derrick explained his thinking about students misunderstanding that the direction of acceleration and the direction of motion do not have to be identical. To this, Kristina expressed discomfort with the level of understanding that Derrick sought for students.

Kristina: I feel like that's a lot deeper than what I was thinking. I was thinking simply that they would be able to tell me that there is negative and positive acceleration, and not necessarily that they would be able to identify that, like on a graph or anything, but to be able to state that they can see positive and negative acceleration in their car.

Kristina's reaction spoke to her desire to troubleshoot students' misunderstandings, but for her, those existed at the level of using the terminology correctly. As she mentioned before, her students were having trouble recognizing that acceleration can be used to describe not only an increase in speed, but a decrease as well. Thus, her attention had not been on the deeper understanding of vector direction as described by Derrick, but instead on positive and negative being modifiers of acceleration.

4.1.4. Consistent Terminology

After approximately fifteen minutes of discussion on the topic of positive and negative acceleration, Lisa asked a question about the terms Kristina was referring to. "We've been using the word 'deceleration'…is that not a word; 'decelerate'?"

This began a very brief (10-15 seconds) exchange between Lisa and Kristina diagonally across the table that neither asked for nor received input from the rest of the group.

> *Kristina: I've been discouraging that use just because I know we talk about positive and negative more than we do..., like I don't think the book says "deceleration" I think it says acceleration, and then ... but I'm not sure. I've- I've tried to not use it."*

Looking for further clarification, Lisa asked the group, "So how–in what they do with this, how are they seeing negative accell–when it slows down?" At the end of the discussion Lisa repeated aloud the limited rule that the group agreed on as she wrote it down on a piece of note paper: “positive acceleration is speeding up, and negative acceleration is slowing down.”

4.1.5. The Focus on Words

Due to the fact that the conversation focused on correct terminology, we lack a complete picture of what Lisa and Kristina held for a model of acceleration. Kristina talked about being consistent with the book’s use of positive and negative acceleration, but did not say what might be wrong with using Lisa’s terms other than that “…the book doesn’t say deceleration.” Kristina’s description of her expectations for students did, however, suggest that a student would be assessed on his or her ability to distinguish between uniform and non-uniform motion, and say that acceleration can be positive or negative, without getting into the details of describing changes in velocity.

4.2. The “Speeding Up is Positive Acceleration” Model

The next section explores a model similar to one held by John. Using his expressed ideas and descriptions, we develop a detailed representation of John’s thinking, focused primarily on his use of the terms positive and negative.

4.2.1. A Proponent of Acceleration

John conveyed his strong stance on students’ need to understand acceleration even in the section on uniform motion, which preceded the module on non-uniform motion (the focus of this thesis). More specifically, John had independently made the decision to give a formative assessment probe on acceleration before the topic was explored by students in the instructional sequence. Acceleration also became the focal point of an error-turned-opportunity in an activity from the uniform motion module. This error occurred during an activity in which students were supposed to achieve uniform motion with a ball bearing along an aluminum track. John's class elevated one end of the track in order to get the ball rolling, and instead measured non-uniform motion. Noting the error after the fact, he took the opportunity to discuss the mistake with the students as an example of acceleration, and then repeated the activity correctly. During the meeting, John reiterated the fact that "students should know about positive and negative acceleration" for the assessment.

4.2.2. A Model Defended

I attempted to push on this for clarification by asking, "What do students know about positive acceleration," to which John replied, "It's speeding up…and I think we've always used negative is slowing down." Derrick mentioned the caveat that acceleration does not have to be in the same direction as motion, which brought up the point that the sign of acceleration indicates its direction, but not necessarily the direction of motion. This created discord with John's model, upon which he further explicated his position in an example offered to the group.

> ***John:*** *Let's say you put a big fan at the end; the car's coming toward it. It stops; it goes the other way. That has to be a positive acceleration, because it was speeding up going the opposite direction. It can't be a negative acceleration. Negative acceleration would be the slowing down to the stop, and then a positive… If it's speeding up going in the opposite direction, wouldn't that be positive- still positive acceleration; it's getting faster. I've always seen that positive acceleration is an increase, and the negative- but maybe I'm wrong.*

This example provided sufficient detail to support the model described by John for acceleration as being "positive if speeding up and negative if slowing down." The fact that a situation was described in which there was a change in direction is significant as it elucidated the fact that John maintained logical consistency even in the opposite direction of motion. Having described acceleration as always positive when speed is increasing supports the notion that John was not using positive and negative to identify discrete directions in a reference frame. Instead, these terms served as descriptions of the change in the magnitude of speed independent of the context in which they occurred.

Though John's conception was not scientifically accurate, he had developed an understanding of acceleration that was self-consistent and well defined. Similar to the ways in which student thinking is approached, we seek clarification on exactly where John is at conceptually, giving value to his ideas, and working to identify the root of his error. Though it would be easy to simply discredit John as failing to understand acceleration in light of what he was *not* saying, we pursue a better understanding of his model based on what he *was* saying.

4.2.3. Visualizing the Model Described by John

To better visualize the way in which John was thinking about acceleration, we construct diagrams (Figures 2 and 3) comprising the salient features of John's descriptions. The horizontal axis is an indicator of position relative to the origin and maintains discrete directionality. As previously mentioned, positive and negative are not explicitly used to communicate the direction of motion. It is useful, however, to interpret John's use of forward and backwards as implying motion to the right and left, respectively, given their use in the scenario.

Separately, acceleration is identified as positive or negative depending on the change in speed. Due to the fact that positive and negative were only used to describe the nature of the acceleration, we intentionally separate the representations of motion and acceleration so not to suggest that the terms were used in accordance with the direction of motion.

John's conceptual perspective is maintained in the representation. For example, if the speed is increasing in any direction, acceleration is positive; a decreasing speed in any direction is considered a negative acceleration. This can change during motion and has no effect on the reference frame describing motion. The following section elucidates the representation in light of basic scenarios of accelerated motion.

4.2.3.1. Positive Displacement

In this scenario, we will use the representation of the horizontal axis indicating the car's position at identical time intervals, as in the assessment item designed by the group of teachers. As observed below in Figure 4.1 part (a), acceleration is identified as positive signifying an increasing speed. Consistent with the model described by John, the car is shown in part (b) to be travelling to the right, and slowing down, and the acceleration is identified as being negative.

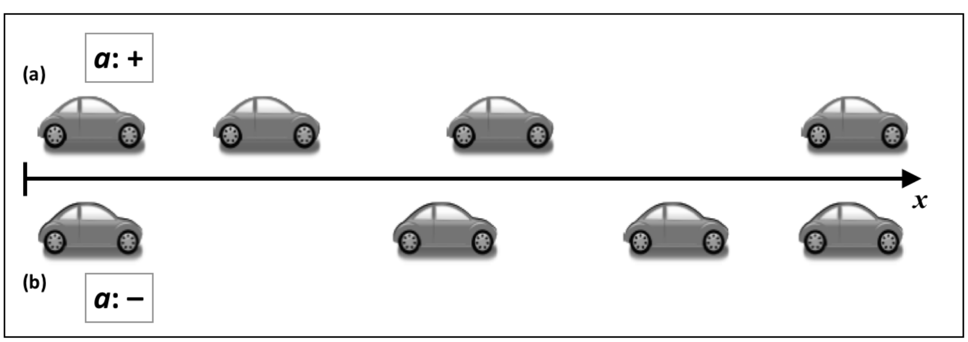


Figure 4.1. Representation of the model described by John for travel in the negative direction.

4.2.3.2. Negative Displacement

Contrary to cases portrayed in Figure 3, the following scenario (Figure 4.2) depicts motion to the left, or in the negative direction. Additionally, the acceleration in part (a) would be positive indicating an increase in speed, as described in John's example: *"That has to be a positive acceleration, because it was speeding up going the opposite direction."* The acceleration of the car in part (b) is identified as negative due to the decreasing speed.

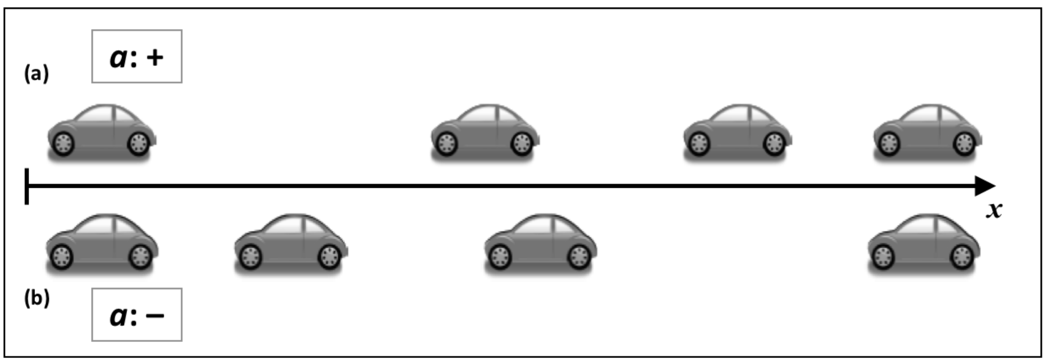


Figure 4.2. Representation of the model described by John for travel in the negative direction.

