ABSTRACT

Title of Document: **A FRAMEWORK FOR RECOGNIZING MECHANISTIC REASONING IN STUDENT SCIENTIFIC INQUIRY**

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A central ambition of science education reform is to help students develop abilities for scientific inquiry. Education research is thus rightly focused on defining what constitutes "inquiry" and developing tools for assessing it. There has been progress with respect to particular aspects of inquiry, namely student abilities for controlled experimentation and scientific argumentation. However, we suggest that in addition to these frameworks for assessing the *structure* of inquiry we need frameworks for analyzing the *substance* of that inquiry.

In this work we draw attention to and evaluate the substance of student mechanistic reasoning. Both within the history and philosophy of science and within science education research, scientific inquiry is characterized in part as understanding the causal mechanisms that underlie natural phenomena. The challenge for science education, however, is that there has not been the same progress with respect to making explicit what constitutes mechanistic reasoning as there has been in making explicit other aspects of inquiry.

This dissertation attempts to address this challenge. We adapt an account of mechanism in professional research science to develop a framework for reliably recognizing mechanistic reasoning in student discourse. The coding scheme articulates seven specific aspects of mechanistic reasoning and can be used to systematically analyze narrative data for patterns in student thinking. It provides a tool for detecting quality reasoning that may be overlooked by more traditional assessments.

We apply the mechanism coding scheme to video and written data from a range of student inquiries, from large group discussions among first grade students to the individual problem solving of graduate students. While the primary result of this work is the coding scheme itself and the finding that it provides a reliable means of analyzing transcript data for evidence of mechanistic thinking, the rich descriptions we develop in each case study help us recognize continuity between graduate level learning and elementary school science: part of what students are able to do in elementary school finds its way to graduate school. Thus this work makes it possible for researchers, curriculum developers, and teachers to systematically pursue mechanistic reasoning as an objective for inquiry.

A FRAMEWORK FOR RECOGNIZING MECHANISTIC REASONING IN STUDENT SCIENTIFIC INQUIRY

By

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2006

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Acknowledgements

This material is based on work supported by the National Science Foundation under Grant Nos. “Learning How to Learn Science: Physics for Bioscience Majors” NSF REC-0087519, “Case Studies of Elementary Student Inquiry in Physical Science” ESI-9986846, “Towards a New Conceptualization of Progress, K-16: Resources, Frames, and Networks” NSF REC-0440113. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

During my graduate career at the University of Maryland, David Hammer has served both as my technical advisor and intellectual mentor. I cannot overstate the value of his help and advice. He both allowed me to explore my own areas of interest and directed me towards research that might contribute to and support those interests. I attribute any success in my research to his encouragement of my ideas and substantive discussions about my work. I owe a great deal to him.

In addition, I am lucky to have been surrounded by the thriving intellectual community of the Physics and Science Education Research Groups at the University of Maryland. Edward F. Redish, Rachel E. Scherr, Andy Elby, Emily van Zee, and Janet Coffey have strongly influenced both my research and future career path: through tangible feedback on my work and general discussions about education research and life. I also want to thank the past and present members of that research group who have listened to my mechanism schpeel more times than they can count: namely Paul Hutchison, Matty Lau, Leslie Atkins, Dan Levin, Tim McCaskey, Ray Hodges, Jonathan Tuminaro, Rebecca Lippmann, Tom Bing, Renee-Michelle Goertzen, Paul Gresser, Brian Frank, Luke Conlin, Steve Kanim, Saalih Allie, David May, Laura Lising, and Ayush Gupta.

Lindley Darden from the Philosophy Department at the University of Maryland played a crucial role in the development of this work. It was in taking her course and engaging in discussions with her that I first conceived of this dissertation. I am thankful for her patience with and attention to the process of modifying her work for my purposes.

My family has supported me throughout my time in Maryland with their visits, phone calls, emails, and prayers. Specifically, I want to thank my mom and dad (Sandy and Wayne), sister and brother-in-law (Claire and Ben), my second mom and dad (Janet and Bill), and my brothers and sisters-in-law (Brian, Audrey, Stephen, and Erin). I appreciate you all more than you know.

Finally, I could not have completed this research without the constant love and encouragement of my husband John. He has supported me through every stage of my work, rejoicing with me in my successes and providing strength during my trials. I am blessed to have him in my life.

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Chapter 1: Introduction and Motivation

Introduction

Einstein said “the whole of science is nothing more than a refinement of everyday thinking.” Similarly, extensive cognitive-historical analysis of episodes of discovery in the work of scientists such as Faraday and Maxwell has led Nersessian, a philosopher of science, to argue that “the problem solving strategies scientists have invented… over the course of the history of science are very sophisticated and refined outgrowths of ordinary reasoning” (Nersessian, 1992, p. 2). Science does not lie in the terminology, laws, and equations commonly memorized by students or written in textbooks. Instead, doing and learning science requires a “thinking as basic” stance (Greeno, 1992). Greeno argues that:

> Significant mathematical and scientific thinking is done by children, and that the task of school learning should primarily be to strengthen and refine those capabilities, rather than primarily providing knowledge of terms and procedures that are thought to be the materials on which thinking is based. (p. 41)

In this view, the role of the teacher is not to give students terms and laws to learn but rather to recognize the good thinking that students are already doing and provide opportunities for them refine it into something productive for scientific understanding. Such a view is congruent with the traditional constructivist paradigm of education: teachers should be able to identify fruitful seeds and use them to build students’ science knowledge. Einstein suggests and Greeno proposes that those fruitful seeds are abilities to think and reason, rather than assorted pieces of conceptual knowledge. But what, specifically, do these fruitful seeds look like in the classroom? What sorts of things can educators expect, or hope, to see when their students are engaged in "good" scientific thinking?

Some professional educators already have insight into these questions. Teachers and educational researchers who spend their careers listening and responding to student thinking develop intuitions about when students are doing well and when they are not. They observe students engaged in a discussion and recognize thinking that is valuable for science learning. Practicing research scientists may also be able to identify moments when students are being especially "scientific." Consider the following example from an interview by Chin and Brown (2000) in which an eighth grade student describes why salt water has a higher boiling point than fresh water.

> **Rick:** Salt in it… makes the water thicker. And it kind of took more heat to melt the water that had salt in it… It [salt] kind of fills up a lot of empty spaces between the [water] molecules. And so the heat couldn't pass through it as fast as it did through the plain water. So it had to add more heat to break through the salt particles and heat up the water. (p. 122)

Even though Rick's explanation is not correct, we may find consensus that he is doing something valuable. Our agreement relies on a shared intuitive sense of what "good" scientific thinking looks like. In particular, Rick gives a causal story that accounts for his observations about heating salt water. Describing underlying causes and effects for natural phenomena is one characteristic of scientific practice and is thus something we might want students to do. However, identifying the specific nature and type of causal descriptions valuable for science is a more sophisticated problem than our intuitions can reliably answer.

Even if we were not always able to articulate the specific kind of thinking we want to see students doing, being able to consistently identify it would be helpful. Unfortunately, while the above example may be clear to many science educators, there are other examples that would be controversial even within this community. Consider the following explanation given by a student in an introductory physics course for why rubbing our hands together doesn't produce static electricity.

> **John:** Because there's so much moisture in the air and it's [our hands] a conductor so… Because it's, it's a conductor so like it's not going to let charge build on your hands because it's a conductor so [charge] can easily jump off and disappear. Before it actually builds up enough so that you'd see a spark.

This explanation is more difficult to assess than the first one. Is the student engaged in "good" scientific thinking? Which seeds of productive reasoning are shown and which are absent? He uses the term "conductor" - vocabulary typically associated with electrostatics – in his description of why our hands don't produce a spark and he attempts to connect properties of a conductor to the observed phenomenon. It is unclear whether he has developed a coherent connection between the cause ('conductor-ism') and the effect (lack of sparks). Even with well-developed classroom intuitions, it is difficult to distinguish whether John is thinking well about the wrong ideas (in which case his *thinking* need not be refined) or whether the thinking itself is inappropriate or ineffective for scientific discussions.

Our attempt to assess John's explanation indicates that it may be especially difficult to identify the beginnings of scientific thinking, when our understanding of what we are looking for is at the level of "we know it when we see it." In order to reliably recognize and promote the fruitful seeds of scientific thinking in the classroom, we need to make these intuitions about when students are doing well more explicit. There are two pedagogical reasons for this need. First, those who do not share our intuition may find the above assessments inaccessible; it may be difficult for them to identify this type of reasoning as mechanistic. Second, we must be able to state clearly and precisely what "good" reasoning looks like so that others, including our students, are aware of our expectations and can agree with or challenge them. There are also ways in which making intuitions explicit will aid research. Doing so will support systematic analysis of narrative data that may help discover patterns in student thinking. Without a robust framework for identifying nascent versions of scientific thinking, researchers may not know what curricular elements will promote them, educators may not know how to refine or evaluate them, and students may not know when and how to use them.

Theoretical Framework

As educators, we constantly use information about what we see students doing to make decisions about what is happening in their minds. For example, in assessing Rick and John's comments above (or grading a written exam question), we take what students say as evidence of what they understand. To draw a parallel to traditional physics research, our *theory* of student thinking is grounded in our *evidence* of that thinking just as the theory about the wave nature of light is grounded in evidence such as Young's double slit experiment. However, just as evidence in science is theory laden, what we see and promote as valuable student contributions to science discussions is constrained by our ideas about what students can or cannot do and how they can or cannot think. That is, how we conceive of what is going on in Rick and John's mind affects our interpretation and assessment of their comments. So although this work concerns the phenomenology of student thinking: what we see students doing or saying, it is grounded in and influenced by a particular ontology of mind: what cognitive structures we attribute to students' minds that give rise to what they say and do in science classrooms.

Much current science education research considers student knowledge in terms of the *conceptions* (mis-conceptions, pre-conceptions, alternative conceptions) that they *have* about certain science topics. In this view of knowledge, researchers attribute students with stable units of cognition for particular areas of thought that always govern how the student thinks about a set of circumstances (Hammer, 2004). Some central (perhaps tacit) assumptions of this perspective include the idea that these conceptions are the result of prior learning and are so entrenched as to interfere with new learning (Smith, diSessa, & Roschelle, 1993). As such, the role of instruction is to evaluate the conceptions for correctness, eradicate or dislodge those that prove to be in conflict with canonical knowledge, and replace them with correct conceptions (Hammer, 1996). An appropriate research agenda is then to "examine student data for a *wrong but coherent* way of thinking" (Scherr, accepted, p. 3, emphasis hers) and identify problematic conceptions. We refer to this perspective as *unitary* (Hammer, 2004).

In contrast, the work presented here relies on a view of ontology in which student knowledge is composed of diverse smaller pieces, a variety of which might be applied to any particular area of thought. In this view, knowledge and reasoning are "comprised of many fine-grained resources [pieces] that may be activated or not in any particular context" (Hammer, Elby, Scherr, & Redish, 2005, p. 92). These pieces of knowledge themselves, unlike conceptions, are not intrinsically right or wrong; they are, instead, appropriately or inappropriately applied to a given situation. In this view, the role of instruction is not to rid students of their wrong ideas but to help students select, evaluate, and refine which of their existing resources are productive in which cases. Research is then designed to examine student data for appropriately applied resources as well as "*potentially useful, but inappropriately applied* ideas that could account for student responses" (Scherr, accepted, p. 3, emphasis hers) to identify valuable candidates for future reasoning. We refer to this perspective as *manifold* (Hammer, 2004).

The differing instructional implications of these two theoretical viewpoints are best shown with an example. Hammer (1996) describes a conversation from a non-calculus based high school physics course in which students are discussing whether a ball rolling on a level surface will keep moving at constant velocity.

Bruce: If there is no gravity and no friction, and there is a force that's making it move, it's just going to go in a straight line at constant speed… What's making the ball move?

Amelia: The forces behind it.

…

Steve: The force that's pushing it. (p. 1317)

We will first examine this episode from the unitary perspective. These students *have* the misconception that a force is required to make objects move; Bruce questions the idea that the ball can move at constant velocity without something "making" it move and Amelia and Steve both claim that there some force behind the ball pushing it. Their "explanation is assumed to stem from a 'pre-compiled' knowledge that is simply wrong" (Hammer et al., 2005, p. 95). This wrong idea that *motion is caused by force* hinders these students' ability to understand Newtonian mechanics and must be overcome before more instruction can occur (Hammer, 1996). For an instructor with this view, helping these students gain correct science knowledge would involve either explicitly showing them evidence of or providing theoretical arguments for force not causing motion – perhaps using an air track table to show a hockey puck sliding long distances in low friction. Either way, after students discovered that force does not cause (constant) motion the teacher could then present the idea that force causes acceleration.

From the manifold perspective, these students have perhaps activated a more general piece of knowledge about *maintaining agency* (Hammer, 1996). While inappropriate in this case, there are many situations in which the idea that an effect continues when maintained by a cause applies; for example "an engine maintains the motion of a car" (Hammer, 1996, p. 1319). The idea of maintaining agency is not wrong: it is just not relevant to objects moving on tables at constant speed. An instructor would not want to eliminate the idea of maintaining agency because it can be usefully applied in other situations – such as in understanding momentum (Hammer, 1996). Instead, they would want to activate another more appropriate resource. These students no doubt have experience with *actuating agency* in which an effect outlasts it cause; for example "the strike of a hammer causes a bell to ring" (Hammer, 1996, p. 1319). For an instructor with a manifold view, helping these students understand inertia would involve helping them recognize the difference between their actuating agency and maintaining agency resources – possibly by drawing students' attention to the push that started the ball rolling and contrasting that to the time when it keeps rolling at constant velocity. In contrast to a unitary instructor who might focus on how to eliminate wrong ideas, one with a manifold view would helps students adapt and apply their existing intuitive knowledge to so that it is more productive in the particular context (Hammer, 1996).

A particular ontology of mind – either unitary or manifold - can influence our understanding of student reasoning as well as of student conceptual knowledge. Those with a unitary model of learning may perceive students as either *having* or *lacking* general reasoning abilities just as they can have or lack knowledge elements (Hammer, 1996). Such a view may grow out of Piagetian developmental stage research where students progress through several "stable, equilibrated stages" (Hammer, 2004, p. 325). The manifold view in contrast argues for thinking of students as having finer-grained resources for reasoning skills. In practice, this perspective translates into not assuming that how a student reasons in one particular context at one particular time represents the entirety of his or her abilities. For example, although students may engage in concrete thinking in one situation they may also be capable of extremely abstract and sophisticated reasoning in others. Classrooms then become venues to "draw out and support ways of thinking and talking that are, in general, productive for physical science" (Hammer, 2004, p. 336).

The present work is grounded in a manifold ontology of mind; that is, we expect student reasoning to be variable. This theoretical framework affects our interpretation of student discourse. As Scherr (accepted) suggests:

> Many of us who are physics instructors and physics education researchers use either the pieces [manifold] model or the misconceptions model to inform our instructional and research agendas (perhaps implicitly). We necessarily see our students through a theoretical lens that shapes our interpretations. (p. 11)

We do not assume that an observation that a student is not engaged in sophisticated scientific thinking at one time means they are incapable of such reasoning; John might reason in a more obviously productive way in other conversations than he did when talking about electrostatics. Nor does seeing students reasoning well in one instance mean they will always do so; Rick might not have developed such a scientific explanation in his classroom as he did in his interview. As a result, this work describes the possibilities of student thinking - what they can (but might not always) do in science classrooms. By explicitly characterizing these possibilities, we as educators are better prepared to recognize and promote them so that they become the norm.

Themes of the Dissertation

This work is devoted to recognizing the conversations that occur when students are using productive resources for thinking about science. This goal translates to providing some answers to the questions posed casually in the introduction: What do the fruitful seeds (resources) of scientific thinking look like? And what should educators expect to see when their students are engaged in “good” scientific thinking?

We attempt to make progress in answering these questions along one dimension of scientific thinking: reasoning about causal mechanisms for phenomena as one fruitful seed of scientific thinking ability. There is good reason to suspect that such thinking, which “explains the process by which a cause brings about an effect” (Koslowski, 1996,

p. 13), is valuable for science. Within the history and philosophy of science, the "scientific revolution" that gave rise to modern science as it is practiced today has been characterized as a shift from "occult" to causal mechanistic accounts of the natural world (Shapin, 1996; Teeter Dobbs & Jacob, 1995; Westfall, 1986). Mechanistic thinking is now firmly established as inherent in the values and practices of science (Kuhn, 1977; Nersessian, 1992; Salmon, 1978; Teeter Dobbs & Jacob, 1995).

Given its prevalence in the values and practices of professional science, assessing student scientific reasoning should include assessments of when and how students seek causal mechanism in their understanding. We explore science discussions centered on students' "very rich starter-set of resources for understanding physical cause and effect" that are the building blocks for constructing mechanistic descriptions for phenomena (Hammer, 2004, p. 337). In order to help educators recognize these kinds of productive conversations, we articulate an explicit characterization of mechanistic reasoning that is not limited to intuitive assessment of "goodness." The framework, developed from philosophy of science research (predominantly Machamer, Darden, and Craver, 2000), describes seven aspects of reasoning that students may engage in during their attempts to construct mechanistic explanations for phenomena. While doing any of them alone does not constitute complete mechanistic reasoning, used together they allow students to make substantial progress in understanding physical phenomena. This framework describes the components of mechanistic reasoning so as to make it more easily identifiable for instructors and researchers wanting to recognize and promote nascent or incomplete versions of it.

The framework not only helps reliably identify causal mechanistic reasoning but also provides an analysis technique for understanding the dynamics and value of student science discussions. Our purpose in this work is both to describe the framework as a tool for detecting quality reasoning and to illustrate its use in several lines of study. We present a range of case studies from first grade to college courses and small group work to large teacher-led discussions. When taken together, these studies demonstrate the value of the coding scheme as a lens for assessing student inquiry across all levels of classroom science. In doing so, the mechanism framework allows us to think about the kinds of progress students can make in understanding science.

The analysis also challenges assumptions about science learning by revealing abilities that may be overlooked by more traditional assessments. While developmental stage models of reasoning skills might take a lack of student sophistication at one moment to indicate an overall lack of ability, analyzing student thinking using the mechanism coding scheme shows that students often transition quickly and fluidly between the least and most sophisticated aspects of mechanistic thinking (chapter four). Traditional conceptual assessments may underestimate the value of student conversations in which the correct canonical knowledge is not discussed; mechanism coding shows that students can be engaged in sophisticated mechanistic reasoning regardless of whether the concepts themselves are correct (chapter five). The view that school science ought to consist predominantly of conducting and analyzing formal empirical investigations undervalues students reasoning in a productive way about informal, anecdotal evidence (chapter six) – reasoning that can be identified with the mechanism coding. While many outside of the field (and some within it) tend to think of *real* physics as heavily or solely mathematical, analysis of upper level student work using the mechanism framework reveals the crucial and often unacknowledged role mechanistic reasoning plays in solving problems (chapter seven). This work provides a lens for finding aspects of student reasoning that are intuitively valuable for science but are obscured by more traditional measures.

Chapter Review

Chapter Two: The Case for Attending to Mechanistic Reasoning in Student Inquiry

The following chapter provides a of review existing research on student thinking and learning during inquiry. We argue that the conceptions of inquiry heralded by much of this literature, while valuable in many ways, have two major weaknesses: they are disconnected from the kinds of thinking that students engage in naturally in the everyday world, and they rely on incomplete and distorted views of professional science. We outline literature that supports these claims, specifically work that suggests the inclusion of mechanistic reasoning in inquiry as a remedy for these problems. Finally, we describe the strengths of conceiving of inquiry as largely including mechanistic reasoning and the limitations of current characterizations of mechanism that the present work is designed to overcome.

Chapter Three: Methodology of Developing and Using the Mechanism Framework

This chapter begins by reviewing the general literature from the philosophy of science on scientists' mechanistic reasoning and provides a more detailed description of work by Machamer, Darden, and Craver (MDC) which serves as the basis for this dissertation research. We present an initial attempt to use MDC's mechanism language to analyze student reasoning from a first grade classroom discussion about whether or not seeds can grow in sand. We then explain the development of a more systematic framework that is used throughout the rest of the work to reliably identify and track student mechanistic reasoning in nascent science. We describe the coding scheme in detail including its stages of revision and then provide examples from science discussions to illustrate its use. Finally, we discuss the methodology employed to analyze student thinking during inquiry with this framework.

Chapter Four: Mechanistic Reasoning in Young Children

This chapter presents the first of four case studies that provide phenomenological evidence of student mechanistic reasoning and demonstrate the usefulness of the framework for recognizing and tracking it. Analysis of a transcript from a student discussion among first graders about the rate of falling objects confirms that the framework matches intuitive interpretations of the quality of student thinking. This data also shows that the framework developed from accounts of professional science identifies corresponding mechanistic reasoning in first-graders, and so identifies the beginnings of science in children's thinking as they move fluidly between various levels of mechanistic sophistication. By applying the coding scheme, we gain insight into the dynamics of the discussion and identify several points of transition in their mechanistic reasoning that were not easily discernable from classroom video or transcript.

Chapter Five: Mechanistic Reasoning Independent of Correctness

In this chapter, analysis of a discussion from a second grade science classroom about why empty juice boxes collapse when you suck on their straws helps challenge the assumption that inquiry is best evaluated by how well student conceptual understanding aligns with canonical knowledge. We find that assessments of content can misrepresent and obscure the quality of student inquiry; students who give the wrong answer have mechanistic explanations equivalent in sophistication to students with the right answer. This analysis first shows the value of the coding scheme for analyzing *reasoning* in itself as distinct from the concepts. Second, it calls into question whether conceptual correctness is always the appropriate instructional target for K – 16 science classrooms.

Chapter Six: Mechanistic Reasoning with Informal Empirical Evidence

The case study analyzed in this chapter comes from an introductory college physics course and differs from traditional conceptions of inquiry that focus on controlled experimentation. During a small group discussion, students make qualitative observations and draw on their prior experiences to develop a model of static electricity. The mechanism framework is used to describe several ways their experiential and anecdotal evidence supports their construction of a mechanistic explanation even though that evidence is not produced by formal investigations. We show several different manifestations of the cyclic relationship between mechanistic reasoning and informal results where each one informs the other. We describe the strengths and weaknesses of each for helping the students understand electrostatics.

Chapter Seven: Mechanistic Reasoning with Mathematics in Graduate Level Physics

The final analysis chapter centers on upper level physics students' solutions to a classical mechanics problem on a PhD qualifying exam. Using both written data and interviews, we show that advanced students use mechanistic reasoning to supplement mathematical formalism in problem solving and that they use mathematics to express their sense of mechanism. Another important result of this analysis is that the coding scheme developed from characterizations of professional bioscientists and successfully applied to elementary science and introductory physics can give insight into what mechanistic reasoning might look like in upper level physics. The value of mechanistic reasoning is not limited to use in introductory or conceptual physics topics, it is part of the fabric of graduate (even expert) physics understanding.

Chapter Eight: Reflections on Current Work and Directions for Future Research

This chapter summarizes the work of this dissertation. We describe both its motivating assumptions about student learning and the implications of the case studies for science education research and practice. We then step back from the specifics of each case study and reflect on the "bigger picture" of the research. Finally, we suggest that an appropriate avenue for future research involves studying the ontology that gives rise to the phenomenology described in this work.

Chapter 2: The Case for Attending to Mechanistic Reasoning in Student Inquiry

Introduction

The discussion of what types of thinking and learning are productive for science is both fervent and long-standing. It has become common for educators to use the term *inquiry* in describing the kinds of things that should happen in science classrooms. Research on student scientific inquiry spans several academic cultures – from science education to educational psychology to cognitive science to subject-matter disciplines. Despite its diversity of origin, much of this research shares a common conception of inquiry: it equates inquiry, either tacitly or explicitly, with formal empirical investigation.

Educational literature suggests mechanistic reasoning is an additional, perhaps more essential feature of inquiry that maintains the strengths of controlled experimentation and avoids its weaknesses. However, that literature is limited in that its characterizations of mechanistic reasoning are imprecise and rely on abstract notions of causality. The rest of this dissertation constructs a framework for analyzing inquiry that overcomes the limitations of current characterizations of mechanism.

Inquiry in Science Education

The word "inquiry" is used extensively in literature on the teaching and learning of science. Several decades of reform in science education that have encouraged a shift from teaching students a body of canonical conceptual knowledge to also helping them develop abilities for scientific inquiry. Dewey, Bruner, and Schwab were among the most prominent early educational reformers to suggest the value of teaching through and learning about scientific inquiry (NRC, 1996). More recently the *National Science Education Standards*, which serve as a guideline for K-12 science education in this country, claim that "inquiry is central to science learning" and have thus called for "changing emphases to promote inquiry" (NRC, 1996, p. 2 & 113). The National Research Council published an Inquiry Supplement to these *Standards* that not only provides detailed examples of inquiry but also uses current educational research to outline why inquiry is a valuable part of science classrooms (NRC, 2000). Within the discipline of physics, research-based curricular materials for post-secondary students (including undergraduates and pre/inservice teachers) focus on using inquiry to develop a more complete understanding of traditional introductory physics concepts (e.g. McDermott et al., 1996). Even for the more general population, the AAAS *Benchmarks for Science Literacy* (1990) and *Science for All Americans* (1993) emphasize that an understanding of scientific inquiry is central to an understanding the nature of science. The literature on inquiry is extensive and the work of educators, curriculum developers, and researchers all reflects a commitment to having inquiry as a vital part of science learning.

Current Conception of Inquiry: Formal Empirical Investigation

The challenge in achieving this ambition has been in defining inquiry and what it should look like in the classroom. Within the science education literature there are many descriptions of the kinds of things students should be doing during scientific inquiry. These characterizations share the assumption, either explicitly or implicitly, that the most important and valuable facet of scientific inquiry is empirical investigation.

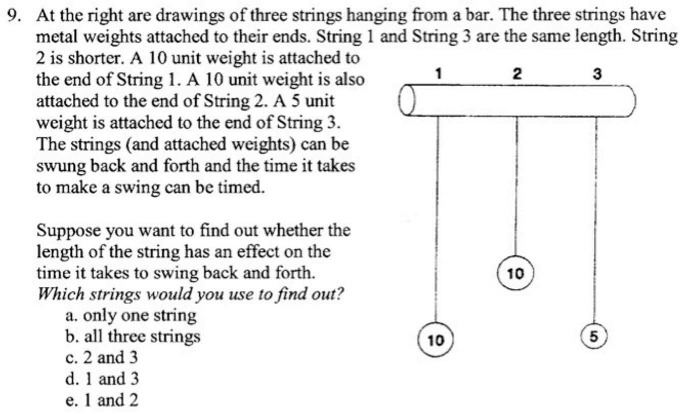
Designing and Conducting Controlled Experiments

Within the current practices of education, the ideal of scientific inquiry that is enacted is a highly empirical one that focuses on students' abilities to design and conduct controlled experiments. Science standards promote formal investigations in which students ask testable questions and negotiate among dependent, independent, and controlling variables during data collection (e.g. AAAS, 1993; MCPS, 2001; MSCS, 2000; NRC, 1996). "Full" inquiry is characterized for the various grade levels as:

> **K - 4:** students "asking a simple question, completing an investigation, answering the question, and presenting the results to others" (NRC, 2000, p. 122)
>
> **5 - 8:** students "begin with a testable question, design an investigation, gather evidence, formulate an answer to the original question, and communicate the investigative process and results" (NRC, 2000, p. 143)
>
> **9 - 12:** students identify questions for investigation based on prior knowledge, design and conduct those investigations, analyze evidence and data to formulate explanations, and communicate their arguments and respond to those of others (NRC, 2000)

Maryland state standards for scientific inquiry focus on students' abilities to pose answerable questions with testable hypotheses, conduct "well-designed procedures" for appropriate investigations (including proper control and safety procedures), analyze data using mathematical tools, and communicate their findings (MSCS, 2000). In these standards for inquiry, science learning proceeds by performing formal investigations and analyzing data to reach conclusions.