In sum, John's description was consistent with the idea that acceleration is an indicator of changing speed, and positive or negative serve as descriptors of said change. Though incomplete, this model is coherent with the notion of positive acceleration as always describing an increase in speed, and negative acceleration, a decrease. This rationale is maintained independent of the direction of velocity. Furthermore, if information is known about acceleration being positive or negative, the resultant change in magnitude of speed can be deduced. In both cases, the direction of motion is irrelevant.

4.3. The "Directions Are Independent" Model

Derrick also expressed ideas about acceleration. Like John, Derrick focused on what is meant by positive and negative. We describe his viewpoints in the next sections.

4.3.1. Treatment of Positive and Negative

The most notable feature of the conceptual model described by Derrick was the idea that positive and negative denote a vector direction, rather than a change in magnitude. Consistency was maintained in his coupling of positive or negative with direction as he talked about both the direction of motion and the direction of acceleration. At the crux of Derrick's argument was the fact that "acceleration does not have to be in the same direction as the motion," which motivated his thoughts about how students might become confused.

4.3.2. Student Ideas and Potential for Confusion

Derrick: …and I'd start thinking about how would they misunderstand negative acceleration. One, I would tell them- kid might think you are accelerating in the opposite direction, but you are, but that you might be actually moving, you know. The whole idea of like 'net forces equal motion' – I know we aren't talking about forces yet- but you know, so if it's negative acceleration, does that mean that am I actually going in the direction? Does motion happen in the direction of the acceleration?

Derrick's talk about how a student could interpret acceleration as the object actually moving in the negative direction, or that it could be slowing down in the positive direction. There is potential for confusion when we talk about direction of acceleration. Contrary to interpreting positive or negative velocity, which specify the direction of motion, a positive acceleration could indicate increasing speed if traveling in the positive direction, but could also indicate decreasing speed if travelling in the negative direction.

4.3.3. A Case Lacking Coherence

At various times during the meeting, Derrick offered pieces of an argument that he never managed to articulate in a concise manner. Derrick's utterances are juxtaposed here to illustrate their separation in time and his conceptual consistency as he struggled to make his point.

01:10:36 - …so if there's a net force slowing it down, negative acceleration that they might think whichever way is the net- see we're not talking about force yet, I know, but if you're telling them, that is negative acceleration, I just wonder if someone might say, "Well negative acceleration…that must mean that instead of like positive acceleration, that negative is moving backwards, like a [negative] change in position."

01:11:10 - So would negative acceleration be a change in position, I mean it could be, but it could also be slowing down.

01:11:25- …[the] problem is that you coul- I mean it means, it doesn't necce- it means you're accelerating in that direction, but it doesn't mean that you're moving in that direction. See what I'm saying?

The point Derrick was trying to make, but did not have a clear grasp of, was that the sign of acceleration neither indicates whether an object is speeding up or slowing down, nor does it indicate the direction of motion. Context is required in order to determine these things. Knowledge of one or the other is necessary. Similarly, the direction of the net force acting on an object lacks resolution of the change in velocity. Negative acceleration or net force could indicate a decreasing positive velocity, or an increasing negative velocity.

The model as described by Derrick is not nearly as coherent as John's description. We observed Derrick trying to invoke knowledge of force, coordinate systems, and the fact that acceleration does not give us information about the direction of motion, only a description of the change velocity. Though Derrick was clear about some points, such as the potential for motion and acceleration to be in opposing directions, he was not able to construct a case with concision. Thus, we receive fragments of Derrick's conceptual understanding.

4.3.4. Identification of Unknown Variables

Derrick's attention was on three variables: the direction (sign) of acceleration, and the direction (sign) of the velocity, and the change in magnitude of the velocity. He placed emphasis on the fact that only knowing the direction of acceleration does not allow one to know about the other two, and that one of the others must be known in order to determine the third.

4.3.5. Visualizing the Model Described by Derrick

Derrick's contributions to the group conversation provided evidence that describe a conceptual model that, though incomplete, appears consistent with a scientifically correct model. We examine cases of motion in the positive (Figure 5) and negative (Figure 6) directions, as in the previous section, with similar representations. However, in light of the model described by Derrick, acceleration is represented as a vector having a direction that is consistent with the function of direction of velocity in that the sign is indicative of a particular direction.

4.3.5.1. Positive Displacement

Figure 4.3 part (a) depicts the car moving to the right and increasing speed. Derrick described the acceleration in this case to be to the right, or in the positive direction. In Figure 4.3 part (b) we see a car with a rightward decreasing speed. Consistent with the model described by Derrick, the acceleration is indicated by a vector pointing to the left, or negative direction. Derrick spoke to the latter case by describing the potential for student confusion: "*So would negative acceleration be a [negative] change in position? I mean it could be, but it could also be slowing down.*" Case (b) is represented by the second remark made by Derrick, in which the car has a displacement in the positive direction, and a decreasing velocity, indicative of acceleration in the negative direction.

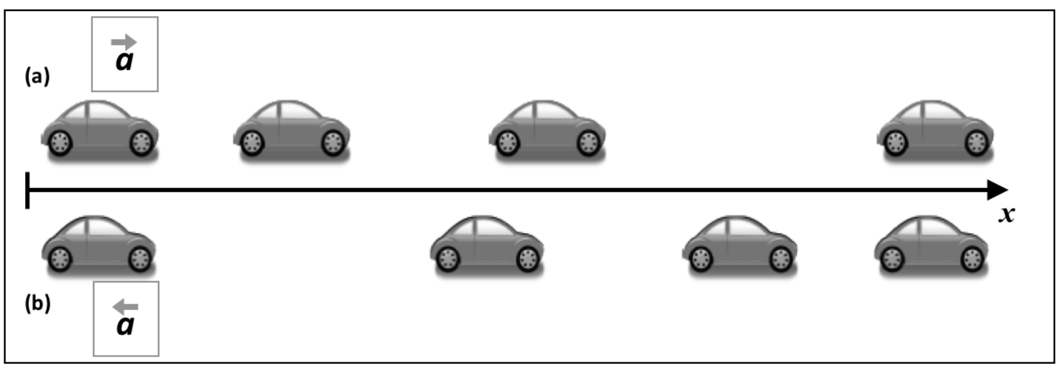


Figure 4.3. Representation of the model of acceleration described by Derrick for travel in the positive direction.

4.3.5.2. Negative Displacement

Representing motion in the negative direction, Figure 4.4 part (a) depicts the car moving to the left and increasing speed. The model described by Derrick would deem the acceleration in this case to be to the right, or in the positive direction. In Figure 4.4 part (b) we see the car with a leftward decreasing speed. We use the same statement from the previous section to illustrate Derrick's notion of the ambiguity of the sign, or direction of acceleration with a lack of additional contextual information. "*So would negative acceleration be a [negative] change in position? I mean it could be, but it could also be slowing down.*" Derrick's initial remark is represented by case (a), in which acceleration is negative, and displacement is in the negative direction with increasing velocity.

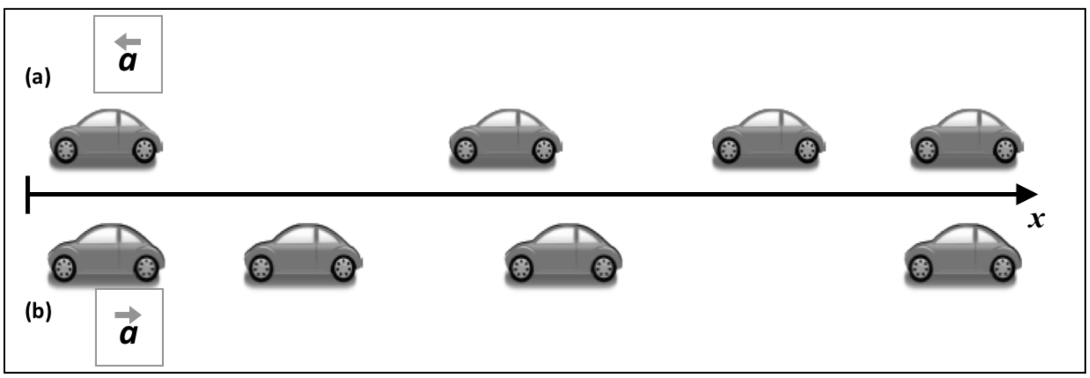


Figure 4.4. Representation of the model described by Derrick for travel in the negative direction.