Literature from science education research on student inquiry similarly shares the assumption that the primary abilities of inquiry are designing and conducting formal investigations whose data analysis will help in developing explanations. Chinn and Malhotra's (2002) evaluation of school inquiry tasks defines features of “epistemologically authentic inquiry.” They claim that the cognitive processes used during authentic inquiry include generating research questions, designing studies by selecting and controlling variables, explaining empirical results, and developing theories from results and other outside knowledge. In describing the *ThinkerTools* Inquiry Curriculum, White and Frederiksen (1998) explicitly state their view of inquiry expertise as movement through the *Inquiry Cycle* consisting of formulating a "well-formed, investigatable research question," generating "alternative, competing hypotheses and predictions," designing and carrying out real and virtual experiments, analyzing data to construct models, and applying models to new situations to help generate new questions (p. 10). Roth and Roychoundury's (1993) study of student development of process skills relies on the notion that "identifying variables, interpreting data, hypothesizing, defining, and experimenting" are the most valuable "higher-order" abilities of scientific inquiry (p. 148). On Lawson’s widely-used multiple-choice diagnostic of scientific reasoning skills, eleven of the twenty-four questions probe student abilities to design or explain the results from valid experiments (Coletta & Phillips, 2005). The following question from the test is representative of that emphasis.



9. At the right are drawings of three strings hanging from a bar. The three strings have metal weights attached to their ends. String 1 and String 3 are the same length. String 2 is shorter. A 10 unit weight is attached to the end of String 1. A 10 unit weight is also attached to the end of String 2. A 5 unit weight is attached to the end of String 3. The strings (and attached weights) can be swung back and forth and the time it takes to make a swing can be timed.

Suppose you want to find out whether the length of the string has an effect on the time it takes to swing back and forth. *Which strings would you use to find out?*

a. only one string
b. all three strings
c. 2 and 3
d. 1 and 3
e. 1 and 2

Figure 1

A pattern begins to emerge in conceptions of inquiry held by this literature. As in the standards, evaluating scientific inquiry involves evaluating student abilities to design, conduct, and interpret empirical investigations.

Researcher conceptions of inquiry can not only be identified from explicit statements like those given above, but also inferred from the context of their studies on scientific inquiry. Much science education research is conducted in what its authors describe as "inquiry" settings. Their choice of these settings represents their tacit views about the definition of inquiry. For example, Sandoval and Morrison's (2003) work on biological theory change tracks student learning during an “inquiry unit” in which students pose and investigate questions, then use empirical (computer-simulated) data to support their claims. Elder’s (2002) research into fifth graders’ epistemological beliefs takes place within an “inquiry model of learning” where students “manipulate equipment and materials, conduct experiments, and generate questions for further inquiry” (p. 351). Schauble (1996) purposefully designed her study of scientific reasoning to occur in a setting defined by experimentation, using the following prompt to explain the task to her subjects:

> Scientists often design experiments to try to find out what makes a difference and what doesn't make a difference in how things work. This week *you are going to work like a scientist...* To find out which features [of the system] do and do not make a difference in [the outcome] you can do some experiments with this system. (p. 106, emphasis mine)

These are but a few examples of a common trend. For a wide variety of topics within the science education literature, researchers conduct their work in “inquiry settings” that involve formal empirical investigations, thus revealing their underlying assumptions about what inquiry is.

Interpreting Controlled Experiments

Other literature on scientific inquiry focuses not on abilities to *conduct* formal experiments but on abilities for *interpreting* experiments by accepting or rejecting hypotheses based on purposefully accumulated empirical results. D. Kuhn's work (1989) on coordination of evidence and theory describes the difficulties children exhibit in drawing appropriate conclusions about causality from empirical data. To probe student abilities for evaluating evidence, Kuhn asked them to decide based on covariation data which of several variables “made a difference” in the outcome of a situation. She found, for example, that students did not make claims that agreed with evidence about whether the size, color, or texture of balls affected the quality of a serve. Instead, students relied on self-constructed theories about what variables might or might not affect outcome. In Kunn’s estimation, the students demonstrated various “weaknesses in reasoning” (p. 683) and inappropriately allowed theory to bias their evidence interpretation. Kuhn maintains the stance that theory “colors” valid evidence interpretation in her other studies on scientific reasoning. In her review of a larger body of Kuhn’s work, Koslowski (1996) notices the following trends:

> One is that Kuhn et al. treat theory or mechanism information as being quite distinct from, and inferior to, evidence that consists of covariation. The other is that Kuhn et al. treat subjects’ reliance on theory to evaluate data as an example of flawed reasoning; it is citing covariation information that is treated as good thinking. (p. 35)

In Kuhn’s heavily-cited work (the 1989 article alone is cited by 149 authors), experimental evidence is given precedence over theoretical ideas and is seen as the arbiter of ‘correct’ scientific knowledge.

Value of Formal Empirical Investigation

Conceptions of inquiry that center on controlled experimentation attempt to capture a portion of the processes of science rather than focusing solely on the products of those processes. An explicit goal of the National Science Education Standards' focus on inquiry is to place “as much, if not more, emphasis on learning the processes of science as on mastering the subject matter of science alone” (NRC*,* 2000, p. 16). These characterizations of inquiry have the potential to send students the message that science does not consist of a collection of facts that must be memorized but also (and perhaps largely) of the activities by which that knowledge came to be produced and accepted. In this way, experimentation represents a step towards a more authentic characterization of the nature of science than those that treat science as an inert set of hard-and-fast rules about the natural world.

Another value of functionally defining inquiry as formal experimentation is that the resulting empirical data provides support for new knowledge claims. Within the science education literature, there has been significant focus on scientific argumentation and the use of empirical data to construct sound arguments (e.g. Driver, Newton, & Osborne, 2000; Kuhn, 1989). Driver, Newton, and Osborne (2000) suggest that inquiry should include opportunities for students to generate well-supported claims and respond to counter-arguments because argumentation is a "core activity of scientists" (p. 287). They further note that within the professional scientific community, "scientists hold a central commitment to evidence as the ultimate arbiter between competing theories." (Driver et al., 2000, p. 296) Kuhn's work (1989) on the coordination of theory and evidence also describes the value of empirical results for deciding among theoretical claims:

> A central premise underlying science is that scientific theories stand in relation to actual or potential bodies of evidence against which they can be evaluated. (p. 674)

These authors point out that controlled experimentation is necessary for science because it allows scientists (and students) to test the predictions of a theory and thus assess its accuracy, scope, and relevance. Experiments are one method by which scientists judge their explanations against others (Brewer, Chinn, & Samarapungavan, 1998).

In this work we contend that while empirical results do provide necessary support for new theories, they are not the only appropriate information to use in arguing for or against rival accounts. Literature on inquiry that heralds formal experimentation draws attention to only one of the means of justification for scientific argumentation.

Limitations of Formal Empirical Investigation

Formal empirical investigation risks conflating covariation with causation

A strictly empirical definition of inquiry carries with it the danger of mistaking covariational relationships for causal ones. Data from controlled experimentation only provides evidence about regularity and covariation among variables; even the best-designed experiments only answer questions such as "Does Y change when X and only X is changed?" During the formal investigations described in the literature, students are encouraged to collect and analyze data using appropriate mathematical tools and then use this information about the *covariation* relationship to draw conclusions about the *causal* connection between the variables. Koslowski (1996) describes this trend in education research and curriculum development as one in which "causation was operationalized in Humean terms, as being equivalent to covariation" (p. 20). There is little within the literature on student or scientist reasoning to support a covariational view of causal understanding.

Formal empirical investigation is not natural for laypeople or students

Inquiry that relies on formal empirical investigations to provide the sole basis for new understandings presents an activity disconnected from students' natural abilities. There is significant literature suggesting that covariation is not the primary information laypeople naturally use when reasoning about novel causal situations. This literature presents the case for the "ecological validity" of a focus on theoretical mechanism by describing "what people do most often, most typically, or perhaps, most naturally" during causal reasoning (Ahn & Kalish, 2000, p. 199). Ahn, Kalish, Medlin, and Gelman (1995) performed a series of experiments to identify what information people request when they are asked to make causal attributions about everyday situations (e.g. "The musician learned to play chess last summer" (p. 342)). They found that in order to make causal attributions, people requested "non-ANOVA" information that would help them understand how a particular mechanism acted in the target event, and *not* how the situation fit into a pattern of covariation data. For example, in trying to decide the cause for "Dave would not eat rabbit meat on this occasion." people ask "Did he [Dave] have a toothache?" more often than "Does Dave usually eat rabbits?" (Ahn et al., 1995, p. 315 & 314) Similarly, people's explanations for those events are more commonly mechanistic. Ahn et al. found that

> people do not spontaneously seek out information about covariation between factors and effects, nor do they seem to use such information when it is provided. The preferred strategy seems to be to gather further facts about the particular event to be explained: facts that are used to test hypotheses about possible underlying mechanisms. (p. 336)

They offer a possible explanation for the prevalence of this strategy; "Although covariation information allows us to identify a factor, we do not know the nature of the connection between the factor and effect [which the mechanism provides]" (Ahn et al., 1995, p. 304). Shultz (1982) undertook a more extensive study to determine whether children and adults use information about generative transmission (i.e. mechanism) in making causal judgments about both familiar and unfamiliar situations (sound generated by tuning forks, wind generated by electric fans, light generated by flashlights). His interview subjects ranged in age from 3 years to adulthood and came from both Western and traditional African cultures. He found that all levels of observers most often "interpret physical causation primarily in terms of the concept of generative transmission [mechanism] rather than in terms of other well-known rules such as covariation, similarity, and temporal and spatial contiguity" (p. Abstract). Koslowski, Okagaki, Lorenz, and Umbach (1989) studied the interaction of mechanism, sample size, sampling method, and covariation information in students' causal attribution. Subjects were presented with a story problem about a common event, for example:

> There is a new gas station in town that sells two types of gasoline, one that is regular and one that has a special additive designed to cover up the odor. Larry wants to find out if using the gasoline with the special additive has something to do with making cars get worse gas mileage. (p. 1325)

The subjects were then given four pieces of information about how Larry went about investigating the problem. They were told Larry's "way of finding out:" sampling method – direct intervention or natural occurrence, "amount of evidence:" sample size – small or large, "additional information:" mechanism – present, ruled out, or none available, and "results:" covariation – present or absent (Koslowski et al., 1989, p. 1325). From this information, subjects were asked to judge how likely it was that the additive affected gas mileage. Koslowski et al. found statistically significant interactions among all the variables and also make the more modest claim that “adults [though not necessarily adolescents] do not treat the presence and absence of covariation as definitive indices of the respective presence and absence of causation” but also treat mechanism information as evidential (p. 1323). This literature supports the claim that when laypeople attempt to identify causes for events, covariation information does not serve the principal role in that attribution. Instead, they rely on knowledge of underlying (or potential) mechanisms that provide the mediating processes between the events.

There is also evidence that students not only can reason about mechanisms for scientific phenomenon but also that they do so spontaneously and from a very young age. In analyzing inquiry from elementary school classrooms, Hammer (2004) presents several instances of young students discussing physical mechanisms for phenomenon and “thinking about the question in ways that drew on their other knowledge and experience” (p. 286). During science discussions about topics ranging from falling objects to earthquakes to magnets, students - sometimes spontaneously and sometimes with prompting - explained their ideas by appealing to underlying causal mechanisms (Hammer & van Zee, 2006). Kuhn’s (1989) studies on children’s abilities to coordinate theory and evidence also revealed their tendency to spontaneously justify causal claims with mechanism rather than covariation information. For example, when presented with covariation evidence between types of cake and illness and asked whether the type of cake affected sickness, a sixth grader replies:

> **Peter:** Yes. Carrot cake is made with carrots, and chocolate cake is made with a lot of sugar. This [carrot cake] is made with some sugar too but it’s made

> with less sugar… Less sugar means your blood pressure doesn't go up. It [type of cake] makes a difference [in whether you get sick]. (p. 676)

Even when expressly and repeatedly pressed to use the provided covariation evidence, the student continued to justify his answer with mechanism. Kuhn found that "subjects appeared unwilling to acknowledge the implications of evidence unless they had a compatible theory in place that provided an explanation of this evidence" (p. 678). Although Kuhn views this reliance on mechanism as a flaw in reasoning, her evidence supports the claim that students spontaneously use mechanism information in making causal judgments. Chinn and Brewer's (1998) study of the factors that influence people's responses to anomalous data reveals the prevalence of considerations of mechanism: people may reject the data because it violates an understanding of "how a mechanism operates" or because "there is no mechanism that could account for both the present data and all of the data for the initial theory" (p. 638). Schauble (1996) also notices this trend for students to immediately look for plausible mechanisms to explain their covariation results. When one student came across the surprising covariation between canal depth and boat speed she spontaneously constructed a mechanism to explain it: "The only thing I can figure out is that the depth of the water would have something to do with the buoyancy. The added water, the depth of the water adds more buoyancy, making the boat, you know, sit up higher in the water, which makes it easier for the pulley to pull it through" (Schauble, 1996, p. 116). Similarly, in developing a case for the use of *Intermediate Causal Models* in science instruction, White (1993) describes how students who were not given mechanistic models of circuit behavior "spontaneously invented their own" to help guide them in making predictions about current behavior (p. 196). She also notes that students' difficulties in reasoning about circuits decreased when they were given causal reductionist (mechanistic) explanations for the laws.

Students can and do naturally make sense of the world around them using information about mechanisms. Defining inquiry in a way that systematically requires students to approach science by conducting experiments runs the risk of disengaging the spontaneous sense of mechanism they have built from everyday experiences (diSessa, 1993) in favor of engaging less organic knowledge about the logical structure of covariation.

Formal empirical investigation is not representative of professional science

Inquiry science learning is partly intended to reflect the practices of professional science. However, by emphasizing procedural techniques for controlling variables and analyzing data for covariations, current conceptions of inquiry give an inaccurate representation of professional science by demoting the role of mechanistic reasoning. Hodson, in his 1988 article *Towards a Philosophically More Valid Science Curriculum*, argues that in current inductivist models of inquiry where theory is derived directly from observation,

> theories are subordinated to experimentally gathered "facts"… As a consequence, children get an inflated sense of the importance of their "experimental results" and a grossly misleading view of the relationship between theory and evidence. (p. 26)

In her review of the psychology and education literature on student scientific reasoning, Koslowski (1996) similarly argues that characterizing inquiry as formal controlled experimentation distorts the nature of science by omitting one of its crucial aspects – considerations of mechanism. To support this claim, she cites philosophy literature on the nature of scientific reasoning:

> Realists and empiricists alike agree that, in actual practice of causal or scientific reasoning, Humean strategies (such as, identifying the cause of a phenomenon by finding out what covaries with it) cannot be applied independently of one's knowledge about the phenomenon (including knowledge that, whatever its philosophical reconstruction, is represented by scientists as knowledge of unobservable causal mechanisms or processes). (p. 9)

The work of scientists cannot accurately be described as relying only on covariation; it must also include searching for and using mechanisms to make sense of physical phenomena and data. Mechanistic reasoning, at the very least, accompanies analysis of covariation data in scientific inquiry.

Evidence from accounts of scientific practice strengthens the assertion that the role of mechanistic reasoning in inquiry should not be neglected. The history and philosophy of science literature is filled with rich descriptions of historical and current scientific practice that depict an activity centered on the search for mechanisms. Westfall (1986) focuses on the notion of mechanism in his examination of the construction of modern science as it is known today. He characterizes the 17th century scientific revolution as a shift from "occult" to mechanistic accounts of the natural world. He claims that mechanical philosophers such as Galileo, Descartes, and Kepler "conceived of nature as a huge machine and sought to explain the hidden mechanisms behind phenomena" (Westfall, 1986, p. 1). Shapin (1996) provides a similar account of the scientific revolution in which “proper mechanical accounts of nature were widely recognized as the goal and the prize” (p. 30). In these mechanical accounts:

> Everything in the natural world was to be explained with reference to the irreducible properties of matter and its states of motion: that was one thing that made the interpretation of nature like the interpretation of machines. (Shapin, 1996, p. 46)

These general trends of the scientific revolution were reflected in the work of individual scientists. Teeter Dobbs and Jacobs (1995) describe the influence of the mechanical philosophy on Newton, especially in his early attempts to construct a mechanistic account of gravity using “an all-pervasive material medium that served as an agent of change in the natural world” (p. 12-13). Newton’s subsequent decision to abandon this traditional mechanical account of inert matter in motion precipitated the reformulation of mechanical philosophy to include action-at-a-distance forces (Westfall, 1986). Nersessian (1992), who is known for her extensive analysis of scientific discovery episodes, characterizes Faraday and Maxwell’s study of electromagnetic fields in part as a search for mechanisms. She highlights Maxwell’s own admission that he derived the field equations “by using a method he called ‘physical analogy’ to exploit the powerful representational capabilities of continuum mechanics” (Nersessian, 1992, p. 17). He constructed a mechanical electromagnetic medium and used ideas about known mechanical phenomena (e.g. wheels turning, fluids moving) to guide his thinking. These two episodes exemplify the work of scientists during the rise of the mechanical philosophy. Literature from the history of science depicts these explanations as fundamental, privileged, and prevalent in scientific practice.

Contemporary scientific practice continues to value mechanistic reasoning just as highly. Salmon (1978) defines scientific explanation and our sense of what constitutes such an explanation in the following way:

> It [scientific explanation] provides knowledge of the mechanisms of production and propagation of structure in the world. That goes some distance beyond mere recognition of regularities, and the possibility of subsuming particular phenomena there under. It is my view that knowledge of the mechanisms of production and propagation of structure in the world yields scientific understanding, and that this is what we seek when we pose explanation-seeking why questions. (p. 701)

In the biological sciences, philosophers have studied the structure and nature of mechanisms precisely because of the key role mechanisms play in explaining and understanding the world (e.g. Bechtel & Richardson, 1993; Glennan, 1996; Machamer, Darden, & Craver (MDC), 2000; Tabery, 2004). Machamer, Darden, and Craver (2000), whose work serves as the basis for much of this thesis, support their interest in mechanisms by noting that

> in many fields of science what is taken to be a satisfactory explanation requires providing a description of a mechanism. So it is not surprising that much of the practice of science can be understood in terms of the discovery and description of mechanisms. (p. 1-2)

Tabery's (2000) attention to mechanism is similarly grounded in the claim that "the search for and discovery of mechanisms in science abounds" and "what is taken to be a causal explanation [in science] often consists of the description of a mechanism" (p. 1). Glennan (1996) argues that mechanisms function as the basis for all causal understanding and that "all but the most fundamental laws of physics can be explained by reference to mechanisms" (p. 49). Both Nersessian's study (1992) of physicists and Dunbar's study (1995) of geneticists suggest that analogies continue to play a part in how scientists think precisely because they give scientists access to more familiar mechanisms. Beyond discussions from the philosophy of science, there is evidence that real scientists attend to mechanism in their research. A quick literature search reveals that within the year 2005 alone, there were 333 articles in *Science* and 1677 articles in all the APS *Physical Review* journals with the word "mechanism" in the title or abstracts (search modified from MDC, 2000, p. 2). For scientists in many fields of research, adequate explanations for natural phenomena require the identification and description of the underlying mechanisms at work.

Current conceptions of inquiry either altogether neglect mechanistic reasoning or relegate it to the job of interpreting of empirical results. However, the practices of science value reasoning about mechanism in and of itself. Literature from the history and philosophy of science gives reason to suspect that the search for mechanisms constitutes the central aim of scientific research.

If anything, empirical investigations occur in the service of that search for a mechanistic explanation and not vice-versa. In focusing heavily on formal controlled experimentation, current definitions of inquiry misrepresent professional science.

Formal empirical investigation leaves out hypothesis generation

Empirical investigations in school science often involve performing experiments in which the question, hypothesis, and relevant variables are already known or easily found. Characterizing inquiry as that kind of experiments distorts the nature of science by placing undue importance on hypothesis *testing*, at the expense of hypothesis *generation*. Professional scientists, however, often spend an extensive amount of time in hypothesis generation. One key means of identifying hypotheses involves using knowledge about mechanisms of physical change to develop theories or questions that may later be formalized by investigations. Students and scientists develop that knowledge of causal mechanisms through their experiences (both informal and formal) with the natural world (diSessa, 1993). In science, it is often necessary to take time to consider everyday phenomena and their underlying mechanisms in order to generate hypotheses to test.

Imagine a simple example from an introductory physics class where students are investigating pendulum motion. It is in thinking about what causes the pendulum to swing (namely gravity and the string) that students might reasonably decide to test the effect of mass and length on the system. It is unlikely that students will control for color in the experiment precisely because there is not a plausible mechanism by which color affects the motion. Dunbar (1995) describes another case from a molecular biology research lab studying retroviruses. During one lab meeting, the group used an analogy to another class of viruses to understand the possible relations and mechanisms working in the retrovirus. That theoretical discussion helped them generate questions to pursue in the retrovirus. In their study of student approaches to learning the function of a device, Klahr and Dunbar (1988) found that students who began with some theoretical basis for their experiments/hypotheses discovered the function in significantly less time and with fewer experiments. The students' search of the "hypothesis space" was aided by previous knowledge of and informal experiences with the subject area, which we suggest (following diSessa (1993)) contribute to a sense of the physical mechanisms at work. This search helped the students decide which experiments to pursue systematically. If nothing else, exploration of mechanisms before experimentation helps to pare down which of the infinite number of possible variables will be tested (see a more in depth discussion of this point in a later section).

Many educational researchers have made the case for including theory- and mechanism-generative conversations in scientific inquiry before beginning formal investigations. Hodson (1988) quotes distinctions made by Schwab (1962) between stable and fluid inquiry and T. Kuhn (1963) between normal and revolutionary science to justify including "creative speculation" (p. 29) in school science (i.e., fluid inquiry or revolutionary science). Given the *two* phases of scientific discovery described by philosophers of science, Hodson claims that

> a child's science education would be seriously deficient if it concentrated on the processes of hypothesis testing to such an extent that hypothesis generation was neglected. (p. 30)

Windschitl (2004) agrees that inquiry must include time for generating questions or hypotheses and justifies his call for moving away from atheoretical, ungrounded hypothesis testing by drawing on "analyses of practice in scientific communities" (p.

483) from the work of Alters (1997), Knorr-Cetina (1999), McGinn and Roth (1999), and Latour (1987, 1999). Klahr and Dunbar (1988) also cite literature from the history of science to support the claim that hypothesis generation is crucial to scientific discovery. They begin their work by noting that

> The successful scientist, like the successful explorer, must master two related skills: knowing where to look and understanding what is seen. The first skill – *experimental design* – involves the design of experimental and observational procedures. The second skill – *hypothesis formation* – involves the formation and evaluation of theory. Historical analyses of scientific discoveries (e.g. Conant, 1964; Mitroff, 1974) suggest that the interaction between experimental design and hypothesis formation is crucial to the success of the real scientific endeavor. (p. 2)

Other literature advocates including time for making sense of anecdotal observations as a way to generate hypotheses that may later be formally tested. Hawkin's (1974) suggests that "messing about" in science inquiry is crucial because it allows students to become acquainted with new phenomena and "build an apperceptive background, against which a more analytical sort of knowledge could take form and make sense" (p. 68). Without making informal observations of phenomenon, students have no sense of the mechanism behind it on which to base a hypothesis test. In his brief survey of student abilities for scientific inquiry, Hammer (2004) suggests that students should be encouraged to spend time thinking about things they notice (perhaps accidentally) about the natural world and tossing around hypotheses that may never make it far enough to be rigorously tested. He draws a parallel between that activity and the work of Jocelyn Bell, the physicist who discovered pulsars: when Bell informally observed an unknown radio signal, she first searched through her sense of mechanism to discover plausible causes for it before she began honing these hypotheses for further study. The practice of science and its characterizations in the science education literature attest to the value of using knowledge of mechanisms that exist in the world to formulate questions and hypotheses – regardless of whether they lead to controlled investigations. The logical steps of controlled experimentation fail to capture this informal "jumble of irrational goings-on" (Hodson, 1988, p. 28) of hypothesis generation so crucial for science.

By leaving out the phase *preceding* hypothesis testing, current characterizations of inquiry fail to help students learn the value of hypothesis generation strategies (such as searching for mechanisms) that are crucial for scientific discovery.

Another Conception of Inquiry: Mechanistic Reasoning

A new conception of inquiry is needed to address the limitations of the controlled experimentation model. In particular, we agree with other educational researchers who describe a new conception that includes theoretical mechanistic reasoning in scientific inquiry. Such a characterization of valuable classroom practice is at least on par with empirical ones in that it captures the processes of science and helps students form reasonable arguments. In addition, it more accurately represents both professional science and how people reason naturally. Literature supporting this view of inquiry suggests that having students make sense of the world by reasoning about causal mechanisms for phenomena should be a prominent instructional goal; students should attempt to explain how things happen and teachers should recognize and promote their efforts.

Definitions of mechanism

In the following section we review what this literature defines as mechanistic and thus valuable for science.

Non-teleological

Educational research has made progress in defining the mechanistic explanations crucial for scientific inquiry by contrasting them with teleological ones. In describing the cognitive development of causal understanding, Carey (1995) distinguishes between mechanistic reasoning and a functional mode of explanation in which changes in the properties of objects are attributed to their desire/intent or their vital nature/function. Similarly, Abrams and Southerland (2001) contrast students' causal mechanistic explanations and those that are goal driven or describe "the why (the rationale)" for change (p. 1276). In tracking the development of students' explanations for how a set of gears works, Metz (1991) found that although some students attribute the action of the gears to its function or purpose, "no aspect of teleological thinking is manifested [in mechanistic explanations]" (p. 795). Her more current work echoes the distinctions Piaget (1927) made in his early studies of children's causal understanding between animistic, artificial, moral, or finalistic explanations and mechanistic ones. This literature claims that students in science classrooms should not use teleological explanations to make sense of natural phenomena.

Causal

Many characterizations of mechanism in the literature on student reasoning center on giving causal stories for how phenomena occur. Brewer et al. (1998) describe the mechanical explanations given by scientists and students as causal models that go "beyond the original regularity" of the phenomenon (p. 127). They suggest that students can and should be encouraged to explain natural phenomena using a causal/mechanical conceptual framework, but do not further spell out the specifics of these frameworks. Hammer (1995) also considers mechanistic reasoning productive for scientific inquiry; he finds value in a student discussion about how objects move partially because they are relying on a sense of mechanism. He describes that sense as follows:

> Students and physicists have rich stores of causal intuitions; reasoning about the causal structure of a situation can help them tap these resources. (p. 422)

Both Brewer et al. and Hammer approximate mechanistic reasoning as causal reasoning. Other research in the education literature extends this definition to include the *process* of causality. Koslowski (1996) claims that scientific reasoning consists largely of giving a mechanism that "explains the process by which a cause brings about an effect" (p. 13). In her study of students' reasoning about causal situations, Schauble (1996) uses the same language; causal mechanism is "the process of *how* a cause brings about an effect" (p. 112, emphasis hers). She also defines mechanisms as "explanatory models, … either structures or processes, that account for the observed phenomena" and "usually link causes with effects" (p. 103). Carey's (1995) work on the origin of causal reasoning illustrates that domain-specific mechanisms that "explain how one event (the cause) brings about another (the effect)" (p. 268) are crucial to adequate understanding of science. Abrams and Southerland (2001) claim that students should give mechanistic explanations that identify physical causes and "the how (the process)" of a phenomenon (p. 1276). Metz (1991) similarly describes mechanistic reasoning in which students account for *how* changes in a system occur. Literature advocating the use of mechanisms to explain phenomenon generally describes them as identifying the process between causes and effects.

Reductive

Some researchers rely less directly on causality and instead focus on the reductive nature of mechanistic explanations. Chin and Brown (2000) articulate the features of sophisticated mechanistic thinking engaged in by students with a deep approach to science. These students

> give "microscopic" explanations which described nonobservable theoretical entities and cause-effect relationships. This type of explanation [mechanistic] was like a model or a minitheory which served as a link between the macro and micro levels. (Chin & Brown, p. 121)

Similarly, Chinn and Malhotra (2002) describe the theoretical mechanisms constructed during authentic science inquiry as composed of "entities that are not directly observable" and linked by causal, contrastive, analogical, and inductive connections (p. 186). White (1993) found that students have the most success in understanding new topics when they use "reductionist physical models" of causal mechanisms that involve "phenomena that one can experience with one's own body, like pushes and pulls" (p. 197). Carey (1995) claims that causal mechanisms rely on “interactions among the entities in the domain” to explain phenomena (p. 273). Researchers commonly use reductionist models to describe the structure of causal mechanistic explanations. In these characterizations, mechanisms account for observations by showing that underlying objects cause local changes in the system by acting on one another.

Built from phenomenological evidence

diSessa's (1993) ontological approach to mechanistic reasoning leads to a different characterization. Instead of describing the overall structure of a mechanistic explanation, he discusses the individual cognitive elements called “phenomenological primitives” from which our sense of mechanism is built. These *p-prims* are abstracted from common everyday experiences and used to reason about novel situations. For example, Ohm’s p-prim (“An agent or causal impetus acts through a resistance or interference to produce a result”) is relevant to a number of physical mechanisms – from pushing a book across surfaces with different friction to inserting new resistors in a circuit (p. 217). diSessa provides numerous other examples and a list of heuristic principles for identifying p-prims. During mechanistic reasoning, students use *p-prims* to assess the likelihood of events, explain what will happen given the past state or what must have happened given the current state, and assign causal credit for what happens in certain circumstances (p. 106).

Value of Mechanistic Reasoning

The value of mechanistic reasoning for scientific inquiry need not only be that “it’s what scientists do.” Indeed many things scientists do would be inappropriate for students to emulate (for example, deciding on a budget for grant proposals). A theoretical justification of mechanistic reasoning is crucial for establishing its role in scientific inquiry. The literature offers several reasons that a focus on mechanism might be more appropriate for students than a focus on controlled experimentation.

Mechanistic reasoning is more effective than formal empirical investigation

One motivation for including mechanistic reasoning in scientific inquiry is purely practical: it would take too much time to perform all the possible controlled experiments on all the possible causal variables for a given phenomenon. As Ahn and Kalish (2000) point out in their article on the role of mechanistic reasoning in causal attribution,

> To determine causal candidates for covariational analyses, one must start out with some understanding of causal mechanisms because, otherwise, one soon runs into a computational explosion. (p. 216)

This "computational explosion" arises because there exist an infinite number of possible correlations in the world. Luckily for scientists, many of them are spurious and only a few are causal. Koslowski (1996) claims that mechanism information helps decide which correlations to take seriously:

> In most circumstances, people do not (nor should they nor can they) treat all covariations are equally indicative of plausible causes. And distinguishing correlations that are genuinely causal from those that are merely artifactual is done, in part, by relying on considerations of theory or mechanism. (p. 47)

Schauble (1996) observed this behavior in students performing experiments to determine which variables caused changes in the buoyant force of water (as measured by spring stretch). She found that subjects decided which variables were worth testing based on their beliefs about "mechanisms that could and could not plausibly be operating in the spring system" (p. 115). Educators do not ask students to perform experiments testing *every* correlation or to take *all* evidence of covariation as an indication of causality; such a method would be ineffective and inefficient for identifying causes for phenomena. Koslowski (1996) presents a striking example to justify this claim:

> If simply applying the covariation rule were sufficient, then we would all be able to contribute to cancer research. The fact that we are not all able to do so illustrates the most basic suggestion about what is rational and important to communicate to students… we need to rely on information about the area [mechanisms] to decide which covariations to look for in the first place, which ones to take seriously when they occur, and which alternative hypotheses to treat as plausible. (p. 276)

Even though many students can perform controlled experiments, they cannot all solve pressing problems of science because it is by knowing what mechanisms act in the systems that scientists pare down the number of variables for further rigorous study. If scientists or students relied only on covariation data, they would be working forever testing infinite numbers of variables only a few of which would actually be important in the situation. Such a method of scientific inquiry "would take unlimited computing time because it could be achieved only through an exhaustive covariational analysis over all objects in the world" (Ahn & Kalish, 2000, p. 205).[1] Considering plausible mechanisms streamlines scientific inquiry by determining which experiments are most likely to yield causal information.

Mechanistic reasoning is more likely than formal empirical investigation to yield correct conclusions

Once the number of possible experiments is reduced to something manageable, there is still the task of deciding whether the covariation information from those experiments gives sufficient evidence of causality. There may be cases where the observed covariation is merely specious and drawing conclusions based solely on that covariation evidence would yield incorrect conclusions. Koslowski (1996) describes one such scenario: although there is evidence that ice-cream consumption is positively correlated with the incidence of violent crime, it would be absurd to assume that eating ice cream causes people to commit violence. Instead, we would look for other mechanisms that might explain the correlation, such as that both ice cream and violence increase in warm weather. In his theory of causal mechanisms, Salmon (1984) provides an example that illustrates the opposite problem, concluding a lack of causality from a lack of correlation. He describes a situation in which a golfer hits a terrible tee shot that goes into the trees; his ball accidentally hits a tree and bounces back in play for a hole-in-one. It could be said then that the tree caused his hole-in-one. However, if we looked at data between tree hitting and hole-in-ones, we would likely find no or negative

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[1] It is true that scientists may sometimes comb extensive amounts of data looking for significant correlations to give them clues as to how a phenomenon occurs. However, the amount of time required to find causal correlations is none-the-less decreased when knowledge of mechanisms is used to narrow the search space.

correlation. The presence of correlation does not necessarily indicate causality, nor does its absence necessarily imply a lack of causation; relying on covariation is an unreliable method of judging causality.

Causal attributions are much more likely to be accurate if a mechanism is known to underlie an existing covariation. Ahn et al. (1995) describe this asymmetry between covariation and mechanism information; while "covariation is perfectly confounded with mechanism: the presence of a mechanism necessarily implies the presence of covariation among the factors involved in the mechanism," the reverse is not true (p. 340).[2] MDC's (2000) account of mechanisms describes the reason why covariation follows mechanism. They claim that mechanisms for phenomena "work always or for the most part in the same way under the same conditions" (MDC, 2000, p. 3). The regularity of a mechanism contributes to regularity in the resulting phenomenon. Glennan (1996) explains how a mechanism approach to causality exploits this fact to overcome the "connection-conjuction" problem of misleading correlations.

> If one can formulate and confirm a theory that postulates a mechanism connecting two events, then one has produced evidence that these events are causally connected. The necessity that distinguishes connections from accidental conjunctions is to be understood as deriving from an underlying mechanism. (p. 64)

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[2] Salmon's example of the hole-in-one may seem to contradict the claim that mechanisms always produce covariations – tree hitting does not correlate with hole-in-ones, though it was the mechanism that produced that particular one. Salmon's example, like other anomalous cases, occurs precisely because some part of the mechanism does not occur "in the same way under the same conditions." The hole-in-one mechanism usually (I imagine) consists of hitting the ball down the middle of the fairway towards the hole; in Salmon's example the tree prevented that mechanism from working. The result is an anomalous phenomenon that is not correlated with its effect.

Shultz's work (1982) investigating which rules of causal attribution are most commonly used revealed two trends relevant to this discussion. The first is that "generative transmission [mechanism] yields fewer attribution errors than do any of the other causal rules [covaration, regularity, similarity, temporal/spatial contingruity]" (p. 46). The second is that people are significantly more confident about their assessments of causality when mechanism information is present. Knowledge of mechanisms makes us more certain of which covariations indicate causality. In Schauble's experiments (1996), she found that subjects adjusted their analysis criteria for what counted as legitimate covariation based on their beliefs about possible mechanisms. When mechanism information is known, the decision about whether two events are causally related is more likely to be accurate than relying on covariation alone. Ahn and Kalish (2000) make the even stronger claim that "without constraints from existing causal mechanism knowledge, probability information can be vacuous and inapplicable" (p. 218). They contrast themselves with researchers who have essentially empirical conceptions of inquiry that allow theory to be used to make sense of data.

> Our claim is stronger than that existing causal mechanism knowledge helps [explain covariation data]. It is that such knowledge does essentially all the work. (Ahn & Kalish, p. 206)

Students should be encouraged to use knowledge of mechanisms to draw causal conclusions because with it they can be more confident that they have done so correctly than had they used only empirical results.

Mechanistic reasoning is more helpful than formal empirical investigations for understanding novel situations

Students should not only be able to make correct causal conclusions about situations they have empirically investigated; they should also be able to make sense of novel phenomena. When faced with new physical situations, it is unlikely that students will already have a store of covariation information collected under the exact same conditions with which to draw conclusions. Covariation information is narrow; it only gives insight into the precise case that generated it. Establishing that a particular variable is associated with a particular result in a very particular set of circumstances (a controlled experiment) does not help predict what will happen when that same variable is found in a different set of circumstances. Only in knowing the properties of a variable and the process by which a cause brings about an effect – the mechanism - can we know what that variable may or may not do in another situation. Information about mechanisms, unlike covariation, is generalizable. Ahn et al. (1995) claim that this fact is exactly why people prefer mechanism-based explanations to those based on covariation.

> [M]echanism-based explanations are projective or generative in the sense that we can make predictions about novel situations…Suppose John had a traffic accident and the mechanism-based explanation for the event is that John is drunk. What if a particular factor were different? For example, what if John was wearing a hat? Would the effect still have occurred? The explainer already knows the preconditions for accidents involving drunk driving and he/she knows that the effect would occur by necessity as long as the conditions are satisfied. Therefore, the projection into this new situation can be easily carried out. (p. 340-341)

The example of John changing his hat may seem silly, but the silliness arises precisely because we have no mechanism relating hat-wearing to car accidents. Less extreme examples also illustrate the insufficiency of formal experimental evidence in novel situations. For example, in a first-grade classroom in which a teacher asks her students whether or not a seed can grow in sand (Hammer & van Zee, 2006), the students have performed experiments growing seeds in soil and have discussed *how* seeds grow, but have not yet tried to grow seeds in sand. They have no relevant covariation information to use in answering the question. However, they are still able to make predictions, because they have a sense of the mechanism by which seeds grow in soil. They then decide whether or not the elements and processes for growth are similar enough in sand to soil for the mechanism to run. The prior experimental evidence was not sufficient because the new situation did not have the same variables. Mechanism information is more valuable than data from controlled experiments because it is more generalizable; it provides a means to predict what will happen in novel situations.

Limitations of Current Characterizations of Mechanistic Reasoning

Lack of precision

While the value of including mechanistic reasoning in inquiry is agreed on by the researchers cited above, the exact nature of that reasoning is not. There has not been the same progress with respect to making explicit what constitutes mechanistic reasoning as there has been in making explicit what constitutes controlled experimentation. Research focused on understanding students' mechanistic reasoning provides many models of exemplary mechanistic descriptions. Consider an example that Brewer et al. (1998) call mechanistic in which a student describes the day/night cycle.

Interviewer:	Where is the sun at night?
Third Grader:	On the other side of the earth. Because when night comes over here the sun goes onto the other side of the earth and it's day on there.
Interviewer:	How does this happen?
Third Grader:	The earth turns around.
Interviewer:	Does the earth move?
Third Grader:	Yeah.
Interviewer:	Does the sun move?
Third Grader:	No. (p. 127)

Unfortunately, not all explanations are as complete as this one; many examples from student discourse represent more partial or ambiguous versions of mechanistic reasoning. Consider the following episode from a college course in which a student studying buoyancy explains her idea about why hollow objects float.

> **Kelly:** ...I would say, I would agree that it's something, it's the air inside of it that [object]…it's just like in the bath, like when you, like if you have a bubble at the bottom, it floats to the top, you know? So that's why I think that the air, the mass of the air inside an object will hold it up in the water.

It is not immediately obvious whether Kelly's explanation is mechanistic, partially mechanistic, or non-mechanistic. Does her explanation do the same "kind of thing" that the day/night explanation did? What insight does the canonical example of the day/night cycle provide in making sense of this possibly ambiguous or incomplete explanation? While the examples from the literature are helpful for describing "the kind of thing" students should be doing, it is difficult to use completed, exemplary explanations to identify specific aspects of mechanistic reasoning that is "in progress." Comparing all explanations to canonical ones forces judgments of mechanism to be all-or–nothing: either an explanation matches the exemplar or it does not.

Reliance on Causality

Mechanistic reasoning is often loosely defined as "causal," and we might hope that cognitive psychology literature on causal learning would provide insight into mechanistic reasoning. Gopnik and her colleagues (2000, 2001) have carried out work prototypical in this field on young children's causal inferences. They designed a "blicket detector" that lights up and plays music whenever "blickets" are brought near it. Their studies have shown that children aged 2-4 can categorize blickets based on their novel "causal power" to set off the detector. They claim that the older of these children also appear able to ignore information about perceptual similarity or covariation in assigning causal power. Das Gupta and Bryant (1989) performed a series of experiments in which they asked children to identify which of several instruments caused the change in another object. For example, children had to decide whether a hammer, scissors, or water caused a wet cup to become a wet broken cup. They conclude that the ability to make "genuine [full] causal inference" in which "the person takes into account the difference between beginning and end states in order to work out a cause" develops around 4 years of age (p. 1138). This work shows that very young children can select which objects cause which effects.

In reflecting on these experiments, it becomes clear that what these authors call causal learning is not the same as what is described above as mechanistic. Though

Gopnik et al.'s (2000, 2001) children may recognize that blickets *cause* the detector to go off it is unlikely that they have any conception of *how* blickets do so. These two levels of explanation parallel T. Kuhn's (1977) distinction between the "narrow" and "broad" causes used in physics explanations. He defines "narrow causes" as particular active agents from earlier events that exert a force to cause subsequent events, similar to Gopnik's causal power. He claims that within the field of physics, this concept of cause has proven too limited to provide adequate explanations. Instead, "broad causes" explain events by showing how

> effects are deduced from a few specified innate properties [mechanical or mathematical] of the entities with which the explanation is concerned. (T. Kuhn, p. 28)

These "broad causes" are more like what we have identified as mechanistic reasoning. Mechanistic reasoning in physics is more than noting which causes are associated with which effects; it describes the process underlying them. Characterizations of mechanistic reasoning that rely mainly on causality risk underestimating its breadth by equating it with the kinds of reasoning described by the cognitive psychology literature.

Other researchers have made the claim, either tacitly or explicitly, that causality in the narrow sense is not sufficient to capture the meaning of mechanism. Piaget (1927) interviewed young children on phenomena ranging from air to bicycles and documented seventeen different types of causality in children's explanations. Although he defines them all identifying causes for effects, only the most sophisticated are termed "mechanistic" in that they remove the influence of internal motors and rely solely on physical "contact and transference of movement" for explanation (Piaget, 1927, p 263). The language White (1993) uses in her work on Intermediate Causal Models makes a similar distinction. She describes the *causality* of circuit behavior by laws such as "A change in conductivity can cause a change in voltage, and a change in voltage can cause a change in device state" (p. 189), and the *mechanism* of circuit behavior as "resistance inhibits charge from flowing freely through a substance by atoms it encounters and collides with within the material" (p. 207). Mechanism both accounts for the causal law governing physical behavior and is more than the causal law. In their study of student's explanations for biological phenomena, Abrams and Southerland (2001) classified students as able to give causal explanations that were still "scientifically inappropriate" in that they failed to describe mechanisms for physical changes. Newton (1996) describes how students generate mental models to make sense of cause-effect relationships. He hypothesizes that it is the desire for more in depth causal understanding that prompts the construction of models that I would call mechanistic. Again, mechanism is something more "in depth" than causality. diSessa (1993) specifically draws attention to his decision to distinguish between mechanism and causality.

> An alternate, simple description of the sense of mechanism would be *causality*. Which events follow which others regularly, and why do they do so? I deliberately use the term *sense of mechanism* [instead of causality] to emphasize that the picture I want to paint of human causality is dramatically different from many other characterizations. It involves diverse and diffuse judgments and impressions more than it consists of some small set of sharply defined and necessary principles. (p. 107)

Carey (1995) is also explicit about “input-output relations” (also similar to Gopnik’s causal power) not being sufficient for causal understanding involving mechanism. She claims that studies like those from the cognitive psychology literature described above, which attempt to show that children have (or can construct) domain specific causal knowledge, are flawed because

> until a child has constructed an intuitive theory of how [a phenomenon occurs], knowledge of mere ‘input-output’ relationships does not constitute causal understanding (p. 284).

In addition,

> knowledge of input-output relations is not the same as a domain specific mechanism - an underlying process of how one event brings about another. (p. 287)

Causal reasoning in the sense described by the psychology literature serves as a starting point for the pursuit of underlying mechanistic explanations, but causal reasoning alone does not define mechanistic reasoning. Characterizations of mechanism cannot be grounded in the notion of cause lest they be confused with this impoverished, less complete notion of narrow cause. Instead, mechanism must be explicitly defined so that its nature and structure can be identified without worrying about which definition of causality is relevant.

Discussion

This review of previous research presents two main arguments. The first is that there is a pervasive tendency in current education research to conceive of inquiry in an inappropriately empirical way. This conception supports students learning about new phenomena by performing controlled experiments and analyzing the resultant covariation data. While valuable in some ways, this conception significantly misrepresents students' natural abilities and scientists' practice.

The second argument is that mechanistic reasoning is an appropriate focus for scientific inquiry independent of controlled experimentation. Students should explain natural phenomena by making sense of the underlying causal processes that produce them. Mechanistic reasoning is valuable and productive for science learning.

However, there is a critical need to supplement the characterizations and examples of mechanistic reasoning from previous research by articulating an explicit definition so that progress can be pursued and evaluated systematically during inquiry. Chinn and Malhotra (2002) acknowledge this deficiency in the literature and claim that researchers in science education must "develop a better understanding of the strategies that scientists use when reasoning on such [inquiry] tasks" (p. 214) and developing mechanistic explanations. In the following chapter, we address this need by using detailed characterizations of the structure and nature of mechanism from the philosophy of science literature to develop a framework for identifying mechanistic reasoning in students.

Chapter 3: Methodology of Developing and Using the Mechanism Framework

Introduction

It remains a central ambition of science education reform to help students develop abilities for scientific inquiry, as outlined in the National Science Education Standards calling for “changing emphases to promote inquiry” (NRC, 1996, p. 113). To meet this objective, science education research has attempted to describe particular aspects of “inquiry” so that it can be assessed in students. Student abilities to engage in controlled experimentation (e.g. Kuhn, 1989) and scientific argumentation (e.g. Driver, Newton, & Osborne, 2000) have been studied with the goal of positing schemes for assessing the sophistication of those abilities.

The progress in defining scientific inquiry with respect to experimentation and argumentation can be characterized as progress in understanding the *structure* of inquiry. However, that structure cannot be the whole of what constitutes scientific inquiry; it is possible to study abilities for coordinating variables in contexts that are not scientific and frameworks for analyzing argumentation can apply to politics or law as easily as to science. In addition to frameworks for analyzing that *structure* of inquiry we need frameworks for analyzing the *substance* of that inquiry. The purpose of the present work is to draw attention to and evaluate the substance of student thinking, particularly their mechanistic thinking, as part of inquiry-oriented assessment.

As discussed in chapter two, other research has begun to attend to students’ mechanistic reasoning. However, most prior analyses of student mechanistic reasoning have relied on exemplary cases and heuristic, intuitive characterizations of causal mechanism in making assessments. These methods are both insufficient and unreliable for understanding *nascent* mechanistic thinking. In this chapter, we present the origin and development of the framework designed to bring rigor and precision to these assessments of inquiry. As such, the framework may begin to bring our understanding of mechanistic reasoning on par with our understanding of controlled experimentation or argumentation.

We provide a brief review of the philosophy of science literature that led us to suspect that a more articulate language for thinking about mechanistic reasoning was possible. We then more fully describe one strand from the literature that forms the basis of our mechanism framework: Machamer, Darden, and Craver's (MDC, 2000) characterization of the mechanisms studied in contemporary professional science. We present an initial attempt to use MDC's language to analyze student inquiry to demonstrate how discussions of *scientists'* search for mechanisms informed our thinking about *student* mechanistic reasoning. This analysis represents an intermediate stage in the development of the coding scheme used throughout the rest of the dissertation.

After describing the origin and transitional stages of our framework, we provide both theoretical and practical justifications for the series of revisions required to make MDC's work align with our goals. The current version of the coding scheme that is used to recognize nascent mechanistic reasoning in student science discussions is presented along with examples of the codes and explanations of their use. We give details as to how the framework is currently used to analyze student discourse. Finally, we describe the qualitative research methodology of this dissertation including a practical discussion of data sources and steps of analysis.

Characterizations of Mechanisms in Professional Science

The "mechanical philosophy" arose in the 16th and 17th centuries, espoused by Descartes, Galileo and others as a new way of understanding and describing the natural world without recourse to psychic and occult powers (MDC, 2000; Westfall, 1986). It conceived of the world as a machine of inert, passive bodies that moved only through physical causation by direct contact, with Newton (and others reluctantly later) adding "action at a distance" later (Westfall, 1986), and it culminated in Newtonian mechanics. Mechanistic thinking is now firmly established as inherent in the values and practices of science (Kuhn, 1977; Nersessian, 1992; Salmon, 1978), to the point that scientists themselves no longer explicitly discuss its presence.

Mechanistic thinking is, however, the focus of many historical and philosophical studies of scientific progress (Bechtel & Abrahamsen, 2005; Glennan, 2000; Tabery, 2004; Thagard, 1998), and the descriptions of what constitutes mechanism have progressed. Glennan (2000) describes a mechanism as "a complex system that produces that behavior by the interaction of a number of parts, where the interactions between parts can be characterized by direct, invariant, change-relating generalizations" (p. S344). He focuses especially on the parts and how they interact (as characterized by law-like generalizations) such that changes in one part bring about changes in another part. Similarly, Thagard (1988) characterizes mechanisms as "a system of parts that operate or interact like those of a machine, transmitting forces, motion, and energy to one another" (p. 66). Machamer, Darden, and Craver (2000) reconceptualize mechanisms as "a series of activities of entities that bring about the finish or termination conditions [from the set-up conditions] in a regular way" (p. 7).

Machamer, Darden, and Craver's Characterization of Mechanisms

We have found Machamer, Darden, and Craver (MDC, 2000) to be the clearest synthesis of contemporary accounts of mechanism in professional science, and we will use it as the principal basis for our analysis of student scientific discourse. It also aligns well with our own perceptions of how research science is practiced. These authors define mechanism as:

> *Entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions.* (p. 3)

Scientists are interested in phenomena that are stable and reliably produced, because they are most useful for ascertaining mechanisms that "work always or for the most part in the same way under the same conditions" (MDC, 2000, p. 3). Typically the search for mechanism follows the identification of these regular phenomena, including the specification of starting and final conditions.

Machamer, Darden, and Craver (2000) focus on elaborating "a mechanistic approach for analyzing neurobiology and molecular biology that is grounded in the details of scientific practice" (p. 2). They take as prototypical those mechanisms from the biological sciences: chemical transmission at synapses (Craver, 2002b; MDC, 2000), protein synthesis (Darden & Craver, 2002; MDC, 2000), and long-term potentiation (Craver, 2002a; Craver & Darden, 2001). We use their example of depolarization – the first stage of chemical transmission – to highlight crucial aspects of their characterization and elaborate some of its finer-grained aspects.

Depolarization is a regular and predictable phenomenon that begins the process in the synaptic gap during which electrical signals in one neuron are converted to chemical signals in another. Specifically, “depolarization is a positive change in the membrane potential” of the neuron (MDC, 2000, p. 8). At the start of depolarization, neuron cells have a negative membrane potential - the fluid inside is more negatively charged than the fluid outside. Positively charged Na^+ ions outside the neuron cell are attracted to the negatively charged fluid inside. They diffuse through a channel in the membrane and reverse the polarity until the fluid inside is more positive than the fluid outside. The Na^+ selective channel itself consists of four alpha helix (corkscrew-shaped) portions of the protein that each contain positively charged amino acids and a “hairpin turn” (MDC, 200, p. 11). The channel is opened when the Na^+ ions inside the cell repel the evenly spaced positive parts of the corkscrew alpha helix and rotate them to create an opening (or pore) in the membrane. The “hairpin turns” that bend into the pore are charged so as to select only Na^+ ions to flow into the neuron cell (Craver, 2002b). We will use the depolarization mechanism throughout this section to describe features of MDC’s characterization of mechanisms.[3]

The mechanisms that underlie phenomena are composed of *entities* and *activities.*[4] Activities are the components of mechanisms that produce change – they are

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[3] A figure depicting the stages of the depolarization mechanism can be found in Machamer, P., Darden, L., Craver, C.F. (2000). Thinking about mechanisms. *Philosophy of Science*, 67, 1-25.

[4] Unlike other philosophical accounts of mechanism that focus on *inter*action among entities, MDC stress the ontological distinction of entities and activities; both can exist independently and neither can be reduced to or subsumed by the other.

the "things that entities do… and they constitute stages of mechanisms" (Craver, 2002a, p. S84). The activities in the depolarization mechanism include repelling, rotating, bending, and moving. Other common activities in biological mechanisms include bonding and docking among molecules; physical mechanisms might more commonly refer to pushes and pulls among objects. Entities are the things that engage in the activities: the entities in the depolarization mechanism are neuron cells with membranes and fluid. Other biological entities for other phenomena might include cell nuclei, organisms, or populations. Physics entities might be electrons, macroscopic objects, or stars. The general properties of the entities involved determine the activities that can occur in a mechanism. In the depolarization mechanism, the membranes have channels made of proteins with alpha helixes and hairpin turns while the fluid has an electric potential that is dictated by free Na^+ ions. The entities and activities that can be used in acceptable descriptions of mechanisms vary; "for a given field at a given time there is typically a store of established or accepted components out of which mechanisms can be constructed and a set of components that have been excluded from the shelves" (Craver & Darden, 2001, p. 123). It is the activities and the relevant entities that constitute the mechanism and produce the phenomenon of interest.

In general, whether a mechanism can proceed depends on the entities' "spatial and temporal organization" (Craver, 2002a, p. S84). If two entities that need to connect in some way are spatially distant or misaligned or if a given activity takes too long to occur or occurs out of turn, then the mechanism cannot proceed (Craver & Darden, 2001). For example, Na^+ ions cannot diffuse and depolarization cannot occur unless the four alpha helices are located next to one another so their rotation produces a channel in the membrane. Understanding a mechanism involves "understanding how one activity leads to the next through the spatial layout of the components and through their participation in a stereotyped temporal pattern of activities from beginning to end" (Craver, 2001, p. 61). The productive continuity of the mechanism for the phenomenon is contingent on the appropriate location, structure, and orientation of entities and temporal order, rate and duration of activities.