4.3.6. Incomplete, but Correct

Interpreting Derrick's description of acceleration identifies it as being consistent with a scientifically correct model. However, it was fragile and ultimately given up on as Derrick's confidence was shaken in the face of John's conviction. After listening to John's explanation, Derrick noted the similarity to his own notion of velocity and acceleration in opposing directions, namely when the car approaching the fan had a positive velocity and a negative acceleration.

Though John's description of speeding up in the opposite direction was incorrect, Derrick deferred to John's insistence.

In sum, Derrick concentrated on the direction of acceleration, and its implication on the direction of motion and the change in magnitude of speed. Derrick tried unsuccessfully to make the point that the direction of acceleration indicates neither the direction of motion, nor the change in speed. As explained, he saw this as a potentially problematic idea for students.

4.4. Words Versus Models

In the previous sections, we witness a variety of ways that the teachers thought about acceleration. While Kristina and Lisa focused primarily on words used to describe acceleration, John and Derrick explained ideas connected to those words, as shown in Figure 4.5, implying they were describing models in order to make sense of these concepts. Though we are not suggesting that Lisa and Kristina lacked conceptual models of acceleration, we lack sufficient evidence to interpret their thinking as such. In light of their contributions to the group discussion, we do notice that Kristina and Lisa shared goals for students' use of the correct terminology, rather than constructing a deep conceptual understanding of the terms.

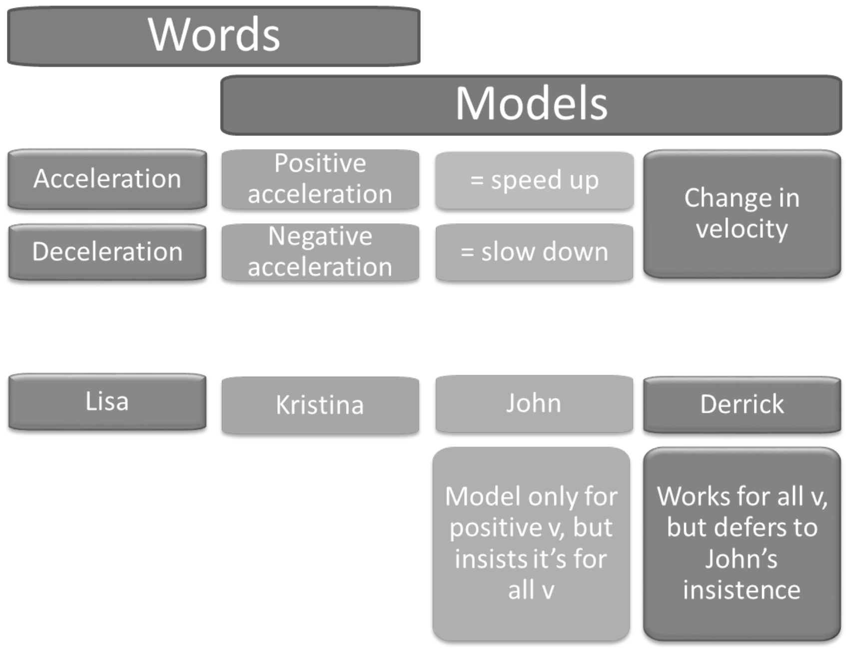


Figure 4.5. Contrast of the focus held by the teachers while designing the assessment item.

Models interpreted from John and Derrick are subject to further analysis in the following sections.

4.5. Comparing Models

As illustrated by the descriptions and examples used by John and Derrick, both models are similar in the use of positive and negative to describe acceleration, but the rationale supporting each suggests that they are fundamentally different from one another. The "speed" model is consistent in the idea that the sign of the acceleration has a direct correlation with the change in magnitude of the speed, regardless of direction of motion. Contrary to this, the "directions" model acknowledges the vector nature of acceleration and identifies the fact that its direction does not necessarily determine the direction of travel, nor the magnitude change in speed.

In Table 4.1 shown below, the models are juxtaposed in their determinations of the sign of acceleration given the four motion scenarios described previously. From this table, we notice that in the case of positive velocity, both models would agree with the sign of acceleration, albeit for different reasons. The two models diverge in consideration of the negative domain, as the speed model deems direction of travel irrelevant, and direction model uses both pieces of information (direction of motion and change in magnitude of speed) to deduce the sign of acceleration.

Table 4.1. Interpretations of Models described by John and Derrick.

Situation	"Speeding Up = Positive acceleration"	"Directions are Independent"
v positive and increasing	$a > 0$	$a > 0$
v positive and decreasing	$a < 0$	$a < 0$
v negative and increasing	$a > 0$	$a < 0$
v negative and decreasing	$a < 0$	$a > 0$

4.5.1. Parallel Agreement: Consistent Terminology, Different Interpretation

01:13:00 John: …the car is coming toward [the fan].

01:13:07 John: …it goes the other way.

01:13:13 John: …it was speeding up going the opposite direction.

Though both models use adjectives for acceleration, they have conflicting ideas about the meaning of positive and negative. Hence, the "directions" model would account for the positive or negative direction of the acceleration, and the "speed" model would mean positive to be an increase, and negative a decrease. As both models would use the same signs to describe acceleration when motion is in the positive direction, we consider them in agreement. However, due to the meanings that these two models hold for the terms positive and negative, we refer to this agreement as being parallel to one another (Figure 4.6).

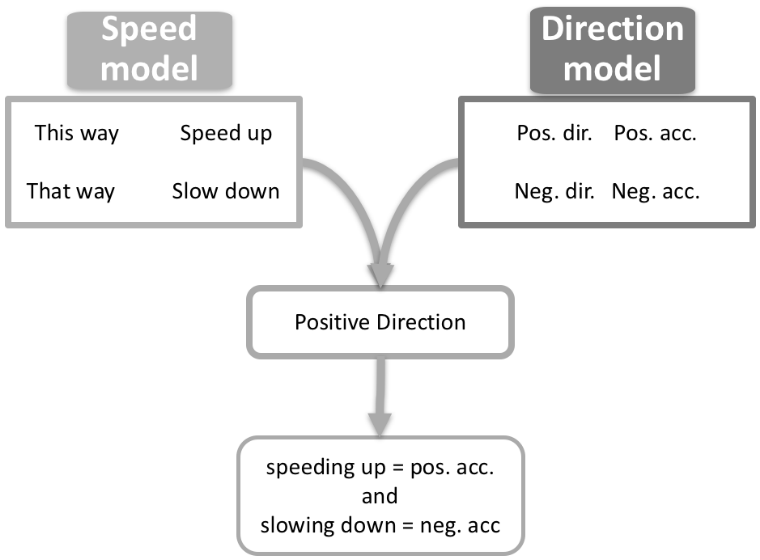


Figure 4.6. Agreement between the models for acceleration described by John and Derrick.

Given motion in the positive direction with increasing speed, both models would agree that the acceleration of the object is positive. The "speed" model would reason that this is because the speed of the object is increasing. The "directions" model would hold the rationale that the object is moving in the positive direction and it is speeding up, thus positive acceleration.

This parallel agreement emerges as the source of the dilemma presented by the resultant assessment item. The next section will explore the nature of this dilemma in light of the two models presented within the context of the item created by the group of teachers.

4.5.2. Contrasting Domains

To elicit the fundamental difference between the “speed” and “directions” models, we consider scenarios in which the motion of an object is in the negative direction.

Self-consistently, the “speed” model describes increasing speed in the negative direction as positive acceleration, due to the increasing speed. However, the “directions” model describes the same case as negative acceleration. There is similar disagreement in describing an object slowing down in this scenario, with the “speed” model concluding that acceleration is negative, and the “directions” model asserting a positive acceleration.

Only in considering the contrasting case of negative velocity do we uncover the meaning ascribed to positive and negative by each model, shown in Figure 4.7. As previously stated, while coherent and self-consistent, the limitation of the “speed” model must be exposed to be better understood. Our knowledge of these two models will be used to evaluate the effectiveness of the assessment question written by the teacher group in the next section.