Mechanisms are nested within one another such that "higher level activities of mechanisms as a whole are realized by the organized activities of lower level components and these are, in turn, realized by the activities of still lower level mechanisms" (Craver, 2002b, p. 69). Although this hierarchical structure makes it possible in principle to reduce all phenomena to atoms and molecules, it is not always desirable or appropriate to do so. For a given domain, there exist different "bottom-out" levels for mechanistic descriptions "that are accepted as relatively fundamental or taken to be unproblematic" (Darden, 2002, p. S356). For example, the depolarization mechanism currently bottoms out at the level of alpha helices of proteins and ions; the fact that those entities and their behavior result from quantum mechanisms involving protons and electrons does not add to biologists' insight about the phenomenon. Similarly there exist "top-off" levels beyond which mechanisms lose explanatory power: studying knee joint reflexes would not give insight into depolarization partly because the physical behavior is too many levels above the mechanism of interest. In general, a complete description of the phenomenon involves "'looking down' a level and showing that properties or activities of an entity can be explicated in terms of lower level mechanisms" and "'looking up' a level and identifying a mechanism that has the item as a component" (Craver, 2002a, p. S91).

Each component in a mechanism both contributes to the productive continuity of a mechanism and can be accounted for by some other productively continuous mechanism.

MDC's framework describes several reasoning strategies that scientists use as they construct their descriptions of mechanisms in a piecemeal fashion (Craver & Darden, 2001; Darden, 2002). One strategy, schema instantiation, involves making an analogy with a known mechanism from another context or field, abstracting the general structure by removing any details about specific components, and then instantiating this schema by filling functional roles with components appropriate to the new situation. The researchers who identified the depolarization mechanism would have known of selective-channel mechanisms in other cellular phenomena, and might have imported that knowledge to account for Na^+ ion diffusion with neurons. In the modular subassembly strategy, scientists begin with groups of components commonly used elsewhere in the field – modules – and cobble them together to build an organized mechanism (Darden, 2002). For example, the helix-turn-helix is a common motif is common in DNA binding proteins (Brennan & Matthews, 1989), making it more likely for scientists to use them together in constructing an account of the depolarization mechanism. Finally, construction may proceed through forward and backward chaining by "reasoning about one part of a mechanism on the basis of what is known or conjectured about other parts in the mechanism" (Darden, 2002, p. S362). By knowing the general properties of entities and activities, much can be said about what must have produced them at earlier stages and what they can produce in subsequent steps. For example, knowing that alpha helices of proteins (entities) are corkscrew shaped with evenly spaced positive charges (properties and organization), scientists can conclude that the positive charges in the membrane repel (activity) those in the helix and cause it to rotate (activity). In discovering mechanisms, scientists use the structure of mechanistic schemas, modules, and components to reason about the phenomena.

MDC's characterization of mechanism also describes several experimental strategies for discovering mechanisms that take advantage of their hierarchical structure (Craver, 2002a; Craver & Darden, 2001). Activation strategies work down from the top levels by stimulating a certain phenomenon to occur and detecting component properties that contribute to it. Interference strategies are the reverse - "bottom-up experiments in which one intervenes to diminish, retard, eliminate, disable, or destroy some component entity or activity in a lower level" and observe the effects on the phenomenon at a higher level (Craver, 2002a, p. S93). Additive strategies work like interference strategies except that instead of diminishing a lower level component, one augments or intensifies it and then observes the effects at the higher levels. In an attempt to discover the mechanism for depolarization, scientists might have used additive or interference strategies by adding or removing variously charged ions from the fluid outside and observing the resulting depolarization. These experimental strategies give evidence for various components of the mechanism by integrating its multiple levels.

Initial application of Machamer, Darden, and Craver to Understand Student Thinking

Here we present an initial attempt to use MDC's characterization of mechanisms as a lens for looking at student discourse. We analyzed a discussion among first graders about whether or not seeds can grow in sand by looking for patterns that resembled the work of scientists. This investigation provides a sense of how the mechanism language described above can be applied to student discourse. It represents the first stage in what would later become more refined and systematic analysis with the development of a coding scheme.

Example from Student Discourse

The discussion analyzed here involves sixteen first grade students at a public elementary school in Montgomery County, Maryland. The students are engaged in science lessons one to three times a week for approximately forty-five minutes each time. Their regular classroom instructor, Ms. Mikeska as her students call her, conducts these activities and discussions; a science education graduate student from the University of Maryland, Mr. Paul, sometimes observes or participates. At the time of this classroom conversation, the instructor was participating in the “Case Studies of Elementary Student Inquiry in Physical Science” (NSF ESI-9986846). This project was to develop materials for teacher education, to help prospective and current elementary teachers gain experience in interpreting and assessing the substance of student reasoning (Hammer & van Zee, 2006).

As part of their science lessons and in accordance with county curriculum, these students have been exploring different aspects of rocks, soil, and sand. They have designed and carried out an experiment to test the effect of vermiculite, an additive in some soils, on bean and flower seed growth. They have observed the growth of the seeds in soil as well as the properties of soil and sand samples brought from home. They have had several conversations prior to this one in which they have discussed their observations and results. The teacher formulated the question of whether or not seeds will grow in sand as a supplement to these previous conversations in class and asked the students to draw or write their answer and an explanation for homework.

The discussion presented here begins with the teacher reintroducing the question "Can seeds grow in sand?" The class then progresses in the following general way. Mark and Aaron both assert that seeds cannot grow in sand, but they provide different reasoning for their answers. Mark focuses on the seeds' supposed need for protein while Aaron talks about the effects of wind and water on the seed. Juan interjects that the seed will grow, but his idea is temporarily set aside to further explore Mark and Aaron's positions. After Aaron suggests that water might be an important element for seed growth, Emily and Brandon both give their models for how water and the sand interact. Bernat interjects a comment about people stepping on the seed, a line of reasoning the rest of the class does not pursue. Juan is given the opportunity to explain to his peers his belief that the seed will grow. Keith and Emily talk with one another in an attempt to flesh out Juan's argument. Alisha wraps up the bulk of the discussion by presenting the idea that the seed cannot grow because sand lacks food for the seed. Emily notices that Alisha's idea is similar to Mark's previous one. The conversation concludes with Emily explaining why she feels that Alisha and Mark's ideas are similar. Throughout the conversation, most students seem to believe that the seed will not grow in sand, although their explanations for their conclusion are varied.

Analyzing Student Discourse

When attentively viewing this discussion from Ms. Mikeska's class, we were impressed with how well the students were doing. They seemed to be engaged in some sophisticated cause and effect reasoning but it was difficult to pin down and describe exactly what we were seeing that gave us that sense. However, in reading MDC's (2000) account of mechanisms, we realized that their descriptions might possibly give us a language to talk about the substance of the children's ideas in this discussion. Below was an initial attempt at such an analysis. In it, we looked for and found correspondences between student reasoning and MDC's framework.

Identifying Relevant Entities and Activities by Analogy

After the teacher solicits volunteers to begin the conversation, Mark expresses his belief that the seed will not grow in sand.

> **Mark:** I think that, I think that seeds will not grow in sand because I wrote [for homework] that it [sand] doesn't have the protein that soil does for the seeds for, for any seed for a plant to grow.

In this comment, Mark suggests that there is something in soil (call it protein) that is necessary for seed growth. He implies that protein does something to make seeds grow. His suggestion seems to correspond to what MDC would term identifying protein as an entity in the mechanism of seed growth; protein is some *thing* that affects whether or not seeds can grow. It is worth noting that Mark's choice of the term protein is probably not random; he might plausibly imagine that protein is required generally for "growth" because he has heard from others (or the media) that protein helps people grow strong and healthy. Mark also makes a comparison between soil and sand; he uses the idea that seeds grow in soil because they have access to protein (which may not be correct) and applies that same model to seed growth in sand to conclude that seeds will not grow there. Mark draws on what he knows from other places (growth in soil and growth more generally) to make claims about what entities are needed in the new situation (growth in sand). In doing so, Mark seems to be engaging in the first step of MDC's schema instantiation: identifying similar mechanisms through analogy. Like their descriptions of scientists, Mark uses "closely related areas of contemporary science… [as] a source for mechanism schemata" (Darden, 2002, p. S360) to aid him in thinking about new mechanisms. Other students in the class follow this strategy.

When the teacher asks for clarification, Mark further explains his idea about seed growth.

Mark: It [the plant] wouldn't, wouldn't grow a thing because like the minerals and all the other good stuff that's in soil to feed the seed isn't in sand.

…

Mark: Because it's like, it [the plant] stops. It, it's like without it [protein] the seed, the seed would just be there. It wouldn't, wouldn't grow a thing because like the minerals and all the other good stuff that's in soil to feed the seed isn't in sand.

Mr. Paul: So protein is something that the seed needs? It's food for the seed?

Mark: Mmm hmm. Like food.

In this excerpt, Mark articulates his idea about what protein (and minerals and other "good stuff") does to help seeds grow; protein *feeds* the seed. In the language of MDC, Mark identifies feeding as an activity in the mechanism when he describes it as "things that entities do" (Craver, 2002a, p. S84) and details "how an item [protein] fits into the… mechanism (showing exactly how it contributes to S's [seed's] y-ing [growing])" (Craver, 2001, p. 62). Mark may be drawing on a previous class discussion about the white balls in potting soil (vermiculite additives) providing food for the seed. Again, his reasoning resembles MDC's strategy of schema instantiation. Mark's suggestion that 'protein feeds the seed to help it grow' corresponds well to MDC's characterization that mechanisms, which may be discovered from other related fields (seed growth in soil) and used to make sense of novel situations (seed growth in sand), are made up of entities (protein) that engage in activities (feeding).

Specifying Set-Up Conditions of the Mechanism

Following Mark's comments about protein's role in seed growth, Aaron offers his explanation for why seeds cannot grow in sand.

Aaron: … When I pick up sand it easily kind of goes through my fingers really fast but when I do with soil it really does not do that. So see sand is like rocks- sand is like beat up rocks –

Ms. Mikeska: Mmm hmm

Aaron: - and so when you are like when you plant it and when there was a windy day, cause it's rocks and rocks do not help stuff. But it could help some stuff but maybe it can help something. But I'm but when wind comes what happens is the sand will just blow right like blow away. The sand would just go.

Aaron begins by describing how sand is like crushed rocks that can be easily blown away. In doing so, Aaron seems to identify what MDC call the "certain kinds of [entity] properties [that] are necessary for the possibility of acting in certain ways" (Darden & Craver, 2002, p. 4). Aaron then suggests that seeds cannot grow in sand because sand fails to protect seeds from wind the way soil does. Aaron's idea about wind blowing identifies a new entity (wind) and activity (blowing) in the mechanism for seed growth. Also, like Mark, Aaron engages in simplified schema instantiation when he uses comparisons to rocks and soil to help him identify important aspects of the situation.

Aaron goes on to say more about the seeds needing protection.

> **Aaron:** - Oh yeah, when the wind comes the sand would just blow away it just would be and it blow be gone unless to be the seed is standing on the plate or the plate what you like put it on. But if you have a cup it could just be like protected.

Here, Aaron suggests that putting the seed into a protected environment in the cup might eliminate the problem of wind blowing the sand away. He seems to be specifying what MDC would call a set-up condition that is required for the mechanism to reliably produce the phenomena of seed growth. Just as scientists often "begin with idealized descriptions of the start or set-up conditions" (MDC, 2000, p. 11) such as frictionlessness, so Aaron presents a constraint that must be initially in place to enable the mechanism to run. His set-up of the problem "includes various enabling conditions" which are "not inputs to the mechanism… [y]et these factors… are crucial to seeing how the mechanism will go" (MDC, 2000, p. 11). The rest of the class can now ignore the problem of wind blowing away the sand because the seed is protected by the set-up condition.

Forward Chaining Using the Properties of Entities and Animated Models

Immediately following his ideas about the need for protection, Aaron offers another explanation for why seeds cannot grow in sand.

Aaron: And cause sometimes when I see some stuff come out of my mouth that's wet and when it drops on the sand I see a little round dot of water and and the sand is like sucks *UP* the water. [Like??] like keeps it to itself like takes the water away from the seed and the seed doesn't have any water but the sand does.

Other students help Aaron clarify his idea.

Ms. Mikeska: What do you guys think about Aaron's idea. He brought up a a a little bit of a different reason. He said well the water if you put water in the sand [unrelated comment to another student] if you put the water in the sand what's going to happen? What's he saying is going to happen? (Nods to Juan.)

Juan: Um the sand takes it away.

Ms. Mikeska: Takes it away. What is it taking it away from?

Aaron: The water, it's like keeping the water to itself.

Here, Aaron suggests that water plays a role in seed growth. As with Mark, he seems to be identifying what MDC call an entity in the mechanism. Aaron also proposes that sand has properties we might describe as sponge-like: sand sucks up all the available water. In MDC's language, he identifies an entity property. He then uses that property to claim that the seed is left without any water because the sand takes the water away and keeps it to itself. Aaron seems to be doing some sophisticated cause and effect reasoning that we want to articulate: he uses properties of sand to explain how it prevents water from getting to the seed.

MDC's language helps that articulation. Aaron's reasoning strategy is similar to what they describe as 'chaining:' scientists use information they have about entities in a mechanism to reason about possible activities. Often, "discovering the structural properties of an entity can … give clues as to the kinds of activities in which it is likely to engage in the next stage of the mechanism" (Darden & Craver, 2002, p. 22). By exploring the "activity-enabling properties of entities" scientists can answer the question, "What could these entities with these properties in these set-up conditions be expected to do?" (Darden & Craver, 2002, p. 23) Aaron's reasoning allows him to answer that question: Sponge-like sand (protected from the wind) will not allow water to flow to the seed, thus the seed cannot grow.

Although Aaron's peers accept that water is an important entity to consider in the mechanism of seed growth, some of them do not agree with the properties of sand he has articulated. Emily responds to Aaron by saying:

Emily: [The seed] is just left alone without the s- the water that helps it grow in soil. Because the soil is like hard and the water is like, pssshhh, blocked. Like with all those sticks and stuff- it's real hard so the water won't get through. But in sand since usually sand will be blown away not sticks into the sand- it's easy that it's not blocked so it just goes—shhhhhhwweeee. (Motions with both hands water flowing down.)

Brandon continues Emily's line of reasoning.

Brandon: I don't think that the seed will grow in sand because um it [the sand] doesn't hold water that good. It just like goes right out.

and

Brandon: Pretend this is the se-sand and this is the water. (Mimes the water going through sand with his hands) It just goes out.

Emily thinks that since sand doesn’t have any sticks to block the water (as opposed to a comparison with soil which does have such sticks), water will just go straight through the sand, leaving none for the seed. Although Brandon does not comment on sticks blocking the water, both he and Emily seem to suggest that sand has properties we might call sieve-like: when water is poured onto sand, sand’s properties allow the water to pass all the way through to the bottom. They then use this property to make claims about what will happen to the seed: since the water goes through the sand there will be no water available for the seed. Emily and Brandon, like Aaron, seem to be engaging in MDC’s ‘chaining’ by describing how the properties (sieve-ness) of the entities (sand) lead to particular activities in the mechanism (water goes through the sand and doesn’t reach the seed).

Forward Chaining from Activities and Clarifying Spatial Organization of Entities

Following Emily and Brandon’s explanations, Juan uses their idea of sand as a sieve to support a new conclusion – the seed will grow. He is the first student to make this claim.

Juan: I think it would grow because, because the water goes through it, and if if the water goes through it might receive some water.

Juan uses the same sieve-like property of sand. However, he then claims that water going through the sand would allow water to get to the seed that is in the sand. This reasoning appears to be another example of MDC's chaining when scientists "use knowledge of the occurrence of an activity in the mechanism to conjecture as to the consequences of that activity for entities and properties in the next stage" (Darden & Craver, 2002, p. 22). To apply MDC's terminology, Juan begins with an activity of an entity and then claims that this activity brings about changes in the surrounding entities: water goes through the sieve-like soil, reaching the seed on its way through so that the seed can grow.

Emily disagrees with Juan's inferences about the properties of seeds that result from water filtering through sand.

Emily: Because if the water is going through it's not exactly where the seed is if you put it near the top. Cause the s, cause the water is going near the bottom…and if it's going near the bottom it's not near the seed it's by the top.

Following Juan's chaining to a contradictory prediction about seed growth, Emily explicitly states her underlying assumption that water must not only be present in the sand, it also must be located near the seed in order for the seed to grow. In her statement, she clarifies what MDC describe as the required spatial organization (near-ness) of the entities (sand/seed/water combination). For scientists attempting to articulate mechanisms for physical phenomena, "[d]etails concerning the geometrical *structure* and *orientation* of the entities in a mechanism… are important for understanding the productivity of the mechanism" (Craver & Darden, 2001, p. 126, emphasis theirs). In MDC's language, Emily's comment indicates that her seed growth mechanism "relies upon the spatial connections among the components" (Craver & Darden, 2001, p. 125).

Even though they use the same entities with the same properties and activities, Emily's required organization leads her to a different conclusion that Juan.

Consolidating Entities with Common Activities

After the students have had several exchanges about the interaction between the sand, soil, seed, and water, Alisha changes the focus of the conversation.

> **Alisha:** Maybe if you, even if you put a seed in the sand it won't grow because there's no food for the plant.

Here, Alisha suggests what she thinks is a new important factor to consider: food. Again, MDC would consider 'food' a candidate entity for the seed growth mechanism. However, another student recognizes that Alisha's idea resembles Mark's original idea.

> **Emily:** I think they're [Mark's idea and Alisha's idea] similar, but he added protein and she didn't. They're still similar- cause she just- even though she just said food, he said food too and that's similar I think she's agreeing. Because they're similar by what I'm hearing with my ears.

When Mark first specifies protein as relevant to seed growth, he does so with a 'science' word that other students may not understand; Alisha appears not to have recognized that food is functionally the same as protein. However, Emily notices that Alisha's 'food' does the same thing as Mark's 'protein.' In MDC's language, Emily notices that Alisha and Mark's different entities engage the same activity. This recognition is sophisticated;

it is the activity that is the important part of each of their mechanistic explanations, not the specific words they used to describe the entities.

Summary of Student Discourse: Mechanism Language

In this analysis, we were able to describe the students' comments using MDC's language. That is, we successfully identified several elements in *student* discourse that corresponded to MDC's rich descriptions of *professional science* activity. There appeared to be significant overlap between the mechanisms that scientists discover in the world and the kinds of things we see students doing when reasoning about mechanisms in the classroom. This initial analysis suggested that MDC's language might help us pin down exactly what we see in students' reasoning. It provided hope that an analysis of student mechanistic reasoning more systematic than those previously undertaken in the literature was possible. Below we describe the development of a coding scheme to aid that analysis.

Developing a Framework to Analyze Student Thinking

Since MDC's language helped us articulate our assessment of student ideas in the seeds discussion, we decided to develop it into a more systematic coding scheme. However, although their language overlapped with our assessments, their goal is different from ours. While their purpose is largely to describe mechanisms – to depict the structure of complete mechanisms that scientists find in the world and invoke to explain physical phenomena, we want to characterize student thinking about mechanisms - what students do and say when reasoning about new mechanisms for phenomena they observe. As such, their framework for characterizing mechanisms discovered by scientists differs in some aspects from our attempts to identify when and how students generate mechanistic explanations. The overall structure and nature of completed mechanisms, while important for MDC*,* is less relevant for us than the individual pieces and reasoning strategies used in constructing them.

Adapting Machamer, Darden, and Craver's Account of Mechanisms

We started with their proposal that mechanisms explain how phenomena are produced by tracing the productive changes continuously from set-up conditions through intermediate stages to termination conditions. If a completed mechanism traces this entire process, then identifying any part of that process would constitute a valid approach constructing an unknown mechanism. MDC's description of the parts of a mechanism helped us recognize those parts that students might identify in their initial discussions of new phenomena. Specifically, we use their idea that mechanisms for *phenomena* (seen in the termination stage) involve *entities*, which have particular *properties* and *organizations*, and *activities* among these entities that regularly take place given *set-up conditions*.

We also translated two of the three reasoning strategies from MDC's framework into language that appropriately describes the work of students: abstract schema instantiation and chaining.[5] Based on what we saw happening in the seeds discussion and in an attempt to use language more common in the education literature, we code for a simpler version of abstract schema instantiation by looking for students using *analogical*

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[5] MDC's modular subassembly strategy is not relevant for the data we have considered thus far, because the mechanisms involved have not been sophisticated or intricate enough to warrant the use of groups of entities and activities. However, we can imagine that looking for this type of reasoning would be appropriate in more advanced settings.

reasoning. By not requiring students to abstract before instantiating the new case, we connect this aspect of MDC's account to discussions of analogy more common in science education literature. Finally, we explicitly code for *forward and backward chaining* and, as discussed below, consider it the heart of quality mechanistic reasoning.

Other aspects of their framework are not helpful for our purpose of identifying how students reason about mechanisms.[6] We do not attend to levels of hierarchy because this facet of MDC's framework describes the overall structure of mechanistic explanations rather than its parts. We do not look for students using the various empirical strategies for discovering mechanisms because we are interested in informal science discussions when students use information from their everyday experiences. Aspects of MDC's framework that are not relevant for our purposes might be valuable for other analyses of student reasoning – for example, analyses of the kind of inquiry that centers on controlled experimentation.

The Coding Scheme

Our initial analysis suggested that MDC's characterization of mechanisms in professional science could be used to describe students' mechanistic reasoning during inquiry. As a result, we developed their language into a more systematic coding scheme that could be applied to episodes when students describe their reasoning either verbally or in written form. There are nine categories in our coding scheme, derived from MDC's work: (1) *Describing the Target Phenomenon; Identifying (2) Set-Up Conditions, (3)*

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[6] Although it is of central concern to MDC and their colleagues in philosophy of science, the question of whether there is an ontological difference between entities and activities is not relevant to our interest in identifying phenomena of student reasoning.

Entities, (4) Activities; (5) Properties of Entities, *(6) Organzition of Entities; (7) Chaining; Analogies; and Animated Models.* We describe and give an example of each in turn. A summary table of the codes can be found in Appendix A.

1. Describing Target Phenomenon (DTP)

The phenomena scientists identify are stable, regular, and reliably produced. Scientists may either begin with knowledge of the phenomenon and then inquire into the mechanism that produces it, or they may describe phenomena as predictions based on their prior knowledge of the relevant components. When students clearly state or demonstrate the particular phenomenon or result they are trying to explain, we code their comments as "Describing the Target Phenomenon." An example would be a student saying "A can of diet coke floats and a can of regular coke sinks in water" during a discussion about buoyancy.

This first code went through two major revisions during the development of the coding scheme as a result of disagreement among coders about its meaning (see Data Analysis section below). Although the code was initially "Establishing Phenomenon," we find that students, unlike scientists, do not always try to reach a consensus about the phenomenon and may report contradictory results without concern. As a result, we changed the code to "Describing Phenomenon" and did not attempt to distinguish times when students intended to reach consensus and times when they did not. Fortunately, this distinction was often made for us by patterns in the coding. When students reported results in an attempt to reach consensus (to *establish* the phenomenon), there were only a few "Describing Phenomenon" comments followed by further elements of mechanistic reasoning. When students reported results without attempting to agree, there were many consecutive “Describing Phenomenon” comments not followed by other aspects of mechanistic reasoning.

Further problems with the “Describing Phenomenon” code occurred because it was unclear which *phenomenon* the code referenced. For simplicity, we decided not to include comments describing tangential or peripheral phenomena in this code (they are covered by later ones). Instead, we changed the code to “Describing *Target* Phenomenon” to reflect that convention and used it only when students describe the overall phenomenon being discussed (often dictated by the question the teacher posed).

2. Identifying Set-Up Conditions (SC)

Set-up conditions are descriptions of the spatial and temporal organizations of components that begin the regular changes of the mechanism that produce the phenomenon. We code as “Identifying Set-Up Conditions” the moments when students identify particular enabling conditions of the environment that allow the mechanism to run. For example, a student discussing the buoyancy experiment might say, “I held both cans of coke under the water *before I released them*.”

3. Identifying Entities (IE)

Scientists recognize that one component of mechanistic descriptions are *entities*: the things that play roles in producing the phenomenon. When students recognize objects that affect the outcome of the phenomenon, we code such comments as “Identifying Entities” even if the entity has been previously identified. For example, a student might say, “I am thinking about the role of *each individual water molecule*.”

There are times when students may identify entities unproductively using scientific vocabulary that they do not understand. In these cases (which we observed several times), we decided to still code the students as "Identifying Entities." We use later codes to distinguish between students using unfamiliar terms and those who are presenting entities meaningfully.

4. Identifying Activities (IA)

Along with identifying the entities in a mechanism, scientists also identify the relevant activities: "the various doings in which these entities engage" (Craver & Darden, 2001, p. 113). Students who articulate the actions and interactions that occur among entities are coded as "Identifying Activities." We use this code whenever students describe the things that entities do that cause changes in the surrounding entities, even if the activity has been previously identified. For example, a student might say, "Each individual water molecule *pushes* up on the molecules on top of it."

We decided to code all the activities that students suggest the entities do, including potentially inappropriate ones (e.g. ones that anthropomorphize inanimate entities). We also use this code in conjunction with the previous one (IE) to code the components of tangential phenomena that students describe, instead of using the "DTP" code reserved for the specific phenomenon they are trying to explain.

5. Identifying Properties of Entities (IPE)

Identifying and isolating only those properties of the entities relevant to the outcome is a vital part of scientific discovery. When coding for "Identifying Properties of Entities," we look for students who engage in this scientific practice by articulating general properties of entities that are necessary for this particular mechanism to run. For example, a student may say, "Water molecules are *little hard balls* that bounce off everything."

This code helps distinguish between students using unfamiliar vocabulary and those suggesting entities that make sense to them. When students are unable to articulate general properties of the entities because they are using unfamiliar scientific terminology, corresponding "IPE" codes tend not to accompany the "IE" code.

6. Identifying Organization of Entities (IOE)

In most cases the mechanism depends on how the entities are spatially organized, where they are located, and how they are structured. When students attend to those same features, we code their comments as "Identifying Organization of Entities." For example, a student may say, "The water *below* the oil pushes on it, while the alcohol *above* the oil also pushes on it."

This code was not initially part of the coding scheme but was added later when we attempted to code a new piece of data. Several student comments in that data (see chapter five) were important to their explanations of the mechanism but were not captured by any of the existing codes. We returned to MDC's account of mechanism to search for a description of the activity and added this code.

7. Chaining: Backward and Forward (C)

A general reasoning strategy that aids the discovery and articulation of mechanisms involves using knowledge about the causal structure of the world to make claims about what must have happened previously to bring about the current state of things (backward) or what will happen next given that certain entities or activities are present now (forward). By knowing the general properties of entities involved, much can be said about the activities that must have produced them and about the activities in which they can engage. Similarly, "characteristic features of an activity may provide clues as to the entities that engaged in it" and the entities that it produced (Darden & Craver, 2002, p. 24).

We observe students reasoning about one stage in a mechanism based on what is known about other stages of that particular mechanism and code this type of reasoning as "Chaining." When students chain backward, they answer the questions "What activities could have given rise to entities with these properties?" - or "What entities were necessary in order for this activity to have occurred?" When students chain forward, they answer the questions "What activities could these entities with these properties be expected to engage in?" - or "If this activity occurred, what changes would I expect in the surrounding entities and their properties?" For example, a student might say "I know that objects fall straight to the ground in air but not in liquids, *so there must be some force pushing up* on objects in liquids that keeps them from falling."

Initially, the chaining code was two codes, forward chaining and backward chaining. However, several attempts to use the two codes to analyze student discourse revealed that it was difficult to tell whether the students had *reasoned* backward/forward to reach their conclusion, or whether they were just reporting their reasoning in that way. We also found some confusion over what exactly backward and forward meant: Was it referring to the direction of reasoning (i.e. A implies B implies C vs. C implies B implies A) or was it referring to whether students were reasoning about something that occurred before or after that observed phenomenon. Not only were the two codes difficult to apply, it also appeared that distinguishing between them did not add anything to our understanding of students' reasoning. For these reasons, we merged the forward and backward chaining codes into one new code: chaining.