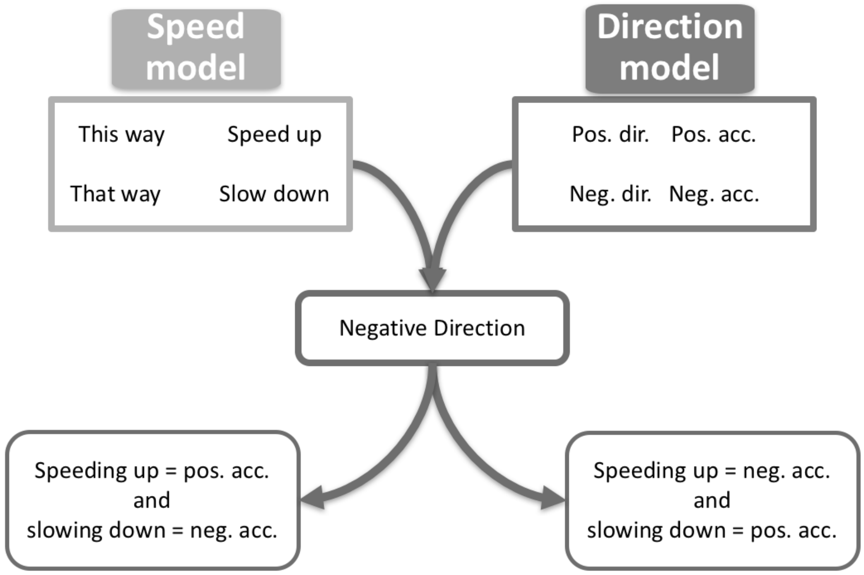


Figure 4.7. Contrasting the perspectives of the models for acceleration described by John and Derrick.

4.6. The Progression of Group Contention, Consensus, and Item Generation

As we have seen, inconsistent views of acceleration surfaced that provided a barrier to deciding on an item for assessment. The next section describes an intervention made by the author as participant observer as a means of guiding the team beyond the obstacle they now faced. As a note to the reader, the direct involvement of the author is described in the first-person.

4.6.1. An Intervention and Avoiding Resolution

It is important to remember that the purpose of this meeting was not to engage in a professional development session on acceleration. In fact, until the conversation actually occurred, I was not aware of the differences in ideas about the topic held by the group members. In the moment, I had to make a quick decision. I knew that Derrick was closer to being scientifically accurate as he was referring to the directionality of velocity and acceleration in his description of their directions. I also recognized the limitations in the “speed” model as described by John. Rather than simply tell the group which model was correct, I alluded to Derrick’s discussion about possible student confusion when interpreting negative acceleration. I knew that he was trying to make the point that it could be speeding up in the negative direction, or slowing down in the positive direction. Trying to make Derrick’s thinking visible for the group, I hastily grabbed the whiteboard and sketched vectors representing the velocity and then acceleration. I explained that while velocity and acceleration were both in the same direction, speed would be increasing. Conversely, velocity and acceleration in opposite directions would result in decreasing speed.

Shaking his head, John interjected, “See… I disag–…” At this point, John gave his example of the car heading toward a fan, described earlier in this chapter. John explained the turnaround point, where the car stopped moving toward the fan, and then began speeding up in the other direction:

#01:13:14-7 John: It can't be a negative acceleration; negative acceleration would be the slowing down to the stop, and then a positive in–

#01:13:19-4# Derrick: Positive in the negative direction?

#01:13:23-2# John: I guess that's the way I would interpret it, but…
#01:13:29-4# Derrick: Hmm, yeah…I guess I’m wrong.

#01:13:31-5# John: If it's speeding up going in the opposite direction, wouldn't that be positive–still be positive acceleration? It's getting faster.

To this exchange, I gently responded, "So, well…that's where it gets tricky, is when you change direction. The sign of the acceleration indicates its direction."

A cacophony of utterances flooded the room as we all tried to make sense of, ask questions about, and comment on the case of negative velocity and positive acceleration. As a result, John questioned his own understanding and sought clarification by asking about a case that did not fit his model: "So can you have negative acceleration speeding up?"

I decided to give him a straightforward answer in the interests of time, limiting further frustration, clarifying the issue, and potentially making progress toward a shared correct model of acceleration. "Yeah," I said. "If you're going in the negative direction." As I attempted to explain further Kristina abruptly led the conversation in a new direction.

Exasperated, Kristina offered, "I really appreciate the discussion, however as the task master, can we…"

"So we'll table, yep…" I interrupted, empathizing with the distress of the group. "Maybe table it until Saturday…" she added.

This exchange prompted a follow-up from John, asking "Okay, so the only other question that I have is: so do I have to fix this? Am I wrong in saying that slowing down is negative acceleration?" I respond that if motion is in the positive direction, that his explanation works, but not otherwise.

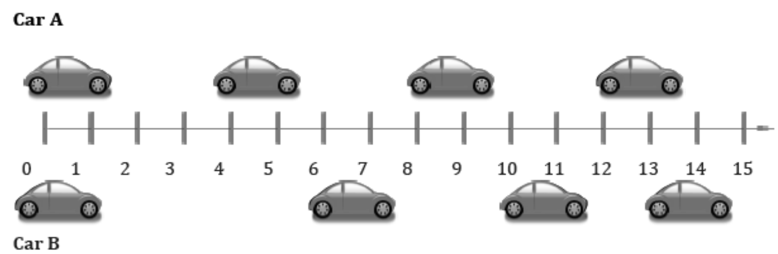
Constrained by time and the need to come to consensus, the group opted to emphasize the case in which they were all in agreement. That case, as discussed earlier is in the event of a positive velocity. Hence, the following clause was used to preface a description of acceleration without being incorrect:

"*As long as you're travelling in the positive direction*… speeding up is a positive acceleration, and slowing down is negative."

4.6.2. Subsequent Assessment Item

Teachers created the assessment item shown in Figure 4.8. Its context is of cars moving in what is shown as the positive direction, with one car slowing down. In keeping with the teachers' conversation, we focus only on part ii of the item. In light of the previously described models, we can analyze how it demonstrates the item's inability to differentiate between models similar to those expressed by John and Derrick.

Item 4. The image below represents two cars riding next to each other. A picture is taken every second to show the cars' position. The number line represents the position in meters. Use the image to answer the questions that follow.



i. Describe the difference between the motion of each car.
ii. Describe the acceleration of each car, and explain your reasoning.
iii. Are they ever travelling the same speed? Explain how you know.

Figure 4.8. Item designed by teachers to assess positive and negative acceleration.

By applying the models interpreted from the interactions of John and Derrick, we consider responses to the assessment item that are consistent with the ideas of each individual shown below in Table 4.2.

As shown, both models lead to a response in which Car B is considered to have a negative acceleration. Though the model described by Derrick includes a description of the direction as part of the explanation, the answers are virtually the same.

Given the benefit of possessing an understanding of both models that extends beyond the response to the item, we are able to assert that their reasoning is, in fact, dissimilar. We attribute John's response of "negative acceleration" solely due to the fact that Car B is slowing down. Derrick's model, however, gives the same response, but indicates that the choice is in light of what is known about both how the speed is changing and the direction in which Car B travels.

Table 4.2. Inferred responses to assessment item (Figure 4.8).

Model	Inferred response
Speed	Car B has a negative acceleration because it is slowing down.
Direction	Car B has a negative acceleration because it is slowing down while traveling in the positive direction.

If only considering the written responses, we are likely to consider both to be correct. As a result, we would lack appropriate resolution of the conflict existing in the “speed” model. The potential for false positive student responses did not allow teachers to resolve accurately a student’s particular conceptual model. Thus, teachers were neither able to provide adequate feedback to students, nor could they use response data to inform successive instruction based on a specific conceptual difficulty. This limitation undermined the utility of the item as a formative assessment tool to attend and respond to student ideas during the process of developing an understanding of positive and negative acceleration.

In the next chapter, we analyze the behaviors of the group in light of conflicting ideas. We will also explore the nature of those ideas to better understand them as a conceptual model. Finally, we infer the consequences of the consensus with respect to meeting the needs of the group.

CHAPTER 5

ANALYSIS

In light of the observations described in the previous chapter, the next sections address the group's behavior in the face of inconsistent ideas, the content nature of those ideas, and finally, the group's consensus as it relates to their objectives.

5.1. What Happens When the Group Becomes Aware of Inconsistencies Among the Conceptual Models They Hold as Individuals?

Through conversation, the inconsistencies between the models held by John and Derrick were highlighted by discussion centered on negative acceleration. We speak to the effect of this inconsistency on the group's decisions and arrival to consensus.

5.1.1. Consensus Without Resolution

With limited time and objectives to meet, the decision was to focus on motion in the positive direction, the situation that yielded group agreement on the correct response. Considering only the limited case of positive velocity did not allow individuals to adequately perceive, much less resolve the differences between the two models in question. This likely has an effect on how the models are treated in the classroom. Due to the correct response of both for the given scenario, it becomes difficult to justify one over the other. The speed model gives the correct answer, and is associated with an intuitive view of motion, rather than the view that recognizes the vector nature of these quantities. Ambiguity in the interpretation of the assessment responses and differentiation of the two models may be perpetuated into a teacher's instruction, lending itself to opportunities for future study.

5.1.2. Emphasizing a Limited Rule

Resulting from attention only to cases of positive velocity, an over-simplified rule emerges for interpreting an object's acceleration. As reported by Stein, Baxter, and Leinhardt (1990), deficiencies in teachers' content knowledge were shown to affect instructional practice. One of these ways was a tendency to overemphasize limited truths. Similarly, we observed the teachers placing emphasis on the qualifier, "As long as you are going in the positive direction…" for their resultant rule for positive and negative acceleration. Utilizing this clause deems the rule conceptually accurate, however students may overlook the significance of it. Indicating motion in the positive direction may not be meaningful to teachers or students who do not hold a view that considers positive and negative as descriptors of changing magnitude. Another drawback to this rule is that students, even if told, have not developed an understanding of why it is only true in the positive direction. To fully understand the rule's limitations requires a more robust understanding of why the rule is untrue when motion is not in the positive direction. Further, the rule can be memorized and used to produce a correct response without requiring an accurate conception of acceleration.

5.1.3. Missed CK Development Opportunity

Considering only those cases that satisfy the over-simplified rule also undermines opportunities for teachers to refine their own conceptual understanding. Should alternative cases be presented, instructors would be faced with the need to understand why their own models did not agree with correct responses in the case of negative velocity or a turnaround point problem. Speer and Frank (2013) showed similar content knowledge development while evaluating student responses. However, as written, the assessment item does not provide opportunities for the presence of these two contrasting models to become apparent.

5.1.4. Fragmented Aims for Assessment

A lack of conceptual clarity amongst the teachers inherently leads to goals and expectations for the assessment that lack cohesion. Without a full understanding of what a correct response is and why it is correct leads to the possibility of not understanding why other responses are incorrect. Increasing the variability in response interpretation negatively affects the validity of the item for the purpose of cross-classroom comparison. This lack of meaningful comparison weakens the ability of the common assessment results to inform focused improvements to the curriculum materials.

The learning target becomes focused on students providing the correct words. “If negative acceleration and slowing down, then correct.” Knowledge of acceleration as a vector is not needed.

5.1.5. Cross-classroom Inconsistency

As previously mentioned, the variable interpretation limits the possible benefits of the item responses to inform change. Additionally, the lack of resolution lends itself to a lack of coherence in cross-classroom instruction. Judging from the conversations of the group, it is not reasonable to assume that a consistent conceptual message is being emphasized in the classrooms.

5.2. What is the Nature of These Inconsistencies, Both Among the Models Themselves, and Also with Those That Are Scientifically Accurate?

Having observed inconsistencies within the group’s shared understanding of acceleration, we look more closely at the models represented. Our aim is to gain a clear understanding of the incomplete model expressed in order to compare it to a scientifically accurate model.

There is no differentiation between the everyday meaning and the scientific meaning of the words positive and negative. The fact that delineating velocity and speed is not granted an in-depth exploration, makes understanding that acceleration has a direction all the more challenging. Again, the difference emphasized between velocity and speed is that velocity is “speed and direction.” However, the concept of direction as a vector component is not explored in the curriculum.

The speed model of acceleration treats acceleration as a scalar quantity identifying the change in the magnitude of speed rather than the change in magnitude and direction of velocity.

This model fails to demonstrate the coherence between concepts of displacement, velocity, and acceleration. This shortcoming is carried forward into concepts of dynamics, and mechanics as a whole.

5.3. Group Consensus and its Influence on the Assessment Item

By asking the question, “What is the nature of the group consensus, and how does it influence decisions for and the efficacy of the assessment item produced,” we consider the decisions made by the group in the face of conceptual inconsistencies. Furthermore, we analyze how these decisions may have affected the ability of the item to uncover dissonant student ideas.

5.3.1. Needs Met by the Item

In this section we discuss the item produced by the group in light of the underlying task and group goals.

5.3.1.1. Group Needs

Construction of the item met the objective of the group to develop an instrument to measure their students' collective understanding of acceleration. As a formative assessment tool, this item helps teachers discern the presence of lingering student difficulties from the preceding module on uniform motion and the ticker tape representation of motion and could inform interventions to address them.

In addition to addressing the needs of the group, the item satisfies individual necessities as communicated during the development meeting.

5.3.1.2. Kristina's Concerns About Conceptual Depth

The item allows Kristina to assess the level of understanding expressed in the meeting, not requiring a student to provide details about acceleration being positive or negative. Respondents are asked to compare the acceleration of the two cars, to which students could state that Car A is not accelerating due to its constant velocity and Car B is because of its decreasing velocity. This being said, the structure of the question does allow a student to provide a more detailed response, enabling Kristina to differentiate her instruction in order to meet the individual needs of her classroom.

5.3.1.3. John's Need for Classroom Consistency

The scenario may allow the model described by John to persist in that slowing down is negative acceleration. This is due to the fact that the motion of the cars is in the positive direction, which is the only case in which the "speed" model provides a nominally identical answer as the correct "directions" model. This is significant as limitations of the "speed" model were clearly communicated to the group. As justified after the identification of the limited case, “slowing down is negative acceleration *as long as motion is in the positive direction.”*

John, concerned about having taught the “speed” model in his class, asked, “Do I have to fix this? Am I wrong in saying that slowing down is negative acceleration?” The group concluded that, no, John was not wrong as long as motion was in the positive direction, which, in the curriculum, is always the case.

5.3.1.4. A Case Consistent with Derrick’s Ideas

As written, the question addressed Derrick’s sentiment regarding possible student confusion about the direction of motion and its relationship to the direction of the direction of acceleration. That “acceleration does not have to be in the same direction as the motion” was expressed by Derrick (though not always so succinctly) at various times during the meeting. In the case given by the assessment item, motion is, in fact, to the right, while acceleration is to the left. The fact that students are given the direction of motion and the change in speed by the scenario serves to avoid the problem had students been given the acceleration and asked to describe the motion. Derrick spoke to this in saying that negative acceleration might mean motion is in the negative direction, “but not necessarily.”

5.3.2. Needs Unmet

Despite meeting the various needs described in this section, we explore a substantial shortcoming of the item as a result of particular events during the planning meeting.

5.3.2.1. Use of the Agreed Terms Not Required

While there was discussion centered on which words to use, the item does not require that students use the terminology positive or negative in describing an acceleration. One could still use the less-technical word decelerating to describe car B. On an individual level, teachers may consider this to be correct, since the car is slowing down. Individual biases in teachers' interpretation speaks to the limited reliability of the item as one teacher may score the same response differently than another.

5.3.2.2. Model Differentiation

As discussed, item response may or may not reveal a conceptual difficulty. From the constricted case of positive velocity, it cannot be determined which model a student may hold in terms of understanding acceleration as a vector quantity.

5.3.3. Beyond an Understanding of Acceleration as a Change in Speed

Limiting the use of acceleration to describing the magnitude of changing speed may fail to uncover acceleration as a physically meaningful description of changing velocity (both in magnitude and direction) with respect to time. Understanding acceleration and velocity as having direction is not required to answer the designed assessment item correctly.

5.3.4. On the Significance of the Limitation

Despite the apparent nuance of the knowledge of acceleration as a vector, we argue that careful attention to it is not merely picking nits. The lack of a basic qualitative understanding of the additive properties of vectors in one-dimension may have a ripple effect on student knowledge development in mechanics. The relationship between forces and motion as described by Newton's second law is a central tenet to physics instruction. Specifically, the direction of acceleration and of the net force acting on an object are inherently the same. A model of acceleration that does not consider it to have a direction would allow cases in which a student may confidently argue that a net force is acting in a negative direction, and there is a positive acceleration. Additionally, the validation of the conception of acceleration as a scalar quantity and a weakly constructed understanding of the direction of velocity provides this naïve understanding with even more intellectual inertia.