The "Chaining" code helps identify students using unfamiliar scientific vocabulary or inappropriately assigning activities. Those using vocabulary without meaning are usually unable to reason backward or forward because they do not articulate general properties of the components that caused one event to occur instead of another. Similarly, students who inappropriately assert that certain entities can perform certain activities tend not to say why those particular activities should be expected and not other ones.

Analogies (A)

Scientists also use analogies to similar mechanisms in other contexts or fields as a framework for understanding new situations (Darden & Craver, 2002; Dunbar, 1995). They frequently begin with a previously articulated mechanism and attempt to fit various aspects from the new phenomenon into the functional roles and constraints of the original mechanism. An "Analogy" code is used whenever students compare the target phenomenon to another. For example, a student trying to describe the properties of water that allow it to support heavy objects on its surface may say "I am thinking about the *surface of water like a rope with tension* that can be pushed down but still resists."

Animated Models (AM)

Reasoning about mechanisms is a potentially taxing cognitive activity, and external models provide the "vehicle for keeping in mind all the complex interactions among the operations" (Bechtel & Abrahamsen, 2005, p. 427). A good diagram or model illustrates the entities, their activities, their organization, and the productive continuity from one stage to the next. When scientists reason about mechanisms by "running them in their heads," animated representations are especially valuable because they "supplement human abilities to imagine a system in action" (Bechtel & Abrahamsen, 2005, p. 431).

We code as "Animated Model" students using external animated models (gestures, body movements, etc) to help their peers conceptualize how they were "seeing" certain entities acting in the mechanism. For example, students might hold hands and then *link arms* to model the idea that the surface of water acts like a tight rope with tension.

Hierarchy of Codes

We arranged the first seven codes in a numerical sequence based primarily on their logical connections and in part on our intuitions about what seems more difficult. For example, identifying the properties and organization of entities would generally require identifying entities, and chaining would involve using information about entities, their activities, properties, and organization to construct a step-by-step story for how the mechanism runs. Chaining seems to be the most difficult. The evidence from coding student conversations bears this out: Higher numbered codes, chaining in particular, rarely appear without lower number codes.

Support for this intuitive arrangement comes from Metz's (1991) work on student explanations of sets of gears. She identifies three phases of explanation that coincide with our hierarchy of mechanistic reasoning - "(a) function of the object as explanation, (b) connections as explanation, (c) mechanistic explanation" (p. 785). In associating causality with the function of an object, the youngest students are identifying entities in the mechanism. By attending to connections, students are considering properties and organization of entities. Finally, what Metz calls the mechanistic phase of the oldest children is equivalent to our identification of activities and subsequent forward and backward chaining. However, although Metz's ranking is developmental (she only observes older students doing the last phase), we expect to see all ages of students reasoning at all levels of the coding scheme.

The last two mechanism codes can be used in different ways. Students may use analogies simply as direct mappings to describe phenomena and identify components, and this may or may not be sophisticated; or they may use them as source of relationships for chaining from one stage of the mechanism to another. Similarly, animated models may be used as visible manifestations of sophisticated reasoning, or they may merely demonstrate the phenomenon that has been observed or predicted. As a result, for these two categories we code their occurrence but do not include them in the hierarchy.

Refined Methodology: Systematic Application of the Coding Scheme

We use this coding scheme when students describe their reasoning about a scientific phenomenon. These descriptions may be verbal descriptions during class or small-group discussion or written explanations such as test or homework solutions.

Although my initial analysis of the seeds discussion analyzed blocks of transcript for general trends, we now use the mechanism framework to systematically unpack every student comment for evidence of any of the nine categories. We code each individual student conversational turn, however long it might be. One comment may have numerous codes: for example, it may include identification of both entities and activities. Comments may also have no codes at all, if none of the categories apply. We do not code teacher utterances. We describe this new methodology in more detail in the following section.

In Table 1 below we code an excerpt from the first graders' discussion about seed growth to contrast this more systematic analysis with what was presented above. Underlined portions of the transcript indicate evidence of the particular codes that were assigned. Although we have only shown three conversational turns from the discussion, all intervening student comments (indicated by ellipses) would be coded in the same way.

Speaker	**Utterance**	**Mechanism Codes**
Ms. Mikeska:	And so that seed in the sand?	
Emily:	Is just left alone without the s- the water that	IE
	helps it grow in soil. Because the soil is like hard	IE, IPE
	and the water is like, pssshhh, blocked. Like with	IE, IA
	all those sticks and stuff- it's real hard so the	IE, IPE
	water won't get through. But in sand since	IE, IA, C
	usually sand will be blown away not sticks into	A, IPE, IE
	the sand- it's easy that it's not blocked so it just	IE, IA
	goes—shhhhhhwweeee. (Motions with both	IA, AM
	hands water flowing down.)	
…		
Juan:	I think it would grow because, because the water	DTP, IE
	goes through it, and if if the water goes through it	IA
	might receive some water.	IE, IA, C
…		
Emily:	Because if the water is going through it's not	IE, IA
	exactly where the seed is if you put it near the	IE, IA, C
	top. Cause the s, cause the water is going near the	IE, IA, IOE
	bottom…and if it's going near the bottom it's not	IA, IOE
	near the seed it's by the top.	IE, C

Table 1

Data Analysis Methodology

In the previous sections we explained the development of the framework used in this dissertation to analyze episodes of student mechanistic reasoning. We now describe the more practical aspects of the research methodology: how we selected and analyzed data.

Case Study Methodology

The analysis in this dissertation follows the tradition of case study methodology from qualitative research. Quantitative methods are not feasible or appropriate here because although there has been much discussion on student mechanistic reasoning in the literature (see chapter two), research in this area has not yet identified what variables determine that reasoning. There is hence no basis for collecting data from a large population, and no well-defined set of quantities on which to perform statistical analyses.

Instead, we analyze a small number of science discussions to develop case studies: rich, detailed descriptions of student reasoning in each episode. Case study analysis is especially well suited to the purpose of this work: to use the mechanism framework described above to develop an in-depth understanding of the phenomenology of student mechanistic reasoning during scientific inquiry. It is possible that this understanding may later lead to the identification of variables that can be tested using more quantitative methods (and the mechanism framework may provide clues to those variables), but we do not undertake or speculate about that task here.

This case study methodology is consistent with the style and tradition of analysis in the Science Education and Physics Education Research Groups at the University of

Maryland, College Park (e.g. Hammer, 2004; May, Hammer, & Roy, 2006; Rosenberg, Hammer, & Phelan, 2006).

Data Selection

In this work, we had access to more than 500 hours of previously collected video data and written work from two different research projects conducted by the Physics and Science Education Research Groups at the University of Maryland, College Park (Case Studies of Elementary Student Inquiry in Physical Science: NSF ESI-9986846, Learning How to Learn Science: Physics for Bioscience Majors: NSF REC-0087519). The data from these projects spanned contexts from elementary school classrooms to introductory college courses. None of this data was collected for the purpose of studying student mechanistic reasoning; it was collected more generally to study issues of student science learning and inquiry. We also had the opportunity to collect additional data specifically for analysis of mechanistic reasoning as part of a project analyzing student physics learning in grades K-16 (Towards a New Conceptualization of Progress, K-16: Resources, Frames, and Networks: NSF REC-0440113). We obtained copies of students' written responses to physics examination problems and interviewed them about their solutions.

We had three goals in analyzing episodes of student discourse: to test the reliability of the coding scheme, to check whether the coding scheme corresponded to intuitions about mechanistic reasoning and understandings of professional science practice, and to begin to study the dynamics of mechanistic reasoning and other aspects of science learning. To achieve those goals, it was necessary to select episodes of student discourse that were rich with mechanistic reasoning and thus rich with moments to code with the mechanism framework. Episodes were initially selected from all the available data based on our sense of what contexts and content topics would most likely generate conversations centered on students' sense of physical mechanism. Preliminary, cursory investigations of possible candidate cases revealed whether the episodes contained 'good code-able stuff;' if our initial sense in watching the video was that it did not contain significant mechanistic reasoning and that systematically coding it would yield mostly no or low-level codes, we did not further analyze that episode. We also selected episodes based on a desire to study mechanistic reasoning at all levels of science learning; we looked for conversations at both ends of the educational spectrum, from lower elementary grades to college and graduate courses. The episodes presented here are not meant to represent a random sample of student science discussions; they are exemplary in their sophistication and clarity. However, while the discussions themselves might not be typical, there is no reason to suspect that the students in these episodes are not generally representative of their peers. Thus these conversations do represent possibilities of the kinds of things that *can* happen in K – 16 classrooms.

The first two case studies (chapters four and five) involve students in the lower elementary grades at two suburban public schools in Montgomery County, Maryland. The third case study (chapter six) occurs in a reformed, introductory, algebra-based physics course at the University of Maryland, College Park. The final case study (chapter seven) analyzes graduate students' written responses to a classical mechanics qualifying exam question in the Department of Physics at the University of Maryland, College Park. The specifics of each population will be discussed in their respective chapters.

Data Analysis: Chapters 4,5, and 6

To study the selected video data, we followed a multi-phase analytical model adapted from the methodology developed by several mathematics educators at Rutger's University (Powell, Francisco, & Maher, 2003).

Phase One: Attentively Viewing and Describing Video Data

After video was selected, the first step in analysis was to watch the video attentively several times. In this viewing, we carefully attended to the substance of student ideas. Powell et al. (2003) suggest that the purpose of this stage is to become intensely familiar with the content of the video without trying to interpret that content. In as much as is possible, we "watch and listen without intentionally imposing a specific analytical lens on [our] viewing" (Powell et al., 2003, p. 415-416).

Video data of student discussions was often so dense and lengthy that it was difficult to become familiar with the details of its content solely by watching it several times; the data needed to be parsed in some way to help make sense of it. To do so, we sometimes divided the video into thirty second time intervals and then 'stop, watch, and describe' each interval. As Powell et al. (2003) propose, we tried to be sure that "the descriptions are indeed descriptive and not interpretative or inferential" (p. 416) and that they remained both simple and factual. The process of observing strict time intervals was very helpful in that it forced us to attend to each individual student comment instead of only noticing longer, more developed statements. This phase was especially helpful for analyzing conversations among younger students as their language was less articulate and they tended to talk over one another more frequently. Through attentively watching and describing the data, we became extensively familiar with the video and with each student, his voice, his comments, and the gestures and movements he makes.

Phase Two: Transcribing the Video Data

After selecting episodes, we transcribed the video and audio data into written form. This process involved recording not only students' verbal remarks, but also actions or gestures that were relevant to their explanations. Completed transcripts used in analysis included teacher and student utterances, important non-verbal cues, descriptions of any external props used, and the length of pauses in the discussion. However, these transcripts were somewhat interpretive; what we chose to record in the written account was necessarily influenced by what we were ultimately looking to study.

Transcription of video data has several benefits for research. As Tuminaro (2004) points out, constructing a written record, like phase one of the methodology, also requires the researcher to watch the video several times and attend to students' exact language; this in turn helps him/her become more familiar with the data including potentially important subtle details. The written record also makes it easier to study particular comments in depth or to compare across comments. As Powell et al. (2003) note, "The production of the transcript and the physical, static rendering of a research session affords researchers opportunities for extended, considered deliberations of talk and noted gestures… with transcript data, one can consider more than momentarily the meaning of specific utterances" (p. 422). Transcript data may also give researchers unfamiliar with the data faster access to the content of the discussion than watching the entire video.

Phase Three: Coding the Video Data and Identifying Critical Events

In the next phase of analysis, we coded the transcript data line-by-line using the mechanism framework described above. At least two researchers independently coded each comment in the transcript. In addition to assigning a code to each line, we also provided memos that described our sense of the students' meaning or elaborated why we coded in particular ways. Powell et al. (2003) describe this process when "researchers write commentary that discusses and justifies the identified material. At this phase, such commentary [in conjunction with the codes themselves] often manifests analytic threads of the narrative or storyline [phase four]" (p. 430). Coding and memo-ing allowed us to be precise and articulate about the mechanistic reasoning we observed in each student comment.

Coding of the data presented some methodological challenges. Although our analysis of the data began with some "deductive or a priori codes" (Powell et al., 2003, p. 429) informed by MDC (2000), part of the objective of this work was to develop codes appropriate for identifying mechanistic reasoning in student discourse. As was expected during this development stage, the first few attempts at coding yielded some disagreements among coders that required resolution and subsequent modification to the coding scheme. In addition to the changes made to individual codes described above (notably the DTP and C codes), several conventions were adopted.

First, we decided to code every time a student identified an entity, activity, entity property or organization instead of only coding it the first time it was said (either by the same or a different student). This convention freed us from having to decide whether a student was just repeating an idea someone else used or was constructing the idea on their own. Second, we decided not to code all comments literally; prior student comments could be used to interpret student meaning in later comments (i.e. to give meaning to pronouns such as ‘it’) but later comments could not be used to infer meaning of prior comments. We felt this was appropriate because meaning evident in later comments might not yet have been developed in earlier comments.

Thus initial attempts to code the data in this phase of analysis led to modification (e.g. DTP), addition (e.g. IOE), and merging of codes (e.g. C) discussed above as well as overall methodological conventions. We do not consider these modifications to indicate a failure in some a priori coding scheme; instead we view them as necessary refinements that help us better capture the meaning in our data. As such, our mechanism framework, while grounded in MDC’s characterization, is also appropriately “inductive and emergent” (Powell et al., 2003, p. 429) from student data. This iterative application and modification of the coding scheme is similar to aspects of grounded theoretical methods but is different in that the codes did not entirely emerge from the data.

The independent coders checked their agreement and resolved all discrepancies through discussion. Inter-rater reliability was calculated for the first two of the four episodes during which most of the modification to the coding scheme occurred. We calculated inter-rater reliability along two dimensions: Data Identification and Coding. The first dimension (Data Identification) is a check on whether the researchers identify the same conversational turns as relevant data for analysis. The other (Coding) is a check on whether the researchers apply the same category of the framework to a given conversational turn. For details see chapters four and five.

After an entire video transcript was coded, we constructed graphs of mechanism code (1- 7) versus utterance (related to time) for the episode. The relationship between the graphs and the video data was bi-directional; patterns in the graphs indicated moments in the video that deserved closer study and moments in the video that seemed especially mechanistic indicated places in the graph to observe possible trends. In this way, study of both the video and the graph helped identify what Powell et al. (2003) call "significant moments" or "critical events" (p. 416). In addition, in citing Gattegno (1970, 1974, 1987, 1988), Powell et al. also describe how "these [critical] events or moments often compel researchers to reflect on their antecedent and consequent events" (p. 418). Constructing a detailed account of the video transcript (coding) and a corresponding graphical plot of those codes helped indicate critical moments that guided our interpretation of the rest of the data.

Phase Four: Constructing a Narrative

The final phase of the methodology was a more free-form, narrative-style analysis aimed at making meaning from the data. It involved "trying to discern an emerging and evolving narrative about the data" that resulted from "making sense of the data with particular attention to identified codes" (Powell et al., 2003, p 430). That process of "constructing a storyline" of the data required us "to come up with insightful and coherent organizations of the critical events" (p. 430) that spoke to the research question. We attempted to precisely describe the dynamics of student mechanistic reasoning in each episode based on the line-by-line coding and critical moments. That is, we were interested in obtaining a picture of *how* mechanistic reasoning develops in addition to just *whether* or not it develops (Maxwell, 2004). This part of the analysis was aided by discussions with other members of the research group (primarily Hammer, Redish, Scherr, and Elby); “shared viewing involving participants or other researchers… can enhance the quality of the interpretations” (Powell et al., 2003, p. 430) because ideas were subjected to critique from multiple perspectives. Building the narrative was the most interpretive and inferential of all the methodological stages because we used the data to tell a story about the nature and value of student mechanistic reasoning. One encouraging result of our analysis with the coding scheme was that the coding supported this phase of the analysis both by helping us identify phenomena in student discussions and by suggesting ways of interpreting the dynamics of those discussions.

Data Analysis: Chapter 7

One notable exception to the multi-step methodology described above is the analysis presented in chapter seven, which comes from the written work of two students on a graduate physics qualifying exam. The written work did not require “attentive viewing” or transcription in the sense described above. However, we did spend extensive time going through student responses in at attempt to understand the meaning of each part of their solution. The written work also did not lend itself to any line-by-line coding; it was unclear what appropriate ‘lines’ would be since each written line of text did not necessarily correspond to time or anything meaningful. Instead, it was coded more holistically as in the example at the beginning of the chapter, by looking for general patterns that corresponded to mechanism codes. The video interview data corresponding to the written work was attentively viewed and transcribed as described above, but it was not coded line-by-line. Instead, it was used to interpret and support the analysis of the written data.

Summary

This chapter describes the motivation and development of a framework for reliably recognizing nascent mechanistic reasoning in student scientific inquiry. Although influenced by the entire tradition in the philosophy of science literature that describes the history of science as the pursuit of mechanisms, we draw most heavily on Machamer, Darden, and Craver's (2000) characterization of mechanisms in contemporary professional science. The language of their account not only aligns well with our conception of how science is practiced by research physicists, it also overlaps with the kinds of things we see students doing in the classroom. We explain how MDC's work was modified and refined into a coding scheme that is used to systematically analyze case studies of student discourse, and described how that analysis is carried out.

The rest of this dissertation (specifically the next four chapters) provides the results of using the mechanism framework to analyze episodes of student reasoning. We show the usefulness of this framework not only for identifying mechanistic reasoning, but also for understanding the dynamics and value of student science discussions. The mechanism framework provides a richer description of the quality of inquiry than is available from intuitive assessments of 'goodness.'

Chapter 4: Mechanistic Reasoning In Young Children[7]

Introduction

Science educators regularly attempt to characterize what school aged children can and cannot do or how they can and cannot think in designing standards, curricula, or assessments. As Metz (1995) notes:

> The field of science instruction has long struggled to define constraints on developmentally appropriate science curricula for children. At the heart of this debate is the issue of what aspects or forms of scientific inquiry are within reach of young children. (p. 93)

The National Science Education Standards (NRC, 1996) claim that the science content standard for elementary school "sets forth some abilities of scientific inquiry appropriate for students in grades K – 4" (p. 121). Educators are rightly focused on designing scientific inquiry that is age-appropriate so that students can engage in it meaningfully.

Given that inquiry should be age-appropriate, the question becomes: What is age-appropriate? Metz (1995) describes that school science assumes that young students should be limited to concrete thinking "with a focus on the processes of observation, ordering, and categorization of the directly observable" because "abstractions, ideas not tied to the concrete and manipulable, are inaccessible to concrete operational children" (p. 93, 95). Hammer (2004) similarly claims, "the lists of process skills organized by

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[7] A version of this chapter (authored by Russ, R.S., Scherr, R.E., Hammer, D., & Mikeska, J.) has been submitted for publication to the Journal for Research in Science Teaching.

developmental level remain the basis for thinking about objectives and assessments with respect to science as inquiry" (p. 326). For example, the National Science Education Standards (1996) encourage elementary teachers to help their students explore the world through "observation, manipulation, and classification of common objects" (p. 123) and "examining and qualitatively describing objects and their behavior" because these activities are "the necessary precursors to the later introduction of more abstract ideas in the upper grade levels" (p. 126). The standards go on to describe several difficulties and limitations of young students' thinking, including that they cannot understand many complex, theoretical concepts. Current school science creates inquiry experiences for elementary students based on the assumption that they are developmentally constrained to concrete tasks and thus cannot generate theories.

However, much of this work systematically underestimates children's abilities; it is grounded in an inaccurate perception of what is age-appropriate for elementary school children. In her examination of the assumptions of school science, Metz (1995) provides examples from Piaget's work and non-Piagetian developmental literatures and finds that they both "indicate that elementary school children are actually capable of much richer scientific inquiry than these assumptions imply" (p. 120). Hammer (2004) and Hammer and van Zee (2006) present a series of case studies from grade school classrooms depicting students engaged in rich, sophisticated inquiry not characterized by experimental process skills; the students engage in theoretical discussions about physical cause and effect using their own common sense and everyday reasoning. These examples "give a general appreciation of the sorts of things children are capable of doing, which go well beyond commonly-held expectations" (Hammer, 2004, p. 283). Other work with children includes similar examples of the richness of students' theoretical reasoning (e.g. Brewer, Chinn, & Samarapungavan, 1998; Kuhn, 1989; May, Hammer, & Roy, 2006). These possibilities for student thinking suggest that age-appropriate inquiry for elementary school students should not be limited by traditional ideas about developmental constraints.

This chapter presents further evidence that the assumptions made by current curriculum designers about elementary student abilities are invalid and that young children are in fact capable of rich, mechanistic reasoning. In it, the mechanism coding scheme that was developed from descriptions of professional science is used to analyze a discussion among first-grade students about falling objects. Mechanistic reasoning is abundantly present even in these young students and appears episodically throughout their conversation. At one moment, the students may be engaged at the highest levels of the coding scheme and the next they are not. As such, this analysis shows that it would be inappropriate to characterize the students as either having or lacking the ability to reason mechanistically based only on a few episodes. Application of the framework gives results consistent with our intuitive assessments and also offers new information about the students' inquiry: it identifies specific transitions into and out of mechanistic reasoning. The framework also gives insight into those transitions.

Context for Analysis

We illustrate the use of the coding scheme with a discussion among first grade students about falling objects. Because the discussion is rich with student statements that seem intuitively to resemble causal mechanistic reasoning, analysis allows us to check whether applying the framework gives results that match our intuitive assessments.

This discussion involves first grade students at a public elementary school in Montgomery County, Maryland.[8] The students are engaged in science lessons one to three times a week for approximately forty-five minutes each time. At the time of this classroom conversation, the instructor was participating in a project to develop materials for teacher education and help prospective and current elementary teachers gain experience in interpreting and assessing the substance of student reasoning (Hammer & van Zee, 2006).

Educational policy in Montgomery County specifies that first graders should be able to "describe the different ways that objects move (e.g. straight, round and round, fast and slow)" (MCPS, 2001). With this goal in mind, as well as personal and mandated inquiry goals, the instructor Ms. Mikeska (as her students called her) introduces a question to her students about two falling objects: a book and a piece of paper.

Synopsis of Classroom Inquiry

On the first day, Ms. Mikeska asks the students to predict what will happen if she drops a book and a *flat* piece of paper at the same time from the same height. The students all agree that the book will hit the ground first and offer several explanations as to why. At the next science lesson, Ms. Mikeska shows the students a tape of their discussion and has them help her summarize their ideas. The students then break up into small groups to test their prediction. After conducting their experiments, students report their results to the class. Different groups report different results (in fact, all possible

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[8] The instructor of the class has written an analysis of this class that appears elsewhere, including both video and transcript data. To be consistent with the video, we use the children's real first names, with consent from their parents. Mikeska, J. (2006). Falling Objects. In D. Hammer & E. van Zee (Eds.), Seeing the Science in Children's Thinking: Case Studies of Student Inquiry in Physical Science. Portsmouth, NJ: Heinemann, pp 72 – 83.

results are represented). The students show no concern over the disagreement. Ms. Mikeska then asks them to predict what will happen when she drops a book and a *crumpled* piece of paper from the same height at the same time. They briefly make predictions before breaking into small groups to try the experiment. In the discussion that follows those experiments, the students all agree that the book and the paper hit the ground at the same time, and spontaneously offer their reasoning for why that occurs.

We have discussed this pair of classes elsewhere (Hammer, Russ, Scherr & Mikeska, in press) with respect to students shifting into and out of modes of inquiry we consider scientific. There our analysis is qualitative and informal; in this chapter we present a more rigorous analysis of mechanistic thinking as one aspect of scientific thinking. Our data for this analysis is the transcript of the second day's discussion, which we provide in full in Appendix B.

Mechanism Coding Inter-rater Reliability

There are two tasks in coding transcripts. One is to recognize that a conversational turn has meaning in it to code; that is, to identify relevant data in the transcript (Data Identification). The other is to decide which categories of the framework apply (Coding). Ultimately, we hope the coding scheme will facilitate both recognition and analysis of mechanistic reasoning, and so we considered inter-rater reliability for each of these tasks.

Moreover, we first assessed inter-rater reliability between R. Scherr, a research scientist in the Physics Education Research group, and myself. Because both are education researchers who work closely together, their agreement might reflect their common but tacit shared perspectives. Such agreement may be viewed as either a strength or a weakness of the coding scheme – a strength in that the coding scheme captures those shared perspectives, but a weakness in that the coding scheme might not be accessible to those not sharing that perspective. As a check against the latter concern, we assessed inter-rater reliability among R. Scherr, myself, and the classroom teacher Ms. Mikeska. The result showed a somewhat lower agreement in Data Identification (0.79 instead of 0.88), but a comparable agreement in those codings (0.88 and 0.86).[9] By separating these two groups, we were able to determine whether the coding scheme matched both educational research intuitions and tacit instructional perceptions.

A summary of the pre-discussion inter-rater reliability scores is given in Table 2 below. After discussion, there was 100% agreement among all coders for both categories.

	Data identification	**Coding**
1st and 2nd Author	0.88	0.86
1st, 2nd, and 4th Author	0.79	0.88

Table 2

These figures for inter-rater reliability do not include the first code (now "Describing Target Phenomenon") because it was revised twice during the analysis of this transcript. An initial check for agreement among coders revealed that the first code had significantly lower inter-rater reliability than the rest of the coding scheme; discussion indicated differences in code interpretation. Originally, the first code in the coding scheme was

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[9] Agreement in Coding among R. Scherr, Ms. Mikeska, and me is higher than among just R. Scherr and me because it is for the reduced set of commonly identified data.

"Establishing Phenomenon," a code ideally meant to capture times when students, like MDC's scientists, were attempting to reach consensus about the outcome of the phenomenon. Practically, however, we found it difficult (perhaps impossible) to tell whether students were intending to come to agreement. To avoid having to make such judgments but still maintain the spirit of recognizing when students discuss phenomena they hope to explain, we changed the code to "Describing Phenomenon" and did not attempt to tease apart times when students agreed and when they did not. Another problem with the "Describing Phenomenon" code occurred because it was unclear which *phenomenon* the code referenced: the primary phenomenon of the discussion, or also possible tangential or peripheral phenomena. For simplicity, we changed the code to "Describing *Target* Phenomenon" and used it only when students described the primary phenomenon being discussed (often dictated by the question the teacher posed). Since these changes occurred during the coding of this transcript, independent inter-rater reliability of the new code (DTP) could not be calculated for this data set. However, subsequent application of this coding scheme to other data with other independent coders has shown comparable inter-rater reliability when including this code (Russ & Hutchison, 2006).

Student Mechanistic Reasoning

In what follows, we highlight several portions of the second day's discussion, starting when the student groups present their results for the experiment with the book and the flat piece of paper.

Low-level Mechanistic Coding

1. Class discussion

Ms. Mikeska began the large class discussion by asking students to report their results. She expected all students to report that the book hit the ground first, and was surprised when three different results were reported.

Teacher: What, what happened when you dropped the book and the piece of paper at the same time, at the same height? Huh, what happened? (Students raising hands.) Okay, Ebony why don't you go ahead and begin.

Ebony: To me, first, the paper fell first.

Student 1: No way, no!

Brianna: Whoa!! The book fell first.

Ebony: No, to me the paper fell first.

Students: No!

Student 2: It fell at the same time.

Ebony: No, the book, um – the paper fell – the paper fell first to me!