5.3.5. Formative Assessment Implications

The group's arrival at an oversimplified rule for acceleration and an assessment item that lacks discernment of student ideas demonstrates the interplay between subject area knowledge and knowledge needed to assess the concept of acceleration. The result undermines the opportunity for students to develop a fundamental understanding of acceleration and vector quantities in general. Not only is the assessment inadequate in determining student understanding of acceleration, but the implications of the item's limitations on student learning capacity, as described in the previous section, are not recognized.

The created item does not provide teachers with the response clarity to take action and adjust instruction based on a specific conceptual difficulty, disrupting the feedback loop shown in Figure 5.1. Unless this is identified as an issue, it is not likely to influence a focused intervention or curriculum adjustments. The possibility of false positive responses allows for an inflated sense of mastery by both teachers and students. Such an interpretation does not identify necessary actionable steps for teachers to provide students with descriptive feedback. Thus, the item, by definition, cannot be used as a formative assessment for the purpose of assessing students' understanding of positive and negative acceleration.

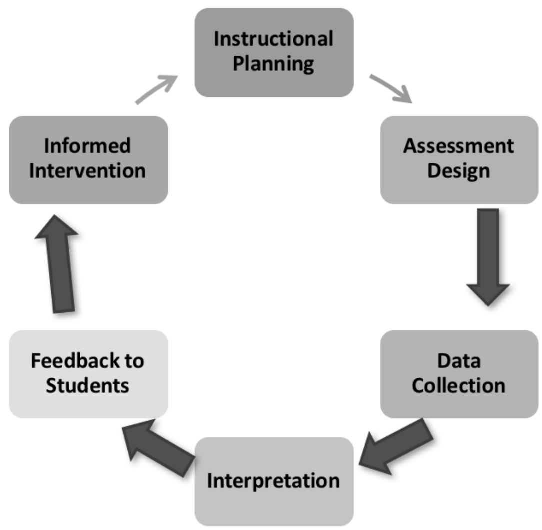


Figure 5.1. The teacher/student feedback loop disrupted by assessment limitations (thick arrows represent disruptions in the cycle)

5.4. Causality is Not Obvious

Limited by the single case of a small group of participants, it is hard to point to a single cause or solution here. This is messy and complex, as most everything having to do with humans interacting with one another is. In the events of the observed case are aspects of science content knowledge, assessment literacy, personal philosophies towards assessment, and social dynamics. While not all of these things are what this research is focused on, we acknowledge them as factors that cannot easily be disentangled without a robust protocol for gathering teachers' perspective of the event through reflection and interviews.

Teaching, learning, interpersonal relationships, and physics are difficult to manage simultaneously, as we have witnessed. However, while they appear to confound each other, maybe the interactions between these entities can also play supporting roles. We posit that the culture of our social interactions may be the most fruitful area of attention with respect to supporting the others. Formative assessment is built on the premise of finding out what another is thinking in order to most effectively respond for the purpose of further knowledge development. Empathy is required to sufficiently understand the perspective of another. To understand is not merely to listen, but also to consider. In order to best support the learning process of our students, teachers must be curious about their thinking, and consider their ideas. Teachers need to know the details of where their students are at, where they need to go, and how to get them there. Formative assessment lies at the heart of answering these questions. As educational researchers, we would do well to remain cognizant of such principles and practices.

CHAPTER 6

IMPLICATIONS

In the process of our study we observed middle school science teachers developing assessment items on acceleration for use across their classrooms. The next sections serve as a reflection of the research process described in the preceding chapters. As a product of this reflection, we offer implications for instruction and for future research.

6.1. Conceptual Attentiveness

Coffey et al. (2011) identified the "neglect of disciplinary substance" as a significant deficiency in the practice of formative assessment (p. 4). As we have witnessed a case of such with respect to the direction of acceleration, we offer areas for further emphasis at all levels of instruction, but specifically for middle school.

6.1.1. Emphasis on Direction and Coordinate Systems

The direction of acceleration proves difficult at all levels of instruction, including for experts in complex cases. We have seen an instance of the lack of attention to direction limiting the efficacy of a formative assessment item designed to interpret student understanding of the very idea. One could argue, however, that the direction of assessment was not intended to be a learning target, due to an incomplete understanding held by the group. Instead, the focus was on the use of the words positive and negative as consistent with said understanding. As discussed, the consensus "in the positive direction, a positive acceleration is positive for speeding up, and negative for slowing down" is not wrong, but it fails to provide the whole story. Likewise, assessing the limited case proves insufficient to provide the whole story of a student's understanding.

To gain a clear picture of both, we would also need to consider motion in the negative direction.

Developing a coherent conception of acceleration is complicated due to its relation to our everyday descriptions of motion. Failing to address the different domains using these words makes it a challenge for students to manage. Though rules make remembering easier, and simple rules are good, oversimplified rules can create barriers to conceptual refinement, as we have seen in this study. Especially vexing is that the rule developed in this study is correct, but only some of the time, making it inherently incorrect at other times.

Emphasis on what is meant by positive and negative needs to be attended to in science instruction. It is essential to let students recognize the parallels between mathematics and science with the meanings of positive and negative. However, students should also be given opportunities to explore ways that science is different. For example, a Cartesian plane, by convention, is defined by positive to the right and up, and negative to the left and down, with respect to a point of origin. Yet in science, we have the flexibility to redefine these parameters to our liking, so long as we communicate our choices to others. Without letting students practice this ability to choose, and purposely flip coordinate systems, they are liable to become rooted in convention of mathematics.

6.1.2. Operational Definitions

As with coordinate systems, students should be given opportunities to practice developing operational definitions to interpret acceleration. Beyond an ability to describe acceleration, it is important to explain the steps necessary for arriving at such a description. A physically meaningful description of interpreting acceleration requires a determination of velocity at two different times, and justifying the change from one instance to the one that preceded it. While this can be a nontrivial task, it is one that requires the direction of velocity to be acknowledged and included when deducing the magnitude and direction of acceleration. Certainly the practice of constructing operational definitions is transferrable to all disciplines.

6.2. The Scope of Formative Assessment

While there is an acknowledged inconsistency regarding the implication of formative assessment, there is perhaps even less awareness of the various scopes of formative assessment (Wiliam, 2006). The most popular notion of formative assessment occurs within a relatively small amount of time, often within the course of a single classroom lesson. This aptly named “short-cycle” formative assessment has variations that involve larger periods of time, namely, “medium-cycle” and “long-cycle”. Wiliam’s (2006) enlightening account of the nuances of formative assessment explain that medium-cycle assessments typically start a feedback loop spanning multiple units of instruction, while long-cycle can gather data that will be used to make adjustments in the following school year.

For the purposes of this thesis, it is appropriate to acknowledge the possibility of a miscommunication between the teachers and the researcher about the intended scope of the assessments being designed. Admittedly, analysis was focused on the short-cycle realm, while perhaps the teachers’ intention was more aligned with a long-cycle formative assessment. More clearly, the author as facilitator was of the mindset of gathering information about student ideas with the intention of adjusting instruction within the learning cycle involving acceleration. Upon reflection, the teachers may have been more attentive to the assessment iteration being developed with the one that preceded it. Assuming this may explain why recognition of the discussed error was not recognized by the group. The ability of the group to merely pose a question involving positive and negative acceleration was a major accomplishment in itself and spoke to the increased quality of conceptual detail inherent in the team's work. Previous to the curriculum update made by the group, the question would not have been fair to ask of students, both in content and in the representations of motion used.

Consideration of the different aims for assessment by the researcher and teacher group is not to minimize the flawed nature of the assessment item discussed. Rather, it is a reminder that in using the term formative assessment, as with other terms, the interpretation of such may not always be identical. Care should be taken to clarify what is meant by any particular group or individual, perhaps even requiring use of an operational definition.

6.3. Studying Teacher Collaboration

In the process of our study we observed teachers collaborating on the design of assessments in force and motion. The ability to witness their interactions elucidated much of their thinking that may have otherwise been unobserved. Teacher collaborations create unique opportunities for educational researchers to get a glimpse of teachers' knowledge in action that traditional surveys and interviews may not. Multiple dimensions of knowledge were expressed in discourse amongst the group members including knowledge of content, knowledge for assessment, as well as their philosophies and goals for teaching and learning. As a caveat, this team had been working with each other and the author as a facilitator for an extended period of time, allowing the team to develop rapport and mutual respect. The established relationship fostered candid discourse, and lowered the threshold of participants' hesitation to admit not understanding an idea and ask for clarification. As teaching proficiency is regarded as highly personal and an evaluated measure of worth, it is likely that the traits expressed by the team in this study are not universal without an established culture of collegiality and respect.

Regrettably, we do not have video of the team's work prior to that described in this thesis. We recommend attention be paid to this formative stage in relationship building as it seems vital to understanding teacher professional relationships, and may have provided greater explanatory power for the observations made during this study. As professional learning communities become increasingly implemented in professional practice, we recommend exploration of this territory as a means of gaining insight into teachers' thoughts and ideas in action through in-the-moment thinking, justification, and negotiation. A key component of our group dynamic was the understood protection of a safe space to share difficulties and frustrations, or to provide corrective feedback in a professional manner, rather than purely evaluative environment.

6.4. Conclusion

The complex nature of teaching cannot be overstated. The dimensions of pedagogical content knowledge needed for teaching require teachers to possess robust understandings of teaching strategies and conceptual principles in their discipline, their students' ideas, educational materials, assessing student understanding, and the scope of knowledge expected of students at the next level of instruction.

Our focus has centered on the collaborative development process of assessments to be used in the classrooms of multiple teachers implementing the same educational materials. As a critical component of learning development, assessment has significant implications for effective teaching. The national effort to develop more effective teachers deems it vital to increase teachers' capacity to effectively assess and respond to their students' ideas. However, we have witnessed teachers' collective content knowledge as a limitation to the development of effective assessment practices. Thus, it remains imperative that we better understand the nuances of these domains of teacher knowledge and how they influence one another.

In our study, a team of MainePSP teachers developed common assessments for a unit on force and motion concepts. During group discussion individual members vetted their own ideas about acceleration comprising the following perspectives: a) terminology used to describe acceleration, b) the sign of acceleration as an indicator of speeding up or slowing down, and c) the sign of acceleration as an indicator of direction, dependent on the change in both the magnitude and direction of velocity. The latter two ideas could be in agreement (when motion is in the positive direction) or conflict (when motion is in the negative direction). The assessment item created lacked the ability to discern between two models of acceleration as described by two different teachers.

The potential for students to provide a correct answer for the wrong reason limited the ability of the assessment item to provide sufficient evidence of which idea students might hold, which would disrupt the teacher-student feedback loop. False positive responses would invalidate teachers' interpretations of student performance by not allowing accurate resolution of a student’s particular conceptual model. Instead, results would suggest an inflated sense of mastery. Thus, teachers would neither be able to provide adequate feedback to students, nor could they use response data to inform focused intervention in successive instruction. This limitation undermined the utility of the assessment item developed by the group as a tool to ascertain and respond to students’ formative ideas during the process of developing an understanding of acceleration.

Our findings suggest that an incomplete understanding of acceleration limited the teachers’ ability to resolve their conceptual inconsistencies. Further, the item’s susceptibility for students to provide correct answers for the wrong reasons was not recognized at the time. This example of direct interference between teachers’ knowledge of the content and knowledge for effective assessment of student ideas suggest professional collaboration may be a fruitful opportunity to witness the dynamics of these and other domains of teacher knowledge. Insights afforded by further research efforts in such settings will serve to strengthen teachers’ ability to best support students throughout the stages of knowledge development.

REFERENCES

Alonzo, A. C. (2007). Challenges of Simultaneously Defining and Measuring Knowledge for Teaching. *Measurement: Interdisciplinary Research & Perspective*, *5*(2-3), 131–137. http://doi.org/10.1080/15366360701487203

Arons, A. B. (1997). *Teaching Introductory Physics*. *Teaching Introductory Physics*. New York: John Wiley & Sons, Inc. Retrieved from http://per.physics.helsinki.fi/kurkisuo/6.3.C/98-EJP-ARONS.pdf

Avargil, S., Herscovitz, O., & Dori, Y. J. (2011). Teaching Thinking Skills in Context-Based Learning: Teachers' Challenges and Assessment Knowledge. *Journal of Science Education and Technology*, *21*(2), 207–225. http://doi.org/10.1007/s10956-011-9302-7

Ball, D., & Bass, H. (2000). Interweaving content and pedagogy in teaching and learning to teach: knowing and using mathematics. *Multiple Perspectives on the Teaching and Learning of Mathematics*.

Ball, D. L., Lubienski, S. T., & Mewborn, D. S. (2001). Research on teaching mathematics: The unsolved problem of teachers' mathematical knowledge. *… of Research on Teaching*. Retrieved from http://www-personal.umich.edu/~dball/chapters/BallLubienskiMewbornChapter.pdf

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content Knowledge for Teaching: What Makes It Special? *Journal of Teacher Education*, *59*(5), 389–407. http://doi.org/10.1177/0022487108324554

Black, P., Harrison, C., Lee, C., Marshall, B., & Wiliam, D. (2004). Working Inside the Black Box: Assessment for Learning in the Classroom. *Phi Delta Kappan*, *86*(September), 8–21.

Black, P., & Wiliam, D. (1998). *Assessment and Classroom Learning*. *Assessment in Education: Principles, Policy & Practice* (Vol. 5). http://doi.org/10.1080/0969595980050102

Bloom, B. S. (1969). Some theoretical issues relating to educational evaluation. *Educational Evaluation: New Roles, New Means: The 63rd Yearbook of the National Society for the Study of Education*, (part II), 26–50.

Bowden, J., Dall'Alba, G., Martin, E., Laurillard, D., Marton, F., Masters, G., … Walsh, E. (1992). Displacement, velocity, and frames of reference: Phenomenographic studies of students' understanding and some implications for teaching and assessment. *American Journal of Physics*, *60*(3), 262. http://doi.org/10.1119/1.16907

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics*, *50*(1), 66. http://doi.org/10.1119/1.12989

Coffey, J. E., Hammer, D., Levin, D. M., & Grant, T. (2011). The missing disciplinary substance of formative assessment. *Journal of Research in …*, *48*(10), 1109–1136. http://doi.org/10.1002/tea.20440

Cowie, B., & Bell, B. (1999). A Model of Formative Assessment in Science Education. *Assessment in Education: Principles, Policy & Practice*, *6*(1), 101–116. http://doi.org/10.1080/09695949993026

Creswell, J. W. (1998). *Qualitative inquiry and research design: Choosing among five traditions*. *Qualitative Inquiry and Research Design: Choosing Among Five Traditions*. Thousand Oaks: Sage Publications, Inc. http://doi.org/10.1111/1467-9299.00177

Darling-Hammond, L. (2005). Teaching as a Profession: Lessons in Teacher Preparation and Professional Development. *Phi Delta Kappan*, *87*(3), 237–240. http://doi.org/10.2307/20441976

Davis, B. (1997). Listening for Differences: An Evolving Conception of Mathematics Teaching. *Journal for Research in Mathematics Education*, *28*(3), 355–376. http://doi.org/10.2307/749785

Derry, S. J., Pea, R. D., Barron, B., Engle, R. a., Erickson, F., Goldman, R., … Sherin, B. L. (2010). Conducting Video Research in the Learning Sciences: Guidance on Selection, Analysis, Technology, and Ethics. *Journal of the Learning Sciences*, *19*(1), 3–53. http://doi.org/10.1080/10508400903452884

DuFour, R., Eaker, R., Association for Supervision and Curriculum Development VA, A., & National Educational Service IN, B. (1998). *Professional Learning Communities at Work: Best Practices for Enhancing Student Achievement*. Distributed by ERIC Clearinghouse.

Flores, S., Kanim, S. E., & Kautz, C. H. (2004). Student use of vectors in introductory mechanics. *American Journal of Physics*, *72*(4), 460. http://doi.org/10.1119/1.1648686

Gold, R. L. (1958). Roles in Sociological Field Observations. *Social Forces*, *36*(3), 217–223. http://doi.org/10.2307/2573808

Hake, R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, (May 1996), 64–74. Retrieved from http://pdfserv.aip.org/AJPIAS/vol_66/iss_1/64_1.pdf

Halloun, I. A., & Hestenes, D. (1985). Common sense concepts about motion. *American Journal of Physics*, *53*(11), 1056. http://doi.org/10.1119/1.14031

Hammer, D., & Elby, A. (2003). Tapping Epistemological Resources for Learning Physics. *Journal of the Learning Sciences*, *12*(1), 53–90. http://doi.org/10.1207/S15327809JLS1201_3

Hayes, K., & Wittmann, M. C. (2009). The role of sign in students' modeling of scalar equations. *The Physics Teacher*, 5. http://doi.org/10.1119/1.3361994

Herman, J., Osmundson, E., Dai, Y., Ringstaff, C., & Timms, M. (2011). *Relationships between teacher knowledge, assessment practice, and learning-Chicken, egg, or omelet? (CRESST Report 809)*. Los Angeles, CA.