Henok: Yeah, but not to me!

Ebony: To me, it fell, the paper fell first (Voice trailing off.)

Jorge: Yeah, but did the book fall first, just like the paper?

Ebony: No, the papers fell first.

Henok: The book fell first.

Ebony: No, the paper – to me.

Alison: To Ebony – to Ebony the paper fell first.

Student 3: To me, not to you.

Brianna: And to all of us the book might've fell first to us.

Students: Yeah.

Jorge: Our paper – our paper goes slowly. It's, it's, it's a little bit out of [practice?].

Rachel: With me and Julio twice the book and the paper tied – twice.

2. Informal observations

Ms. Mikeska was frustrated when the students showed no interest in reconciling their contradictory observations. Her instructional assessment was that the students were not doing quality scientific reasoning in this segment. Indeed, the students' lack of interest in establishing a common phenomenon is in contrast to the ideal behavior of scientists, for whom the first step in accounting for a phenomenon is agreeing on its existence. In this segment, we see the students as participating in a "show-and-tell" activity, in which everyone is entitled to her or his own account: "To Ebony, the paper fell first," and to others "the book might've fell first" or tied with the paper.

3. Mechanistic analysis

Ms. Mikeska asked the students to observe and explain the result of the "race" between the book and the flat piece of paper. Ebony began the discussion by describing the target phenomenon (DTP) that he supposedly observed in his small group: the paper fell before the book. Brianna, Student 2, Henok, Jorge, and Rachel all responded to Ebony by reporting other phenomena (DTP) – either the book falling first or the book and the paper reaching the ground at the same time. Alison, often a leader in class discussions, firmly restated Ebony's phenomenon (DTP) as "his," giving other students license to have their own potentially different results.

Analysis of this segment shows repeated "DTP" codes that are not followed by higher level mechanistic codes (*e.g.,* identifying entities/activities and backward/forward chaining). Were the students working together to describe a phenomenon they could then explain, there would more likely be only a small number of “DTP” comments followed by other elements of mechanistic reasoning. The students’ acceptance of unreconciled, contradictory phenomena indicates that they may not be approaching the conversation in a scientifically sophisticated way; scientists often attempt to agree on targets for explanation and then proceed to construct those explanations. By using the mechanism coding scheme we are able to identify and articulate the nature of students’ lack of progress during this part of the discussion.

Intermediate-level Mechanistic Coding

1. Class discussion

In response to Ms. Mikeska’s explicit request for an explanation of the conflicting results — “How could it be that we got different results when we did the same thing?” — many of the students shrugged their shoulders and claimed ignorance about the question. One student suggested an answer.

Teacher: Do you have an idea? Rachel has –
Rachel: Forces of gravity?
Henok: Yeah.
Teacher: Rachel has an idea.
Rachel: Forces of gravity.
Alison: Yeah!
Diamond: What are forces of gravity?
Rachel: Gravity is what –
Alison: Gravity, gra – you know how when we jump we always land back on the ground.

Rachel: Exactly. It's what keeps us down on the ground. (Patting the ground.)

Student 1: Yeah.

Autumn: Like ground magnets.

Ebony: And no gravity. No gravity is when you're like in space and you can never ever really fall down. [??]

Julio: You know, you just float in the air. (Ebony nods in agreement.)

Alison: Gravity – see how when I jump (Stands up and jumps.) I'm just landing at the same place on the ground that - because gravity, gravity is just pulling me down.

…

Teacher: Okay, so, so what you're saying is that a for – what is a – you're saying that the force of gravity –

Rachel: - is pulling it down at different times.

Teacher: So you're saying the force of gravity is pulling the book down at a different time than the paper.

Rachel: Yeah probably, and sometimes it's pulling it down at the same time, or pulling the paper down… before the book and then the book's pulling it down before the paper. Gravity's pulling the book down before the paper.

2. Informal Observations

Although it seems good for the students to move beyond declaring their contradictory outcomes, we have mixed feelings about Rachel's use of the term "gravity." Rachel may have been making a substantive suggestion, trying to identify a relevant causal agent for falling that could somehow account for the results – perhaps thinking gravity might be like wind in that it can act with different strengths at different times. Or she may have seen Ms. Mikeska as looking for a more scientific-*sounding* answer, and responded with a science vocabulary word for that reason.

3. Mechanistic analysis

Rachel identifies gravity as an entity in the mechanism (IE) and both Henok and Alison agree with her. Alison and Rachel both use analogies (A) to jumping to help them identify a property of gravity (IPE): it keeps us on the ground. Autumn makes the analogy (A) of gravity being like magnets. Alison presents the animated model of jumping (AM) to draw the other students' attention to the role of gravity and specifically identifies the activity that gravity engages in: pulling down (IA). In response to the teacher's questioning, Rachel reasserts that gravity is pulling (IA) and suggests that it can pull at different rates.

Unlike in the previous episode, intermediate-numbered codes appear in this segment of the discussion. However, the students do not identify any set up conditions (SC), general properties of gravity (IPE), or spatial organization (IOE) that would cause gravity to pull things at different rates. The presence of IE codes without corresponding IPE codes in this section of the transcript provides some evidence that Rachel is using unfamiliar scientific vocabulary she does not understand; if students use entities that are meaningful and make physical sense to them, we would expect to see them also able to identify relevant properties of those entities. In addition, the students do not do any backward or forward chaining (C), perhaps because they have not identified general properties through which the entities would participate in a causal chain of events.

High-level Mechanistic Coding

1. Class discussion

Ms. Mikeska decided to conduct several trials of dropping the book and the flat sheet of paper, so that the students could all see and agree on what happens. She went on to pose the question of what would happen if she crumpled the paper, and the students predicted that the book and paper would then fall at the same rate. They went off to try it, and then gathered again to discuss their results. This time they all quickly agreed that the book and paper fell at the same time, and without prompting they began to discuss differences between the flat and crumpled pieces of paper.

Julio: Um, crumpled up paper us is kind-of heavy. (7 second pause)
Brianna: If it's balled up it's still not heavy it's the same size.
Autumn?: It's just a little bit like -
Brianna: If you need the heaviest. (She picks up the crumpled paper and uncrumples it.)
Autumn: Why are you doing that?
Students: [Laughter.]
Brianna: It's still at the same size. (Lifts the paper up and down in front of her.) It still feels – (Crumples the paper back up.)
Students: [Laughter]
Brianna: - it still feels um –
Student 1: Can I see?
Autumn: It's not heavy.
Brianna: It still feels –
Alison: My, my dad could probably throw that –
Brianna: It still feels [??] light. It's still light.

2. Informal observations

The students were now talking about the "heaviness" of the ball of paper compared to the flat piece, returning to a theme from their conversation on the first day when they had predicted the book would fall more quickly because it was heavier (or, they also said, had more "strength") than the flat sheet of paper. They disagreed, though, over whether the crumpled paper is heavier, with Brianna offering her argument for why it cannot be heavier: The paper is "still the same size" whether it is crumpled or flat.

3. Mechanistic analysis

Julio identified a property of the crumpled paper – it is heavy (IPE). It is possible he inferred its heaviness from his reasoning, like everyone's the day before, that heavier objects fall faster; it is also possible that the paper felt heavier to him and he was using this property to explain the result.

Brianna responded to Jorge by forward chaining (C) from an activity to an entity property, making the argument that the activity of crumpling (IA) cannot change the size (presumably associated with weight) of the paper (IPE). Brianna then picked up the paper, flattened it, and crumpled it again (AM), demonstrating that nothing is lost or gained in the process. She "weighed" the paper in her hand to support her claim (AM). Autumn, who had earlier asked Brianna why she was manipulating the paper, supported Brianna's conclusion about heaviness (IPE) after seeing the visible model.

Brianna's comments convinced the students to drop the idea that "heaviness" caused the book to fall faster and pursue other mechanisms for the phenomenon, in spite of the fact that the students had all agreed on the "heaviness" explanation the previous day. There are two possible reasons for the power of her argument. First, Julio simply stated that the crumpled paper's weight had changed, without backward or forward chaining from any other known properties of the entities. Brianna, in contrast, turned the class's attention to the only activity that could have caused any change in the paper's properties – the crumpling – and helped the other students recall that crumpling doesn't change an object's amount of "stuff." Second, Brianna's use of an animated model helps the students follow each step in her mechanism, thereby reducing the amount of cognitive work they have to do to understand her idea. Our understanding of the value of Brianna's reasoning emerges from the mechanistic coding scheme: Brianna supported her idea to the class by forward chaining from known activities and providing an animated model.

Recognizing Shifts between Levels of Coding

In addition to aligning with our intuitive impressions from the conversation, the mechanism coding scheme has also helped us recognize phenomena in the data that we might otherwise have missed. That, in the end, is our purpose with it: Having a systematic coding scheme allows us to establish target phenomena for our research, ultimately to support development of models of knowledge and reasoning.

Coding mechanistic reasoning for the entire conversation revealed patterns in the students' thinking: High level codes tended to cluster, a phenomenon that seems to recur in our data and that we can then try to explain (Hammer, Russ, Scherr & Mikeska, in press). The graphical display in Figure 2 shows the occurrence of mechanism codes (on the vertical axis) over time (indicated on the horizontal axis by transcript line number). A diamond indicates an analogy and an X indicates an animated model.

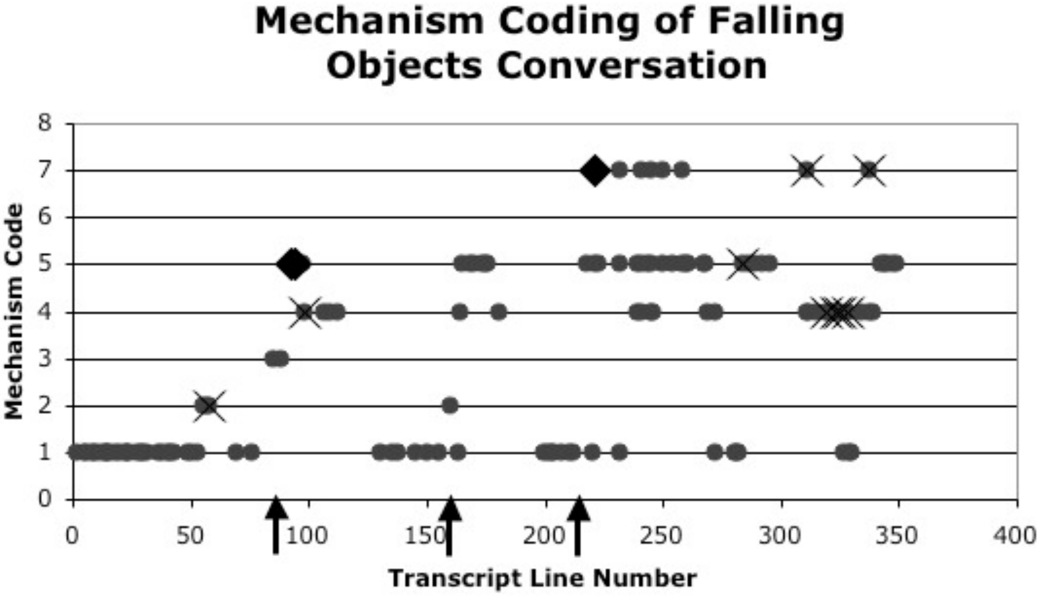

Figure 2: Mechanism coding of student conversation about falling objects. Arrows indicate apparent shifts in the conversation. The mechanism codes are as follows: (1) Describing Target Phenomenon, (2) Set-Up Conditions, (3) Identifying Entities, (4) Identifying Activities, (5) Identifying Properties of Entities, (6) Identifying Organization of Entities, (7) Chaining (Backward and Forward).

The graph shows that the pattern of codes shifts several times over the course of the conversation; we note three significant shifts with vertical arrows.

The first shift, at line 82, shows students transitioning between low-level codes to high-level codes. This transition corresponds to the point in the conversation when the students move from describing the target phenomenon in a "show-and-tell" manner to identifying entities, activities, and properties through analogies and animated models (from episode one to episode two in the above analysis). Line 82, interestingly, is the teacher's question: "Why do you think that is [that we all got different results]? Why did that happen? How could it be that we all got these different results?" After her question, intermediate mechanistic codes prevail for several minutes but do not progress to higher-level codes. The students then revert to the lowest level, describing the phenomenon, around line 130. We can make sense of why the students could not go further: The unfamiliarity of the entity they identified ("gravity") made identifying properties, set-up conditions, or organization of entities inaccessible.

The reasoning remains at a low level until the teacher again explicitly asks them to explain their results at line 175. The graph suggests that the students transition again into a higher level of sophistication. However, inspection of the transcript reveals that during this time, the students are joking about gravity being "tired" – engaging in a "fantasy mechanism" rather than a serious one. The mechanism coding does not distinguish the two, which highlights, for us, the importance of closely inspecting the transcript. It is interesting to observe that this particular episode of fantasy reasoning does not include analogies and animated models, which are common when these young students explain their understanding. The teacher recognizes that the students are being silly and attempts to move them out of this mode.

The next shift occurs around line 215 after several students have predicted that the book and the crumpled piece of paper will fall at the same time. The students quickly reach consensus and spontaneously jump to a higher level of sophistication (as described in episode three above). Identification of entities and their properties and activities is followed by attempts to causally connect them through chaining (*e.g.,* when Diamond says that crumpling the paper cannot cause a change in its heaviness). The students' tendency to alternate between levels 3 – 5 and level 7 suggests that codes 3 – 5 provide necessary building blocks for chaining, after which students look for new aspects of the mechanism to pursue. For example, though some students originally attribute the paper falling first to it being heavier (IPE, code 5), it is Brianna's attention to the crumpling (IA, code 4) that allows her to chain (C, code 7) that the property they identified cannot be relevant in this case. After that chaining eliminates the properties students were using in their explanations, the students automatically return to reasoning at mid-level codes by looking for other causal components of the situation (either IE, IA, or IPE). Diamond suggests that the shape of the paper (IPE) is potentially important because flat paper rocks back and forth (IA) on its way down but the book and crumpled paper do not. She explains:

> **Diamond:** 'Cause the piece of paper was balled up, it don't go like this no more (Shows a rocking motion with her right arm.)
>
> **Brianna:** No, yeah. It don't, yeah. It just drops, kind of like the booklet.

The students use the shape (IPE) and activity of rocking (IA) of the paper to reason as to why (C) the crumpled paper falls at the same speed as the book. The coding scheme helps identify these more subtle shifts in reasoning as well as larger transitions.

We can also begin to speculate about why those shifts might occur. For example, the initial transition from the lowest to the middle level codes is transitory; the students fall back into lower level quickly. This shift back to the lower level may result from students' unfamiliarity with the entities they are discussing (which prevents them from identifying properties or chaining to construct a complete mechanism for the phenomenon) or it may result from their disagreement over the target phenomenon for discussion. These possibilities give clues as to how the students may be viewing the purpose of the conversation, either as show-and-tell story time or a sense-making discussion.

When studying the episodic nature of the conversation, it is important to note that some of the same students who in one episode are reasoning at the lowest levels shift to higher levels in another episode. In that way, not only does the conversation transition among levels (as indicated by the graph), the individual students do as well. If we were to assess student abilities based only on one episode, we might obtain an impoverished view of their ability to reason mechanistically. Consider Alison as an example. In the first episode she helps lead the class in a less sophisticated, low-level show-and-tell conversation. However, in episode two she identifies entity properties and activities with analogies and animated models. Brianna is a more striking example. Like Alison, in the first episode Brianna engages in the show-and-tell conversation by unproblematically reporting her contradictory results (the lowest-level code, DTP). In contrast, during episode three Brianna engages in the highest level codes – chaining - to show other students that changes in weight cannot cause the phenomenon they observed.

By looking across episodes we discover that both students *can*, but do not always, reason in a sophisticated way. As such, it is not appropriate or necessary to teach them to reason mechanistically; instead they should be given opportunities to practice and refine the resources they already have (and use at some times) with subject matter that lends itself to mechanistic thinking. That practice will hopefully encourage them to use sophisticated mechanistic reasoning during inquiry when making sense of physical phenomenon so that episodes filled with high-level codes will become both more frequent and longer lasting.

Conclusion

In this chapter, the framework developed from accounts of professional science identifies corresponding mechanistic reasoning in first-graders and so identifies the beginnings of science in children's thinking. This case study adds to others by providing evidence that young children are capable of the kind of rich, theoretical reasoning often excluded from scientific inquiry based on developmental constraint arguments. In doing so, it "suggests higher ceilings [in the possibilities of young children's science instruction] than have previously been assumed" (Metz, 1995, p. 121). The analysis supports previous claims that students, even young children, arrive in our science classes with productive intellectual resources for scientific thinking (e.g. Hammer, 2004; Hammer & van Zee, 2006).

The analysis here also shows that children may only apply their resources for mechanistic thinking episodically and as such demonstrates some of the variability we expect from our manifold resources ontology (see discussion in chapter one). At some moments of the conversation, there is evidence of mechanistic reasoning up to and including *chaining*, "reasoning about one part of a mechanism on the basis of what is known or conjectured about other parts" (Darden, 2002, p. S362). At other moments, students do not even identify entities or activities that could participate in a mechanism. To judge students based on their performance in any one of those moments might misrepresent the breadth of their abilities. This finding supports arguments elsewhere that student thinking is variable with context (e.g. diSessa, 1993) and inappropriately characterized by developmental levels (e.g. Metz, 1995).

The mechanism framework also provides insight into the dynamics of this variability. Whether students transition into or out of mechanistic reasoning may depend on the entities and activities they have nominated.

Finally, the fact that the framework developed from Machamer, Darden, and Craver’s (2000) characterization of professional bioscientists successfully identifies aspects of mechanistic reasoning in young children has implications for studying student learning. It seems that an understanding of mature science can inform an understanding of nascent science. In later chapters the framework is also used to identify mechanistic reasoning in college and graduate physics students, indicating that it may provide one measure of student progress in learning science as they proceed through courses.

Chapter 5: Mechanistic Reasoning Independent of Canonical Correctness[10]

Introduction

Given its prominence in science reform, educators and researchers quite reasonably want to assess the quality of students' inquiry. However, for many of them, evaluating student inquiry equates to assessing whether the conceptual understanding that results from that inquiry is consistent with canonical knowledge of the field, i.e. whether the answer students arrive at is correct (e.g. Lee & Songer, 2003; Marx et al., 2004). For example, Marx et al. (2004) evaluate sixth grade students' learning in an inquiry-based curriculum with questions such as "Which substance occurs in the largest amount in 'clean' air?" and "Explain why it is easy to use a screwdriver to open a can of paint. Use the terms machine, force, and distance in your response" (p. 1076-1077). They also note that assessments of inquiry based on content (and experimental process skills) are ubiquitous in the science education research community. This commitment to assessing students against the canon of accepted science knowledge manifests itself in how teachers respond to incorrect comments, how educational researchers define their research questions and goals, and how policy makers design curriculum and standardized tests.

Despite this trend to formally assess student inquiry along conceptual measures, many educators would agree that having the right answer is not the only important part of inquiry. There are other aspects of inquiry that deserve careful attention. In particular,

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[10] This chapter is an extension of work published elsewhere in Russ, R. S. & Hutchison, P. (2006). *It's Okay to be Wrong: Recognizing Mechanistic Reasoning during Student Inquiry*. Proceedings from the 7th International Conference of the Learning Sciences.

many educators intuitively value student ideas that are mechanistic; there is something ‘good’ about mechanistic explanations (see chapter one). If a teacher hears two explanations, one that is mechanistic and one that is not, he will probably have a sense that the mechanistic one is better and more scientific in some way. In addition to this informal sense that educators have about the value of mechanistic reasoning, reasoning about mechanisms is also one of the primary ways that scientific knowledge is constructed (chapters two and three) and an integral part of how students make sense of novel phenomenon (chapters two, four, six, and seven). Inquiry surely has value beyond whether its products are correct when judged against the canon.

Consider also that within the practice of science itself, the work of scientists is valued regardless of whether or not it turns out to be right. The history of science is full of examples where eminent scientists arrived at conclusions later judged incorrect (Darden, 1998). For example, Isaac Newton formally proposed the Corpuscular Theory of Light in 1704.

> Luminous bodies emit corpuscules that are tiny point particles of light with no mass. The properties of light (as observed at that time) can be explained by applying Newton’s laws of motion developed for objects with mass to these corpuscules. Specifically, light reflection occurs in the same way balls bounce off walls: the surfaces exert a normal (contact) force in the opposite direction on the moving light particles, changing the direction of their acceleration. Light refracts at the boundary between materials because light particles are accelerated at different speeds in different materials.

There are two points worth noting about Newton's theory. First, at the time he presented it Newton's theory was not judged for "correctness" because there was no accepted answer with which to compare it. Instead, it was judged on whether or not it provided a logical, mechanistic picture of the physical world that accounted for all the evidence available to him at the time and made sense based on other experiences (in this case, experience with massive objects). Second, scientists now know that Newton's corpuscular theory does not correctly explain either the reflection or refraction of light; the wave nature of light is needed. However, both Newton and his theory are still valued for making scientific contributions to the study of light.

Bearing in mind Newton's theory, recall the explanation given by the Rick for why salt water has a higher boiling point than fresh water (Chin & Brown, 2000).

> Rick: Salt in it… makes the water thicker. And it kind of took more heat to melt the water that had salt in it… It [salt] kind of fills up a lot of empty spaces between the [water] molecules. And so the heat couldn't pass through it as fast as it did through the plain water. So it had to add more heat to break through the salt particles and heat up the water. (p. 122)

Rick does not give an entirely canonical answer; salt water actually takes longer to boil than fresh water because the salt molecules replace water molecules *on the surface* so that fewer water molecules can vaporize, making it take more heat for the vapor pressure of the water to equal the external pressure. However, he reasons mechanistically that the salt fills up the empty space between the water and thus prevents heat from getting to the water to heat it up. His explanation accounts for all the evidence available to him and makes sense based on other experiences: we can imagine some molecules blocking others from heat in the same way having more people in a room might block a person on one side from finding a person on the other. The nature of Rick’s sophisticated thinking during inquiry warrants attention even though his answer is wrong. As in this case, valuing mechanistic reasoning may involve valuing inquiry even when it leads to incorrect answers, in the same way that valuing Newton’s work means valuing it even when it was incorrect.

Educators who want to be aware of and promote mechanistic reasoning in their classrooms cannot reasonably limit assessment of student inquiry to conceptual correctness because such assessments miss the mark. Judging student work against the canon cannot capture the sophistication of mechanistic reasoning. For example, evaluating Newton and Rick based on how well their conceptual understanding aligns with canonical concepts misrepresents their inquiry by giving an impoverished view of good scientific inquiry that arrives at incorrect conclusions. Alternatively, such assessments might judge inquiry highly in instances when the students provided correct answers they do not understand. Such judgments assume (perhaps tacitly) that if students do inquiry well they’ll get the right answer. Good scientific inquiry does not guarantee true knowledge - either historically or in the classroom.

In this chapter, the framework for identifying mechanistic reasoning is used to reveal valuable aspects of student inquiry overlooked by current research that focuses on correctness. The coding scheme is applied to a discussion between second grade students about why empty juice boxes collapse when you suck on the straw; we find that it is possible to judge the quality of student mechanistic reasoning independent of their correctness. While traditional conceptual assessments may dismiss student conversations in which the correct canonical knowledge is not discussed, analysis with the mechanism coding shows students engaged in sophisticated mechanistic reasoning regardless of whether the concepts themselves are correct. Evidence from the transcript suggests that in overly attending to correctness, teachers may actually undermine their own objectives by pushing students out of a more sophisticated reasoning mode that would help them make sense of current and future inquiry.

Context for Analysis

In the discussion analyzed here, seven second-grade students talk with a science teaching specialist about why juice boxes collapse when you suck on the straw. This data was chosen for two reasons after initial observations revealed that the conversation is rife with both correct and incorrect student mechanistic explanations. First, application of the coding scheme helps check whether the mechanism framework can reliably identify quality student reasoning distinct from conceptual correctness. Second, although some educators may respond negatively to this conversation because students do not come to the correct answer, analysis using the mechanism coding scheme helps articulate other, perhaps more important, value of their inquiry.

The conversation takes place in a public elementary school in Montgomery County, Maryland. In addition to their regular science lessons with their classroom teacher, these students also met several Friday's throughout the year for 50-minute science enrichment sessions. As with the teacher in chapter four, this instructor participated in a project at the University of Maryland to develop materials for teacher education and help prospective and current elementary teachers gain experience in interpreting and assessing the substance of student reasoning (Hammer & van Zee, 2006).

Since he did not have to cover the standard county curriculum in this context, the teacher was free to choose topics based on what he thought would engage the students. The teacher chose to have students discuss collapsing juice boxes because he speculated the students would have productive intuitions about it based in their everyday experiences. In reflecting after the lesson, the teacher was pleased with the ideas the students generated and pursued in their conversation.

Synopsis of Classroom Inquiry

The teacher begins the discussion by giving the students full juice boxes and having them drink out all the juice. After the boxes are empty, the students observe that the sides of the box cave in when they suck on the straws. When the teacher asks them why that happens, several students reference the air inside the box. One student suggests that the air inside the box blows out on the sides of the box and the box caves in because there is less air inside. Another student suggests that the air outside the box pushes in on the sides of the box and when air inside is removed, the outside push crushes it. Other students present ideas similar to the two already given, either that air and juice inside the box push out to hold the box's shape, or that air outside forces the box in. One student combines these ideas; he suggests (correctly) that *both* the air inside and the air outside box push on the box, and their unequal pushing is what causes the box to cave in. After a few more student explanations corresponding to one of these three models, the teacher shifts the conversation by demonstrating the same effect using a shop vacuum/blower and a large orange juice carton. This analysis is focused on the time before the teacher demonstration. The full transcript of this discussion is found in Appendix C.

Mechanism Coding Inter-rater Reliability

The transcript of the class discussion was coded by P. Hutchison, another graduate student at the University of Maryland, and myself. Inter-rater reliability was evaluated along two dimensions. The first dimension (Data Identification) is a check on whether the researchers code the same conversational turns as examples of mechanistic reasoning. High inter-rater reliability, 93%, was obtained for Data Identification, which indicates the coding scheme is very reliable at recognizing statements that are relevant to mechanistic reasoning. The second dimension, Highest Coding, is a check for agreement on the highest code that the researchers assigned to each comment. This measure hopefully indicates whether the coding scheme reliably identifies the highest level of sophistication of each comment. This measure is important given that we are making claims about the overall sophistication of student reasoning. Our inter-rater reliability on this measure was 74% before discussion and 97% after. Our discussion revealed that low initial agreement did not result from difficulties with the coding scheme itself but was partly due to ambiguity in second graders' language. In addition, some discrepancies arose from different coding methodologies: one coder used adjacent lines from the transcript to interpret student meaning and the other coder interpreted each line individually. These two methods led to different interpretations of student meaning that were resolved with discussion. To avoid the same differences in future coding, we adopted the convention to use only previous and not later comments in interpretation of student meaning (see chapter two).

Student Mechanistic Explanations

During the discussion the students presented three possible explanations for the phenomenon - only one of which is correct when judged against the physics canon. The analysis below provides an account of those of the explanations including excerpts from the student discussion. These particular examples of dialog show how the mechanism framework can be used to reveal valuable aspects of student reasoning obscured by measures of conceptual correctness. They also show that two explanations, one correct and one incorrect, can have the same high level mechanistic sophistication.

Correct Explanation: An Imbalance of Pushes from Inside and Out

Only one student in the class gives a correct explanation for why the juice box caves in – noting that both the air inside and outside the box play an important role. He states an 'imbalance of pushes' model - air inside actively pushes to hold the sides out while the air outside pushes in. When air from the inside is removed, the amount of air (and thus the push) on the inside and outside are no longer equal, so the box collapses.