Heron, P., Michelini, M., & Stefanel, A. (2008). Teaching and learning the concept of energy in primary school. *C. Constantinou & N. Papadouris, …*, (Trumper 1996), 1–13. Retrieved from http://lsg.ucy.ac.cy/girep2008/papers/TEACHING AND LEARNING THE CONCEPT OF ENERGY.pdf

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*. Retrieved from http://modelinginstruction.org/wp-content/uploads/2012/08/FCI-TPT.pdf

Hill, H. C., Ball, D. L., & Schilling, S. G. (2008). Unpacking Pedagogical Content Knowledge: Conceptualizing and Measuring Teachers ' Topic-Specific Knowledge of Students. *Journal for Research in Mathematics Education*, *39*(4), 372–400.

Hill, H. C., Schilling, S. G., & Ball, D. L. (2004). Developing Measures of Teachers' Mathematics Knowledge for Teaching. *The Elementary School Journal*, *105*(1). Retrieved from http://www.jstor.org/stable/10.1086/428763

Hill, J. G. (2011). *Education and Certification Qualifications of Departmentalized Public High School-Level Teachers of Core Subjects: Evidence From the 2007-08 Schools and Staffing Survey (NCES 2011-317)*. Washington, D.C. Retrieved from http://nces.ed.gov/pubsearch

Kaiser, A., & Cross, F. (2011). *Beginning Teacher Attrition and Mobility: Results from the First through Third Waves of the 2007-2008 Beginning Teacher Longitudinal Study (NCES 2011-318). National Center for Education Statistics*. Washington, D.C. Retrieved from http://files.eric.ed.gov/fulltext/ED523821.pdf

Kuenzi, J. J. (2008). *Science, Technology, Engineering, and Mathematics (STEM) Education: Background, federal policy, and legislative action*.

Magnusson, S., Krajcik, J., & Borko, H. (2002). Nature, Sources, and Development of Pedagogical Content Knowledge for Science Teaching. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining Pedagogical Content Knowledge* (pp. 95–132). New York: Kluwer Academic Publishers.

McCrory, R., Floden, R., Ferrini-Mundy, J., Reckase, M. D., & Senk, S. L. (2012). Knowledge of Algebra for Teaching: A Framework of Knowledge and Practices. *Journal for Research in Mathematics Education*, *43*(5), 584–615. http://doi.org/10.5951/jresematheduc.43.5.0584

McDermott, L. C., & Physics Education Group University of Washington. (1995). *Physics by Inquiry, Volume 1*. *Physics by Inquiry*. Wiley-VCH.

Merriam, S. B. (2009). *Qualitative research: A guide to design and implementation*. *The JosseyBass higher and adult education series* (2nd ed.). San Francisco: Jossey-Bass. http://doi.org/10.1097/NCI.0b013e3181edd9b1

NGSS Lead States. (2013). Next Generation Science Standards: For States, by States. *Achieve, Inc. on Behalf of the Twenty-Six States and Partners That Collaborated on the NGSS*. Washington, D.C.: National Academies Press.

Otero, V. K. (2006). Moving Beyond the "Get it or Don't" Conception of Formative Assessment. *Journal of Teacher Education*, *57*(3), 247–255. http://doi.org/10.1177/0022487105285963

President's Council of Advisors on Science and Technology. (2010). *Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future*. Washington, D.C. Retrieved from https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-stem-ed-final.pdf

Reif, F., & Allen, S. (1992). Cognition for Interpreting Scientific Concepts: A Study of Acceleration. *Cognition and Instruction*, *9*(1), 1–44. http://doi.org/10.1207/s1532690xci0901_1

Ruiz-Primo, M. A., & Furtak, E. M. (2007). Exploring teachers' informal formative assessment practices and students' understanding in the context of scientific inquiry. *Journal of Research in Science Teaching*, *44*(1), 57–84. http://doi.org/10.1002/tea.20163

Sadler, D. R. (1989). Formative assessment and the design of instructional systems. *Instructional Science*, *18*(2), 119–144. http://doi.org/10.1007/BF00117714

Sayre, E. C., & Wittmann, M. C. (2008). Plasticity of intermediate mechanics students' coordinate system choice. *Physical Review Special Topics - Physics Education Research*, *4*(2), 1–14. http://doi.org/10.1103/PhysRevSTPER.4.020105

Schneider, R. M., & Krajcik, J. (2002). Supporting Science Teacher Learning : The Role of Educative Curriculum Materials. *Journal of Science Teacher Education*, *13*(3), 221–245.

Scriven, M. (1967). The methodology of evaluation. In *Perspectives of curriculum evaluation* (pp. 39–83).

Shaffer, P. S., & McDermott, L. C. (2005). A research-based approach to improving student understanding of the vector nature of kinematical concepts. *American Journal of Physics*, *73*(10), 921. http://doi.org/10.1119/1.2000976

Shulman, L. (1986). Those Who Understand: Knowledge Growth in Teaching. *Educational Researcher*, *15*(2), 4–14. Retrieved from http://www.jstor.org/stable/10.2307/1175860

Smith, III, J., DiSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences*, *3*(2), 115–163. Retrieved from http://www.tandfonline.com/doi/abs/10.1207/s15327809jls0302_1

Speer, N. M., & Frank, B. W. (2013). BUILDING KNOWLEDGE FOR TEACHING RATES OF CHANGE: THREE CASES OF PHYSICS GRADUATE STUDENTS. *Umaine.edu*. Retrieved from http://umaine.edu/merg/files/2012/07/SpeerFrank_RUME_2013_PrelimReport.pdf

Speer, N. M., & Wagner, J. F. (2009). Knowledge needed by a teacher to provide analytic scaffolding during undergraduate mathematics classroom discussions. *Journal for Research in Mathematics Education*, *40*(5), 530–562. Retrieved from http://www.jstor.org/stable/10.2307/40539355

Star, S. L., & Griesemer, J. R. (1989). Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, *19*(3), 387–420. http://doi.org/10.1177/030631289019003001

Stein, M., Baxter, J., & Leinhardt, G. (1990). Subject-matter knowledge and elementary instruction: A case from functions and graphing. *… Educational Research Journal*, *27*(4), 639–663. Retrieved from http://aer.sagepub.com/content/27/4/639.short

Stiggins, R., & DuFour, R. (2009). Maximizing the Power of Formative Assessments. *Phi Delta Kappan*, *90*(9), 640–644. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=afh&AN=38812272&site=ehost-live\nhttp://content.ebscohost.com/ContentServer.asp?T=P&P=AN&K=38812272&S=R&D=afh&EbscoContent=dGJyMNHr7ESeqLM4v+vlOLCmr0uep7ZSsK24SbSWxWXS&ContentCustomer=dGJyMPGptky2q7NNu

Thomas, D. R. (2006). A General Inductive Approach for Analyzing Qualitative Evaluation Data. *American Journal of Evaluation*, *27*(2), 237–246. http://doi.org/10.1177/1098214005283748

Trowbridge, D. E. DE, & McDermott, L. (1980). Investigation of student understanding of the concept of velocity in one dimension. *Am. J. Phys*, *48*(12), 1020. http://doi.org/10.1119/1.12298

Trowbridge, D. E. DE, & McDermott, L. (1981). Investigation of student understanding of the concept of acceleration in one dimension. *American Journal of Physics*, *49*(3), 242. http://doi.org/10.1119/1.12525

US Census Bureau. (2010). Census 2010. Retrieved April 6, 2016, from http://quickfacts.census.gov/qfd/states/13/13135.html

Varela, F. J., Thompson, E., & Rosch, E. (1991). The Embodied Mind: Cognitive Science and Human Experience. *An International Journal of Complexity and*, *1992*, 328. http://doi.org/10.1111/j.1468-0149.1965.tb01386.x

Wiliam, D. (2006). Formative assessment: getting the focus right. *Educational Assessment*, *11*(3 & 4), 283–289. http://doi.org/10.1207/s15326977ea1103&4_7

BIOGRAPHY OF THE AUTHOR

Gregory Douglas Kranich was born in Millinocket, Maine in 1984. After graduating from Stearns High School in 2002, Gregory continued his education at the University of Maine earning a Bachelor of Science degree in Secondary Education in 2009. He has been a physical sciences teacher for four years at the middle and high school levels in Millinocket and Ellsworth, Maine. In 2012, Gregory enrolled as a graduate student in the Master of Science in Teaching program at the University of Maine, and began as a 4-H science youth development professional with the University of Maine Cooperative Extension in 2015. He is a candidate for the Master of Science in Teaching degree from the University of Maine in May 2016.