Hunter:	Um. What I was thinking was when it's empty there's air inside -
Teacher:	Okay.
Hunter:	- and if you suck up, and there's like air pushing on the sides. And there's air pushing on the inside, there's air pushing on the sides to keep them out. And outside, um there's air pushing on the outside. [?And it -]
Teacher:	Pushing. So the air outside is pushing which way?
Hunter:	Um it's, um the sides in.
Teacher:	Pushing the sides in. And then -

Hunter: And then [??when we took] some of the air out it won't be equal so, um, the sides start to [?cave/get] in.

Teacher: Equal. That sounds like a math term. What do you mean by that?

Hunter: Um.

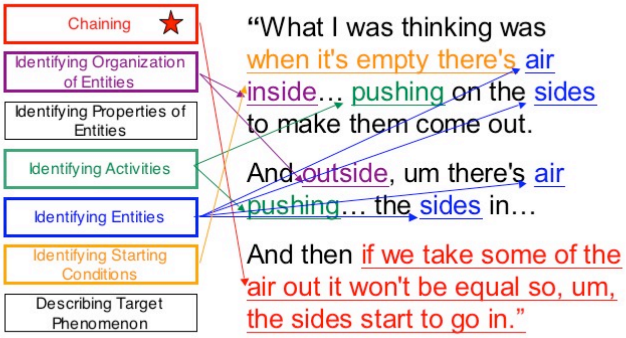
Teacher: What's not equal?

Hunter: They both um, the amount of air is the same.

Teacher: By the amount the same you mean on the inside and on the outside?

Hunter: Yeah.

The quality of Hunter's inquiry does not lie solely in the fact that he gives the correct answer. He does provide a correct explanation, but even more importantly he gives a mechanistic explanation. Figure 3 indicates some of the evidence of mechanistic reasoning in his explanation.[11]



"What I was thinking was when it's empty there's air inside… pushing on the sides to make them come out.

And outside, um there's air pushing… the sides in…

And then if we take some of the air out it won't be equal so, um, the sides start to go in."

Figure 3: The mechanistic coding of Hunter's explanation for the juice box collapsing. Hunter's redundant and teacher comments have been removed.

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[11] Figures 3, 4, and 5 in this chapter a best viewed in color.

Hunter begins by giving the starting conditions and entities that are important to his explanation of the phenomenon - the empty juice box begins filled with air. He also identifies where that air is located – inside the box - and what activities air engages in – pushing. In a similar way he describes another relevant entity, its location, and its activity – the air outside pushes the box in. Hunter then forward chains, laying out a causal sequence of events that follow from one another based on the entities, activities, and properties he has asserted – sucking on the straw removes air from inside the box, which causes an imbalance of the in and out pushes. Since the inward push is now greater the box caves in. This forward chaining provides evidence that Hunter is thinking mechanistically. To assess his response based solely on his conceptual understanding misses the sophistication of his reasoning.

Incorrect Explanation: A Push from Inside the Juice Box

Three of the students focus on the role of the air and/or juice inside the juice box. In one form of this ‘inside-pusher’ model, students suggest that the juice inside the box pushes out on all the sides of the box. Another student explains that the air inside the juice box actively blows out or pushes against the sides of the box, holding the box in its flat, “normal” shape. Thus whenever juice or air is removed from the box, there is no longer anything pushing from the inside to hold the box out, so the sides cave in. Some students articulate that the amount the sides of the box cave in is related to the amount of air left inside the box. While some of these students merely do not mention the air outside, others explicitly assert that air outside the box is either not present or not relevant to the box caving in.

For example, Erin explains her reasoning by discussing the role of the air inside the juice box.

Erin: I think because since you sucked out the air, it's like, it caves in because there's not any air so it has no, nothing's pushing it in from the inside to make it like [?flat] -

Teacher: Like this?

Erin: - like its normal shape. Yeah.

Teacher: Nothing’s inside there so -

Erin: There's not much, not as much is inside so it's, it, there's not mu, as much pushing out so it caves in.

Teacher: Oh. So you mean right now there's air in there pushing out to make it the box shape.

Erin: I think so.

Teacher: And then what happens when I suck? What's -

Erin: You take some of the air out so -

Teacher: - and so why should the sides. (Side comment to another student.) Why should the sides then cave in? I mean, is there anything pushing –

Erin: No –

Teacher: - the outside in?

Erin: - there's nothing pushing.

Teacher: There’s nothing pushing.

Erin: So when –

Teacher: Nothing pushing where, on the inside or the outside?

Erin: Inside.

Erin’s explanation of the phenomenon should not be disregarded solely because she lacks a complete conceptual understanding of air pressure. The mechanism framework comes to our aid in accounting for the value of her inquiry. Although Erin's answer is incomplete (she explicitly rejects the idea of the air outside pushing on the box), her reasoning is mechanistic. Figure 4 illustrates some of the evidence of that reasoning in her explanation.

Figure 4: The mechanistic coding of Erin's explanation for the juice box collapsing. Erin's redundant and teacher comments have been removed.

Erin begins by identifying the starting conditions – the sides of the box are in their "normal shape" and then you start sucking the air out. She then describes a relevant entity and its location/organization – the air inside the box – that pushes out (activity) on the sides holding the box in its starting conditions. Erin forward chains and claims that when some of the air that was pushing out on the box from the inside is removed, the box collapses. The inferences she makes in her forward chaining are all plausible based on her everyday experiences; for example she may have observed that balloons collapse when they are not filled with air or pillowcases collapse when the pillow inside is removed. It is her ability to forward chain from activities to entity properties using her intuitions that makes her explanation valuable even though it is incorrect. A conceptual assessment would give an impoverished view of the quality of Erin's inquiry.

Incorrect Explanation: A Push from Outside the Juice Box

Two students explain the collapsing juice box by appealing to the air outside the box; the outside air actively pushes in on the sides of the box at all times. In the most well articulated form of the 'outside-pusher' model, the air and juice inside the box play the role of passively resisting the outside push. Thus when the juice and air inside the box are removed, there is less resistance so the outside air can push the box more easily, causing it to cave in.

For example, Ben gives the following explanation for what makes the box collapse.

Ben: - The air pushing. [Pushes his hands forward in front of him.]

Teacher: Tell me w, which air. Where is the air that's pushing?

Ben: Outside. [Pushing in on the sides of his juice box with his hands.]

Teacher: Outside. And its pushing what?

Ben: Pushing the sides in. Because there's not much [?] -

…

Ben: - every time you drink it there's less, there's less stuff inside it.

…

Teacher: So there you talked about air, I think outside pushing.

Ben: Yeah pushing it. [Pushes in on the sides of his juice box.]

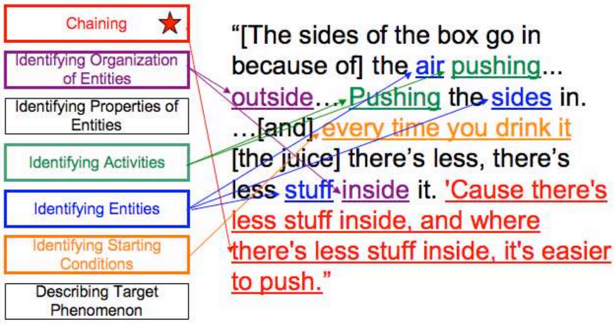
Teacher: Like you're doing it with your hands. But if I do it this way, [Sucks on his juice box.] you're saying that it's the air that's pushing on it.

Ben: Mmm-mmm.

Teacher: Why should it do that? Why is the air on the outside pushing?

Ben: 'Cause there's less stuff inside, and where there's less stuff inside, it's easier to push.

Ben does not give a completely correct answer to the question; he does not articulate that the air inside also actively pushes on the sides of the box. However, as with Erin there is a mechanistic sophistication in his argument. Figure 5 depicts some of the evidence of this sophistication.



"[The sides of the box go in because of] the air pushing... outside... Pushing the sides in. ...[and] every time you drink it [the juice] there's less, there's less stuff inside it. 'Cause there's less stuff inside, and where there's less stuff inside, it's easier to push."

Figure 5: The mechanistic coding of Ben's explanation for the juice box collapsing. Ben's redundant and teacher comments have been removed.

Ben first describes a relevant entity, its location/organization, and the activity it engages in – the air outside pushes the sides of the box in. He implicitly states the starting conditions of the box by explaining how they are changed when you drink from the straw – the box begins with "stuff" (entity) inside and that "stuff" (which he in other places identifies as air) resists the push from outside (entity property). Notice that Ben does not articulate an activity for the inside air; unlike Erin, the inside air does not actively participate in his mechanism. Ben forward chains from the entities and activities he has described – when some of the inside air is removed, the outside air can more easily collapse the box because its push is not encountering as much resistance. His explanation makes sense based on his experiences (for example that its easier to push an empty box than one filled with toys). Analyzing Ben’s explanation for mechanistic reasoning reveals sophistication missed when it is labeled as conceptually incomplete or incorrect.

Teacher Attention and Instructional Interpretation

Analyzing student explanations for evidence of mechanistic reasoning shows that Erin and Ben’s incorrect explanations are equivalent to Hunter’s correct one along that measure. Comparing Figures 3, 4, and 5 reveals striking similarity in the coding of each explanation. In addition to the lower codes, each explanation also contains evidence of sophisticated chaining.

Whether teachers attend predominantly to mechanistic reasoning or instead to conceptual correctness has a significant impact on how they interpret and respond to student ideas. Below are possible responses to Erin and Ben’s incorrect but mechanistic explanations from each of these perspectives. These different instructional interpretations beg the question of whether canonical correctness or mechanistic reasoning is the more appropriate instructional agenda for these second graders (and for science students more broadly). We use data from the class to suggest some negative consequences of focusing too heavily on canonical correctness.

Possible Responses to Incorrect Explanations

For some educators the *primary* target for science is the learning of conceptual knowledge. Other skills may be important in achieving the goal (e.g. experimentation, reasoning, argumentation), but their role is largely one of support. Hammer (1995) describes this stance as:

> *traditional content-oriented*, because it assesses student contributions with respect to what is traditionally seen as the content of the course. Traditional content-oriented evaluation pertains to the correctness of students' reasoning vis-à-vis an accepted body of knowledge. (p. 403, emphasis his)

A content-oriented teacher whose main concern is whether students obtain a canonical understanding of air pressure would interpret Erin and Ben's explanations as close, but not quite complete. A likely reaction would be to start thinking about possible instructional moves to get the students to the right answer before the end of the lesson. The teacher might respond to Erin and Ben by saying "You're almost there!" and then help them identify the conceptual pieces their explanations are missing. For example, to Erin he might ask whether air exists all around the room and if so, what that air does near the box. Were Erin and Ben to turn in their explanations at the end of class, such a teacher might give them partial credit for their "half-right" explanations that are well reasoned, but would certainly deduct points for their lack of correct physics knowledge. Although the teacher might value and encourage their mechanistic reasoning, it is valuable only insofar as it contributes to a correct answer. Attention to correctness prompts teachers to respond to incorrect students comments with specific conceptual feedback rather than more general feedback about the quality of their reasoning.

A different primary target for student inquiry is the development of sophisticated mechanistic reasoning abilities. While conceptual correctness may be a goal of instruction, it is not necessarily one that needs to be reached immediately. A teacher with this perspective might encourage students to spend much of their time reasoning through ideas until they make sense, even if it means the students leave that class period still not understanding correct physics. From this perspective, a teacher might interpret Erin and Ben's explanations as right on target because they are engaged in high-level mechanistic reasoning. A likely reaction might be to think about ways to help the students recognize the sophistication of kind of thing they are doing. The teacher might respond to Erin and Ben by saying "You've got a great idea. That makes sense!" For example, he might give Ben an example from everyday life of pushing getting easier with less resistance (say pushing a small or a large person on a swing) and ask whether its similar to the air pushing on the full or empty juice box. This intervention is less explicit than targeted conceptual feedback. Instead, it sends Ben the tacit epistemological message that drawing on personal experiences with mechanisms is an appropriate thing to do in science class. Such a teacher values and encourages mechanistic reasoning in and of itself as a productive means to produce and evaluate science knowledge regardless of whether that knowledge is canonically correct. Attention to mechanistic reasoning prompts teachers to respond to incorrect student comments in the same way he responds to correct ones, by providing feedback about whether they are engaging in behavior that will help them make sense of the concepts. Teachers with this perspective might only provide conceptual feedback *after* (if at all) the students have developed a stable mechanistic approach to science.

Pitfalls of Primarily Attending to Conceptual Correctness

It is important to notice that the direction of primary teacher attention leads to dramatically different interpretations of Erin and Ben's incorrect explanations. For a teacher focused on canonical correctness, Erin and Ben have *almost* reached the goal but need to be pushed a little further conceptually. In contrast, for a teacher focused on mechanistic reasoning Erin and Ben, like Hunter, have *already* reached a major goal and only need to be shown that their reasoning is productive and desirable for science learning. These different interpretations influence how teachers respond (either positively or negatively) to students, which in turn influences (either positively or negatively) how students engage in inquiry.

There may be significant negative consequences on both student participation and epistemology if teachers allow their desire for correctness to precede their desire for quality mechanistic reasoning. We find evidence of this in the air pressure discussion. The teacher's primary focus on correctness leads him to repeatedly push the students to give the correct answer even when the students have developed a reasonable wrong explanation that is plausible and makes sense to them. This instructional move has an immediate impact on how one of the students engages in inquiry in the moment and also sends the student an inaccurate message about productive approaches to learning science.

Recall the sophisticated mechanistic explanation Erin gives when the teacher asks why the juice box collapses when you suck on the straw.

Erin: I think because since you sucked out the air, it's like, it caves in because there's not any air so it has no, nothing's pushing it in from the inside to make it like [?flat] -

Teacher: Like this?

Erin: - like its normal shape. Yeah.

Teacher: Nothing’s inside there so -

Erin: There's not much, not as much is inside so it's, it, there's not mu, as much pushing out so it caves in.

Teacher: Oh. So you mean right now there's air in there pushing out to make it the box shape.

Erin: I think so.

Teacher: And then what happens when I suck? What's -

Erin: You take some of the air out so -

Teacher: - and so why should the sides. (Side comment to another student.) Why should the sides then cave in? I mean, is there anything pushing –

Erin: No –

Teacher: - the outside in?

Erin: - there's nothing pushing.

Teacher: There’s nothing pushing.

Erin: So when –

Teacher: Nothing pushing where, on the inside or the outside?

Erin: Inside.

Erin responds to the teacher’s request with a well-articulated inside-pusher explanation that is mechanistic. Erin continues to reason mechanistically about ideas that make sense to her even after the teacher hints at the correct answer by asking “Is there anything pushing the outside in?” The teacher then asks her to explain more fully and his doing so produces a startling transition in her approach to the task.

Teacher: So why, if there's nothing pushing on the inside, why should the outsi, why should the box's sides cave in? [3 second pause] (Unrelated comment to another student)

Erin: 'Cause uh, there's not as much air in [this/it?].

Teacher: Okay, so there's less air in the inside that way.

Erin: Yeah.

Teacher: But I don't understand why that makes the sides have to go in. [5 second pause]

Erin: Maybe its pressure I don't know.

Teacher: What's that? Pressure?

Erin: It's something that's hard to explain. Um. [4 second pause] It's something that's [6 second pause] like, it's hard to explain.

Teacher: Okay. Let's try, as a group and individually.

What is startling about this episode is the change in Erin's reasoning from her previous mechanistic explanation. The first time the teacher asks for clarification, Erin responds with a meaningful restatement of her mechanism. Erin reads his question as a request for a causal story and responds accordingly; she is still trying to makes sense of the situation. However, the second time he asks, Erin spends five seconds considering his question before changing both her response and the type of response. Instead of continuing with her mechanistic reasoning, she responds to the teacher's repeated question by adding pressure to her explanation in what seems to be an attempt to satisfy him. The instructional push for correctness causes Erin to shift from reasoning mechanistically with entities and activities that make sense to her (air and pushing) to invoking technical vocabulary she does not understand (pressure). Erin's suggestion of a new entity (pressure) is not followed by any further evidence of mechanistic thinking such as identifying entity properties or organization, activities, or chaining. Her more productive reasoning strategies are suppressed in the moment by the need for conceptual correctness.[12]

Following Erin's introduction of pressure, the teacher turns the conversation away from making sense of how pressure fits into her previous mechanistic story and towards defining the term pressure "as a group and individually." In doing so, he may tacitly (and inadvertently) confirm Erin's suspicion that correct vocabulary was what he wanted. We do not claim that the teacher is explicitly looking for scientific vocabulary; he may only be searching for a correct answer, which in Erin's case manifests itself as terminology. Instead, we suggest that Erin may interpret his question and response in that way. The teacher's response to her pressure idea sends Erin the epistemological message that inquiry is about producing correct, scientific-sounding answers rather than about constructing causal mechanistic accounts for phenomenon. This experience may inappropriately teach Erin that mechanistic reasoning is neither appropriate nor valuable for science. As such, she may be less likely to engage in it when she is asked to learn scientific concepts in the future.

Interventions such as this one that are driven primarily by a desire for students to learn the right answer might also ultimately damage those conceptual goals. As Hammer (1995) describes:

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[12] It is possible that the teacher is only pushing Erin in this way because he thinks her sophisticated reasoning indicates she is prepared to go farther with her explanation. However, the result remains that his questions pushed Erin out of a (fairly stable) mechanistic reasoning mode.

> Instructors may too quickly undermine their own objectives for students understanding by insisting too quickly on correctness… Students may learn to produce correct statements without developing understanding. (p. 427)

If students are pushed too quickly toward a correct answer that does not make sense to them over an incorrect answer that does make sense to them, they may accept that correct statement without attempting to understand it. In the air pressure discussion, the teacher's focus on achieving complete conceptual correctness forces Erin out of a productive reasoning mode that would help her make sense of that correct knowledge. In addition to suppressing mechanistic reasoning in this episode, his attention to correct vocabulary may also discourage Erin from engaging in reasoning in future inquiry that would help her construct *meaningful* science knowledge. In allowing their desire for correctness to overcome their desire for quality reasoning, teachers may lose access to the very reasoning that would support an understanding of correct canonical concepts.

Discussion: Mechanistic Reasoning as an Appropriate Instructional Target

Analysis of the air pressure discussion demonstrates that the mechanism framework can be used to evaluate student inquiry independent of whether the products of that inquiry are correct. As such, the framework helps to more rigorously define an instructional target that teachers might want to pursue; just as canonical correctness has been easy to assess because it is well defined, assessments of mechanistic reasoning may now be more accessible. In addition, our assessment of the three explanations identifies similar value in all of the students' reasoning, despite the fact that two are wrong and the other is right. Assessing their mechanistic reasoning allows us to observe student sophistication in areas that the history and philosophy of science have shown to be valuable for understanding science but are obscured by traditional measures of conceptual correctness.

Like the teacher in this discussion, educators are often faced with incorrect explanations during inquiry. How teachers respond to those explanations depends on their primary instructional agenda for the class. For a teacher focused on correctness, Erin and Ben have not yet met the goal for the discussion (a balance of pushes model of the juice box phenomenon) and thus need more conceptual guidance. For a teacher focused on mechanistic reasoning, Erin and Ben have met an important goal (sophisticated mechanistic reasoning) and thus should be helped to recognize the value of that approach to inquiry. Although the teacher in this classroom might see value in Erin and Ben’s reasoning, there is evidence that he makes the former interpretation. The analysis suggest that if educators truly want to promote mechanistic reasoning as a productive way to construct scientific knowledge, they may ultimately be required to value inquiry that leads to sophisticated, mechanistic, but incorrect answers.

Close analysis of the transcript reveals some possible pitfalls of attending too heavily or pushing too quickly for complete conceptual understanding. Repeatedly pushing students who articulate mechanistically plausible but incorrect explanations towards the right answer may in turn push students out of a productive mechanistic reasoning mode. It may also send students the message that such reasoning is inappropriate for scientific inquiry. In doing so, teachers who focus on correctness may ultimately suppress their students’ abilities to understand and make sense of the canonical knowledge teachers rightly want them to have.

We assert that mechanistic reasoning is an appropriate instructional target for these second graders. We suggest this not only because of the negative consequences of attending primarily to correctness presented in this chapter, but also because we suspect more generally that mechanistic reasoning is the kind of thinking that contributes to the progress of science. Forward and backward chaining allows scientists (and students) to assess hypotheses by pursuing the implications of an idea to a place where they can be empirically tested (see chapter five). Similarly, it may help students trace and evaluate the individual steps of rival hypotheses to identify inappropriate conclusions and ultimately decide among them (also chapter five). Finally, its reliance on physical intuition encourages students to search for explanations that are plausible when judged against their knowledge from everyday experience.

The argument presented in this chapter may be easy to agree with for these young children: it is okay to primarily value Erin and Ben's reasoning because it is okay if they leave their second grade class not knowing about air pressure. However, we would like to at least suggest that mechanistic reasoning is also an appropriate instructional target for students in high school and college. That is, we suggest that sophisticated mechanistic reasoning should be an objective of inquiry in its own right, rather than merely a method for learning correct content. This view aligns with one presented by May, Hammer, and Roy (2006) with regards to analogical reasoning. Placing mechanistic (or analogical) reasoning as a stand-alone instructional target stands in opposition to the view that "there is no value to student inquiry that diverges from those [canonically correct] concepts, except in so far as it exposes incorrect thinking that instruction should address" (May et al., 2006, p. 328).

In contrast to the above view, we suggest that to truly value mechanistic reasoning as a productive approach to science, it must be pursued even if it leads to incorrect answers. Although we as scientists and educators know that such reasoning supports meaningful science learning, many students come to our classrooms still not believing that such reasoning is an important part of science and scientific inquiry. These students may fail to learn appropriate ways to construct meaningful scientific knowledge if we continue to send them the message, either explicitly or tacitly through our lectures or grading, that it is less important to reason mechanistically and make sense of phenomenon than it is to get the right answer. We need to help students establish and maintain a productive stance towards science knowledge that includes the expectation that mechanistic reasoning will support their understanding. Once that foundation is established, they will be better prepared for us to help them learn canonically correct content.

Chapter 6: Mechanistic Reasoning with Informal Empirical Evidence

Introduction

Within the current practices of education, scientific inquiry is defined in a highly empirical way. Science standards and classroom teachers promote investigations in which students ask testable questions, design formal experiments, and collect and analyze data from dependent, independent, and controlling variables (e.g. AAAS, 1990; MCPS, 2001; NRC, 1996; Windschitl, 2004). Research into both student and scientist inquiry skills centers on the ability to correctly control variables and accept/reject hypotheses based on purposefully accumulated empirical results (e.g. Chinn & Brewer, 1998; Kuhn, 1989; Roth & Roychoudhury, 1993).

Although controlled experimentation is a valuable aspect of science learning, it is inappropriate to assume that scientists or students can only do quality inquiry when they are engaged in or working towards formal investigations. In fact, there are many examples in the literature to the contrary (e.g. Hammer & van Zee, 2006; Rosenberg, Hammer, & Phelan, 2006). Consider the following excerpt from an introductory college course in which students try to develop a model for static electricity. After discussing various objects that charge one another, they try to figure out how rubbing objects together creates charge.

Claire: Like the actual electrons leave one object and go to another one

John: Right. Right. And I think its just, its due to like them getting excited, you know what I'm saying.

Claire: Yeah.

John: Like they'll get excited so they'll jump up and [moving his hand up step levels) 'Cause they need ener, it takes energy for them to just transfer, you know.

Claire: To go.

John: So they'll get excited and they'll go.

…

Claire: Yeah. You create energy [by rubbing] and that energy is used to excite the electrons and allow them to like transfer to the other one.

In this episode Claire and John do not identify variables to control or analyze trends in a set of data. Instead, they use anecdotal evidence from observations and prior knowledge from other classes (energy levels from chemistry) to think about how charging by contact might work. Even though the students are not designing or performing a controlled experiment, many science educators would likely agree that Claire and John are having a valuable conversation that will contribute to their understanding of electrostatics. Surely this kind of exploration ought to be included in our conceptions of scientific inquiry so that students (and educators) will recognize such discussions as appropriate and productive ways to construct science knowledge.

This chapter attempts to more precisely describe the nature of some informal explorations that prove valuable in a particular episode of scientific inquiry. It begins with a review of the argument laid out in chapter two for including mechanistic reasoning in inquiry. The mechanism framework is used to explore how the above group of students uses experiential observations to construct a mechanism for electrostatic phenomena. Several relationships between mechanistic reasoning and informal empirical results are identified in which each one informs the other as students move fluidly between them. Some strengths and weaknesses of each relationship are described.

We do not claim that the relationships identified here are prototypical; we do not suggest that they will be present in all inquiry or that they should be. We only present them as possibilities for the kind of thing that can happen when students are allowed to engage in inquiry apart from controlled experimentation. Analyzing the ways in which students' experiential data contribute to their mechanistic understanding of in phenomena in this case provides insight into how this less formal aspect of inquiry may proceed productively more generally.

Inquiry as more than Controlled Experimentation

The empiricist tradition for inquiry may be grounded in an interpretation of Piaget's levels of reasoning that limits young students to concrete operational thought (and thus physical experimentation) to the exclusion of abstract thinking. It may also grow out of the Humean ideal of assessing causality through the theory-independent and domain-general rules of data covariation. Whatever its source, formal empirical investigation is a pervasive focus in current conceptions of scientific inquiry. By ascribing to these characterizations, educators tacitly or explicitly imply that theoretical reasoning about mechanisms is either beyond the reach of school children or inappropriate for science. Such a depiction of scientific inquiry is both incomplete and distorted in comparison to student abilities and the work of practicing scientists (Koslowski, 1996).

To mandate that inquiry consist solely or even mostly of "well designed investigations" (MCPS, 2001) gives an impoverished view of student abilities because it places too much emphasis on the logic of controlling variables during formal experiments. There is evidence not only that students can reason about mechanisms for phenomena but also that they do so spontaneously and from a very young age (e.g. Hammer, 2004; Metz, 1991; Piaget, 1927). By systematically requiring students to approach inquiry from the perspective of conducting experiments, we run the risk of disengaging their natural sense of mechanism built up from everyday experiences (diSessa, 1993) in favor of engaging less organic knowledge about the logical structure of covariation. We should instead encourage students to also tap their existing “rich stores of causal intuitions” (Hammer, 1995, p. 422) about mechanisms that describe the processes underlying phenomena (Abrams & Southerland, 2001; Koslowski, 1996; Metz, 1991; Schauble, 1996; White, 1993).

In addition, formal experimentation without mechanism gives an incomplete representation of professional science. The search for mechanisms for phenomena is central to science as a whole and the work of individual scientists (e.g. Machamer, Darden, & Craver, 2000; Nersessian, 1992; Westfall, 1978). Far from being illegitimate sources of evidence that bias data analysis (Kuhn, 1989), considerations of mechanism help decide which experiments to plan, which variables to control, and how to interpret anomalous data (Koslowski, 1996; Schauble, 1996). It is not merely reasonable for inquiry to include mechanistic reasoning from the perspective of student abilities; it is essential for constructing and analyzing formal controlled experiments in science.

Defining inquiry as a theory- (or mechanism-) independent process also distorts the nature of science by placing undue importance on hypothesis testing – using purposefully collected empirical evidence to make logical conclusions. It gives the impression that the primary activity of science is performing controlled experiments in which the question, hypothesis, and relevant variables are already known or easily found. Focusing on formal experimentation leaves out the “creative speculation” (Hodson, 1988) or “messing about” (Hawkins, 1974) that occurs when students and scientists first start thinking about a new phenomenon. Part of science involves tossing around ideas and considering familiar anecdotal evidence that never makes it far enough to be tested more rigorously by the standards defined in classrooms (Hammer, 2004). Klahr and Dunbar (1988) describe such time as hypothesis generation, in contrast to hypothesis testing, that is crucial to scientific discovery. If we want to give a more accurate view of science, the phase *preceeding* hypothesis testing must be acknowledged as part of inquiry.

Context for Analysis

We use a conversation among a group of four college students about electrostatics as a context for observing the relationship between mechanistic reasoning and experiential data outside hypothesis testing. These students are enrolled in the second semester (electricity and magnetism) of a reformed algebra-based introductory physics course taught by a physics education researcher at the University of Maryland. They attend three fifty-minute lectures each week with approximately 200 other students, most of whom are junior and senior health and life science majors. In addition each week there is a required two-hour laboratory and a one-hour session of tutorial that serves 20-24 students per section. The tutorials are conceptual worksheets, based on the model pioneered by the Physics Education Group at the University of Washington, in which students work on in small groups with limited guidance from instructors. As part of a larger project to reform this course (NSF REC-0087519), the Physics Education Research

Group at the University of Maryland redesigned these tutorials to have an epistemological focus; that is, they encourage students to reflect not only on physics content knowledge but also on the reasoning strategies used in constructing that knowledge.

The conversation analyzed here comes from one group of four students working on a tutorial in the third week of the semester. This particular tutorial focuses on helping students develop a model for static electricity from their own experiences. A copy of the tutorial can be found in Appendix D. The data was chosen for two reasons. First, tutorials (in general but for this student group in particular) were known to provoke thoughtful discussions where the students attempted to make sense of unfamiliar phenomena. Second, we suspected that the physics of electrostatics would lend itself to discussions of mechanism. An initial viewing of the data confirmed that it was mechanistically rich. The excerpts below all come from the first half of the tutorial in which students discuss charging by contact. Although the teaching assistants interact with the students several times during the hour, the conversation analyzed here occurs when the group is working on its own.

The following is a synopsis of their discussion. The students begin the tutorial by observing whether or not static electricity is created when various objects are rubbed together: two foam plates, a foam plate and a cloth, a foam plate and a sweater, or two hands. After making these observations and recalling their everyday experiences with static electricity, the students spontaneously discuss *why* some pairs of objects charge and others do not. They come up with several possible explanations, none of which seem to account for all of their experiential data. In particular, one observation they have trouble reconciling involves two pieces of scotch tape that are placed one on top of the other on a table so that the sticky side of one is touching the slick side of the other (Figure 6).

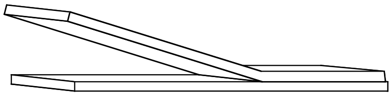

Figure 6

During lecture and again in tutorial, students observe that the two pieces of tape attract one another when they are pulled apart. The students return to this phenomenon repeatedly. (In the excerpts below they refer to the phenomenon as "the tape.") After discussion with the teaching assistant, the students decide that the two objects must be different materials (as Claire says, "provide two different environments for the electrons") in order to produce charge. In addition, they describe that electrons jumping from one object to the other create sparks and a resultant charge. Appendix E is the transcript of the group's discussion during tutorial.

Coding for Mechanistic Reasoning and Informal Empirical Evidence

As a first pass at analyzing the small group discussion of electrostatics, another researcher (R. Scherr) and I coded the transcript line-by-line using the mechanism coding scheme. Independently of the mechanism coding, the transcript was also coded for comments when students cited informal evidence. We counted as evidence any time a student referenced a specific observable phenomenon regardless of whether they recalled it from their everyday experiences outside class or constructed it during tutorial.

Overlaying these two codings on the same graph (Figure 7) allows us to see whether students used informal observations and mechanistic reasoning together.

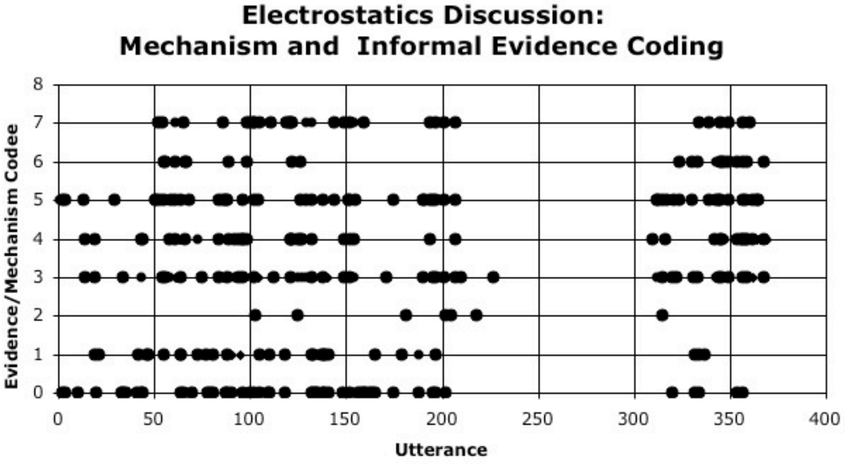

Figure 7: Graph of student conversation about electrostatics. The mechanism codes are as follows: (1) Describing Target Phenomenon, (2) Set-Up Conditions, (3) Identifying Entities, (4) Identifying Activities, (5) Identifying Properties of Entities, (6) Identifying Organization of Entities, (7) Chaining (Backward and Forward). The (0) code indicates moments when informal evidence was cited. Utterances 230-310 were not coded because the teaching assistant was present and guiding much of the conversation.

The graph indicates that during this discussion students used all levels of mechanistic reasoning along with informal empirical results. The mechanism and evidence codes often appear nearly simultaneously indicating that the students quickly flip back and forth between the two. Each of the short excerpts presented below in more detail exemplifies this trend. This fluid movement stands in contrast to what we might expect from even the best controlled experimentation in classrooms where students begin with a theory or mechanism that helps them to make a hypothesis, then collect data, and finally return to their initial theory to explain the data. In much of classroom hypothesis testing, theory and evidence are used separately; students are supposed to spend time thinking about theory and then set theory aside to think about evidence collection. Instead, in this conversation we see students theoretically reasoning about mechanisms in one comment and drawing on experiential data the next. This fluid movement suggests that traditional conceptions of the relationship between theory and evidence may misrepresent how students can engage in inquiry. These students do not seem to be engaging in theorizing and experimentation as separate activities. Instead, it may be more appropriate to think about them as drawing on both theory and evidence together to support the larger activity of making sense of a phenomenon.

The graph does not indicate *how* students use mechanistic reasoning to inform informal empirical results (or vice-versa). It is too coarse a tool for understanding the nature of the relationship between these two. In addition to coding the content of each student comment, below we also make sense of the comments by organizing them into a larger narrative story.[13]

Relationships Between Mechanistic Reasoning and Informal Empirical Evidence

The goal of analyzing this data is to articulate more precisely how "messing about" (Hawkins, 1974) with anecdotal observations might productively inform student reasoning about novel physical phenomena. To do so, we highlight several episodes

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[13] This follows the general methodology outlined in chapter three.

from the discussion in which students use informal empirical evidence in conjunction with various levels of mechanistic reasoning.

Each section below begins by describing a relationship between mechanistic reasoning and empirical results that has been observed in this student discourse as well as research literature. Following that general discussion, we present episodes from the tutorial in which students use each relationship. The analysis, however, did not proceed by first identifying relationships in the literature and then searching for them in the transcript. Instead, the initial coding of the data revealed several moments where mechanism and informal empirical results seemed to inform one another and thus nominated possible relationships. Attempts to more carefully describe those moments led to the articulation of relationships that were later found to be supported in research literature. Do not be misled by the description in each section: we did not decide a priori what relationships were valuable for inquiry and then search the data for them; the relationships emerged organically from the data.

Below we describe four relationships between mechanistic reasoning and empirical results evident in the electrostatics tutorial discussion. They are:

- Empirical results prompt mechanistic questions
- Inducing parts of a mechanism from empirical results
- Reconciling multiple empirical results to elaborate the underlying mechanism
- Constructing empirical tests to flesh out mechanisms

Empirical Results Prompt Mechanistic Questions

When students spend time “messing about” with a new phenomenon, they are likely to observe things that do not make sense to them. As science educators, we might hope that students’ uneasiness or confusion would prompt them to search for a mechanistic explanation for the results. People often formulate “why” questions from informal evidence, both in everyday life and in professional science practice. Hammer (2004) gives an anecdote from a time when he and his son saw a drawing that was taped to the wall fall to the floor. He explains how “We laughed, asked each other “why did that happen?’ and started to talk about possible explanations” (Hammer, 2004, p 281). He parallels this activity with Jocelyn Bell’s discovery of pulsars in which an unexpected observation of a regular radio signal caused her to wonder what was causing it. We have all experienced our own falling drawing or pulsar that has caused us to stop and question what happened. A desire to understand experience can lead us (and students) to ask mechanistic questions during inquiry.

Early in the electrostatics tutorial, students observe that rubbing a foam plate with a cloth creates static but rubbing two hands together does not. Below is the students’ immediate response to those observations (utterances 52 – 57).

Audrey: So why, I don’t get this. What’s the rational explanation for why there’s no sparks between our hands. Is it ‘cause they’re moist?
John: Because -
Claire: Because of moisture.
John: - there’s so much moisture in the air and its a conductor so…
Claire: The air and in your skin. It’s mostly in your skin.
Claire: [To Audrey] But why does, is it just moisture?

Audrey's observation of these two contrasting results prompts her to seek "the rational explanation" for the phenomenon. She both expects that an underlying mechanism exists and wants to know it. Her next question about moisture gives a further indication as to the kind of explanation she wants. She is not looking for a teleological answer such as "hands just don't naturally spark" or a magical one such as "fairies block sparks from building up." Instead, she wants a explanation involving physical causes – a mechanism – and offers moisture as one possible relevant entity in that mechanism.

After a brief discussion in which she contributes several ideas, Claire remains unsatisfied that moisture can account for the observation and asks another mechanistic question. She seems to want to know why or how moisture by itself can affect the mechanism for static electricity. Instead of just setting aside the hand observation as a fluke or automatically accepting it, Audrey and Claire explicitly request a mechanistic explanation to account for the data.

Students continue to ask mechanistic questions such as these throughout the tutorial as they make more observations. For example, John later asks (utterance 86):

> **John:** But why, why wouldn't you get two charges on your hands if you can get two different charges on other things?

Again, he has observed that some objects can be rubbed together to create static but two hands cannot. He wants to know why the mechanism works for some situations but not others. He is implicitly asking what set-up conditions, entities, and activities are required for the static electricity mechanism to run.

The tutorial later prompts students to “mess about” with two foam plates. They observe that two plates do not charge even though a plate rubbed with a cloth does. This result prompts the following “why” questions (utterances 131 - 132).

John: Yeah I don’t see why -

Claire: Why if you rub the plates aren’t they excite, like, if you rub things together we say that electrons get excited and whatever a charge. But like, why wouldn’t it work with plates?

The informal, uncontrolled observation that two foam plates do not charge one another prompts John and Claire to again ask about the underlying mechanism. Claire suggests that the parts of the mechanism they have discussed, *i.e.*, electrons (entities) getting excited (activity), are insufficient to account for this new result. Further pieces of the mechanism are required.

The tutorial does not directly ask the students any of these questions, although the tutorial authors might hope such questions come up. The students spontaneously asked these questions about the underlying mechanism of each other in response to their observations. The informal empirical results themselves prompted the kind of reasoning and discussion about mechanism that many data analysis sections of traditional controlled experimentation labs attempt to foster.

Inducing Parts of a Mechanism from Empirical Results

There are times when a new physical situation appears so disjoint from previous experience and current understanding that students may initially feel unable to propose a possible mechanism. As one way of making progress in understanding what causes the phenomenon, students might consider various examples of it and try to identify commonalities. Klahr and Dunbar (1988) observed students using this strategy in trying to discover how an unknown device works. They describe the strategy as a two-step process of inducing a hypothesis frame from a series of outcomes: "The first subprocess in INDUCE FRAME generates an outcome, and the second process generalizes of the results of that (and other) outcomes to produce a frame [hypothesis]" (p. 33). Elements or properties that are similar across a variety of different cases may indicate important parts of the mechanism. In this unidirectional relationship between informal empirical results and mechanistic reasoning, students use the former to identify possible pieces of the latter.

Near the start of this tutorial, the students are faced with the task of constructing a rule for when static electricity occurs. They are not yet sure of the mechanism that causes static electricity, but they are familiar with several examples of it. In the excerpt below (utterances 138 - 152), students use those examples as a basis for their discussion. The focus of the analysis is on the italicized utterances, but the entire episode is presented for context.

John: *Maybe it has to be two different objects. 'Cause its balloon to head, cloth to plate.*

Claire: *But tape to tape remember?*

John: But it was on a desk.

Claire: I'm pretty sure if you just took the tape [Laughter as she pulls her hand apart like she's holding tape.] The tape desk interaction. [Laughter.]

Audrey: The stupid tape.

John: Could be.

Audrey: *Well we didn't rub the tape together we just stuck it together and pulled it apart. 'Cause like Saran Wrap, that already has like static in it.*

Claire: *From rubbing against itself when you pull it.*

Erin: So.

John: *Maybe foam's not a good conductor. [Putting finger quotes around conductor.] Or Styrofoam.*

Claire: *No because why is, why is it a good conductor when you rub it with something else?*

John: Mmmm. [Shrugs his shoulders.]

In this episode, the students use anecdotal evidence to generate ideas for properties that may be relevant to the mechanism. They cite the balloon/plate and cloth/plate interactions to support the entity property of *different materials*, tape/tape interaction and Saran Wrap against itself to support the activity of *rubbing*, and plate/plate lack of interaction for the property of *conductors*. The students have ample experience with static electricity to draw on here; when one property seems not to fit with some evidence (i.e. *different materials* does not seem to apply to the tape case) they have a store of many other observations to generate new properties. By surveying informal empirical results, students have immediate access to relevant phenomena that give clues to parts of the unfamiliar mechanism of static electricity. "Messing about" can be productive for identifying those parts.

Although the students successfully use their observations to generate possible parts of the mechanism, different observations generate different possibilities. John uses some evidence to support *different materials*, then Audrey draws on other evidence when proposing *rubbing*, and finally John tries again with still more evidence in suggesting *conductor-ism*. In this episode, there are no high-level mechanistic codes (*e.g.,* chaining); the students do not move beyond levels 4 (Identifying Activities) and 5 (Identifying Properties of Entities). The students do not attempt to reconcile or connect the different properties but instead set aside each one when faced with another one. Even Claire's direct objection that the *different materials* property does not account for the tape result only leads John to reject this idea in favor of others without attempting to resolve how his idea might account for her evidence. Since these students do not attempt to chain to show what causes the observed phenomenon, they have difficulty judging among the possible variables (*e.g.,* they have no method for discovering that the *rubbing* Audrey identifies is only a specious correlation among observations). Without attempting to figure out how each possible part of the mechanism accounts for all observations (cycling from mechanistic reasoning back to evidence), students cannot make further progress. This unidirectional relationship between empirical results and mechanistic reasoning, while useful as an entry point for thinking about static electricity, is insufficient for deciding which properties are relevant to the causal mechanism and which are not.

This analysis gives some insight into how we might distinguish between productive and unproductive "messing about." In productive discussions where students make significant progress in understanding the underlying mechanism, the coding scheme would likely identify students both suggesting possibly causal variables (mechanistic reasoning levels 3-6) *and* students using those variables to account for different outcomes (level 7). In contrast, the coding scheme would probably only identify the lower levels of mechanistic reasoning (without chaining) in exploration activities where students merely brainstorm about their experiences without attempting to reconcile them together. Identifying students engaged in chaining helps differentiate less productive inquiry from quality "messing about" in which students are reasoning in a way that may help them discover how a variable causes the phenomenon.

Reconciling Multiple Empirical Results to Elaborate the Underlying Mechanism

As discussed above, multiple commonalities can be identified when considering multiple instances of a phenomenon. Not all of these commonalities are present in all the cases and not all of them are important to the mechanism. When trying to eliminate non-causal properties, students might attempt to explain a seemingly anomalous case using a mechanism component identified from a different empirical result. To do so often involves more precisely articulating exactly *how* the particular mechanism component works to produce the original phenomenon, thereby showing how it can account for the other phenomenon. In this cyclic relationship between empirical results and mechanistic reasoning, students begin by using empirical results to conjecture a mechanism component. Then, when presented with a conflicting empirical result, they elaborate how their component works with other parts of the mechanism to produce the anomalous data.

In this excerpt from early in the tutorial (utterances 87 – 98), students are discussing whether the "different materials" property accounts for their everyday experiences with static electricity. Again, the focus of the analysis is on the italicized utterances, but the entire episode is presented for context.

Audrey: *Well I can, if I take my hand and rub on her sweater then I can touch something spark. I don't think you can do two things that are made out of the same thing.*

Claire: [Simultaneously with Audrey] Well your whole body is [?only one thing]. Like this is a plate and you can charge this [Styrofoam plate]. But, but your whole body is kind-of like a conductor really.

Claire: *[To John] Yeah that's true. Because well it could go back to like what you [Audrey] said before with like it travels through your body.*

John: *But like, I mean, if you touch someone's hand, [?it's fine], you shock each other.*

Audrey: *Yeah.*

Claire: You can create a charge maybe but it doesn't stay there?

John: I think, I think [?it distributes].

Claire: Can you create a charge though?

John: *I don't know if I can get like two different charged hands.*

Audrey: *No. I don't think you can. I don't think just from your hands. [Rubbing her hands together] I think, I think what makes the charge is two different substance things. 'Cause if you figure you walk around and then shock somebody, the charge is -*

Erin: *It's the floor. Yeah.*

Audrey: *- probably created from the carpet on your feet and then you carried it through [your body to your hands].*

Audrey first surveys the available informal evidence observed during tutorial – hand to hand and plate to plate do not produce static but cloth to plate does. These results help her identify a mechanism component – the entity property of "different materials." Then John asks her to acknowledge a result from everyday experience that does not seem to be explained by that property: two hands shocking one another are not two different materials. In response, Audrey fleshes out the mechanism by chaining; charge (underlying entity) is created between the carpet and feet (which satisfies the entity property "different materials") and is carried (activity) through the body (organization of entities) to produce a shock between two hands (empirical evidence). Audrey uses empirical results to generate a mechanism component then elaborates more parts of the mechanism to explain a different observation. The initially anomalous data helps her specify "more precisely the situations in which a mechanism will produce an expected covariation" (Koslowski, 1996, p. 69). In doing so, Audrey makes the different materials property more plausibly causal by using it to account for contrasting cases. Her fluid movement between mechanism and informal empirical results contributes to her construction of the more complete underlying mechanism, and provides a reason for accepting her property over other observed commonalities.

One potential weakness of attempting to reconcile multiple empirical results is that it may lead to ad hoc revisions to the mechanism. To account for anomalous data, students may introduce an additional, independent component that accounts for the new results without discounting the old. Students may then use both unrelated components to explain the phenomenon instead of elaborating how the original component can account for the new data. Consider the following excerpt (utterances 102 – 105) that occurs just after the suggestion that two objects must be different materials in order to become charged.

Claire: What about the tape? Why? Like the tape we did in lecture. Then why did that get staticy that's two of the same thing?

Audrey: I don't know.

John: Those are two separate objects. These [hands] are not, like you have two hands but they're not separate objects, its all connected. [pointing from one hand across his body to the other]

Claire: But if you rub somebody else's hand you still don't get it.

…

John: I gotta think it's because there's moisture then.

Like John in the previous episode, Claire draws attention to evidence that contrasts the entity property of different materials - two tapes stuck together can charge one another. However, unlike Audrey, John does not attempt to elaborate how the "different materials" property can account for the anomalous observation. Instead he adds another independent property of "separateness" to the mechanism; the tapes are the same material and separate objects so they charge but the hands are the same material and not separate objects so they do not charge. Separateness merely supplements differentness; if things are different, they will definitely charge but if they are not, separateness will decide. This ad hoc revision to the mechanism articulates a new common property that may or may not be related to the other one. John does not describe how these parts of the mechanism might together produce the phenomenon. When faced with further evidence that refutes his new entity property (two separate hands do not charge), John rejects both separateness and differentness in favor of the idea that moisture prevents hands from charging (though its not clear whether he thinks this accounts for all cases of non-charging). Cycling between multiple empirical results and mechanistic reasoning is not always productive for further elaborating the underlying mechanism; it can sometimes lead to theoretically unmotivated additions.

Constructing Empirical Tests to Flesh Out Mechanisms

Experience with the physical world provides a wealth of intuitions about the types of mechanisms that can occur (diSessa, 1993). Armed with that information and more formal prior knowledge, students may approach novel situations with a sense of the entities and activities involved in the mechanism. However, this sense of mechanism is rarely complete and students may require empirical results to “fill in unspecified variables” (Klahr & Dunbar, 1988, p. 8). This cyclical relationship between mechanism and empirical results is different from those described in previous sections. Rather than beginning with experiential data that provide clues to the mechanism, students start with an incomplete sense of the underlying mechanism and then seek direct evidence to provide the missing pieces. Students recognize a gap in their understanding of the mechanism and spontaneously construct an informal test to fill it in.

After discussion with the teaching assistant, the students articulate an electron transfer model of static electricity: two different materials can charge one another because electrons move from one to the other. When two pieces of tape are stuck together and then pulled apart, electrons either jump to the sticky side of the top tape or the slick side of the bottom tape. This leaves one tape positive and one negative so they attract. However, when students are asked to answer the specific question below regarding the location of charge, they quickly encounter a gap in their static electricity mechanism.

> **Question:** A bottom (B) piece of tape and a top (T) piece of tape are separated halfway as shown (Fig. 1). Use “+” and “–” symbols to indicate the parts of the tapes that are charged and the type of the charge on a diagram like the one below.

They respond to this question as follows (utterances 324 – 334).

Claire:	So basically one is plus, one is minus, but does it matter which -
Erin:	Which piece? [?]
…	
Audrey:	So does that just mean that the inside surfaces that touch are different? Or like the entire piece of tape is now [?]
…	
Claire:	[Pulls two pieces of tape off the table and away from each other, then brings both sides near each other] No see, but both sides stick.
Audrey:	So you think it goes like, it goes through the –
Claire:	Like slick to slick still touches, still is attracted [Erin nodding]. So it must charge the whole thing.

Claire begins by describing the relevant properties of the tapes: one is "plus" and one is "minus" (she later identifies them as having an excess or deficit of electrons). However, Audrey is unsure about whether the plus and minus are located over the entire tape or just on the inside surfaces. To fill this gap in the mechanism, Claire spontaneously constructs an informal empirical test of whether the entire piece of tape is charged. She pulls the tapes apart and notices that they attract on all sides, not just the inside surfaces that were originally touching. This result helps her chain to discover the organization of the entities: both the slick and sticky sides of both tapes attract, so both sides of the tape must be charged. Audrey's question about a part of the mechanism prompts the construction of an empirical test that is meaningful to the students. Even for people who limit inquiry to controlled experimentation, this episode demonstrates the value of also including “messing about” and mechanistic reasoning in inquiry. Questions of mechanism may lead students to construct informal observations or formal hypothesis tests that are intrinsically and theoretically motivated.

After Claire's test, the conversation continues as follows (utterances 343 - 351).

Erin: So like along this whole surface of this top one would be plus?

Claire: I think the whole piece.

Audrey: Once you open it, right like, this part down here [Unpulled apart section of tape] isn’t charged yet right? ‘Cause you haven’t like taken it apart to make the – [Pulling her hands away from each other.]

Claire: So, can, alright. Am I wrong in thinking of it like the actual electrons go to the other one?

Erin: That’s what I thought. They like jump from one piece of tape to the other one.

Audrey: I thought that when we like -

Claire: To the other so that like the whole piece has more positives, and this whole piece has more negatives.

Erin: Has more negatives, right.

Audrey: Okay.

While the observation explained the organization of entities to Claire, Erin and Audrey are still confused about which part of the tape is charged. In response, Claire uses parts of the mechanism they agree on to chain to her conclusion about entity organization. She explains that if electrons (entities) jump (activity) from one piece of tape to the other one when they are pulled apart, then one entire (entity organization) piece of tape will now have more electrons and the other less (entity properties). Erin and Audrey only agree that the gap in the mechanism is filled ("right" and "okay") after Claire explains why her conclusion about the entity organization must be true based on their own sense of electrons jumping. The empirical result did not convince all the students until chaining among known components of the mechanism further supported it. This finding may indicate why demonstrations and laboratories that are so clear to educators sometimes fail to convince students of the concepts they are meant to illustrate. The results from those experiments may need to be accounted for by chaining from parts of the mechanism accepted by the students. Students can make significant progress in understanding novel phenomena by using a nascent sense of mechanism to construct empirical tests and then explaining those results with a more complete underlying mechanism.

Implications

Current conceptions of inquiry place significant emphasis on developing student abilities to design and conduct controlled experiments. While this skill is important for science, it is inappropriate to limit scientific inquiry to formal hypothesis testing. The analysis described in this chapter presents several episodes from an introductory physics course as candidates for the kind of discussions we might want to include in characterizations of inquiry. Although the students are not selecting variables to test or performing rigorous data analysis, they are nonetheless making significant progress in understanding the physical world by reasoning mechanistically about informal empirical results. These examples illustrate activities that reflect natural student abilities and professional science more accurately than traditional conceptions of inquiry.

If we choose to include this kind of "messing about" and mechanistic reasoning in our characterizations of inquiry, then we must articulate what it means to do them well. Just as controlled experimentation can be done well or poorly, we expect that "messing about" and mechanistic reasoning can both be either productive or unproductive. However, we are far from having a list of standards to identify when students are doing either of these well. In that way our understanding of these parts of inquiry lags behind our understanding of formal experimentation. It is only by carefully analyzing episodes of "messing about" and mechanistic reasoning that we will begin to be able to distinguish features of quality student engagement from less valuable activity. This chapter provides one such analysis of a discussion in which students are, on the whole, productively using both mechanistic and informal ways of understanding the physical world. We describe how the students use each to inform the other and why what they are doing is valuable for inquiry.

Analysis with the mechanism framework reveals that informal empirical results can help students tap their existing causal knowledge and construct coherent mechanistic explanations for physical phenomena. We identify four relationships in this data. Observations can 1) prompt students to ask appropriate mechanistic questions, 2) help students generate parts of unknown mechanisms, and 3) aid in the refinement and elaboration of mechanisms. An incomplete sense of mechanism can prompt the construction of informal empirical tests that then further elucidate the mechanism (4). In all of these relationships, students move quickly between these two activities allowing each to inform the other. This fluid movement may indicate that the traditional distinction between theory and evidence is too strict. It may be more appropriate to understand them as part of the larger activity of making sense of underlying mechanisms with each contributing to that end instead of each representing a end in and of themselves.

To be clear, we do not claim to have provided a list of *the* relationships between messing about and mechanistic reasoning. We do not imagine that what we saw in this discussion would necessarily be present in other instances. In other cases we might identify other relationships. Nor do we suggest that what we saw in this discussion is necessarily the best-case scenario that all other scientific inquiries should attempt to emulate. Instead, we use this analysis to describe the kinds of fruitful relationships that *can* exist between informal empirical results and mechanistic reasoning if students are given the freedom to "mess about" during inquiry. In doing so, we hopefully provide evidence that "messing about" can be a productive thing to do and thus should be something we encourage and are attentive to during scientific inquiry.

Chapter 7: Mechanistic Reasoning with Mathematics in Graduate Level Physics

Introduction

The argument that educators should attend to and encourage mechanistic reasoning as part of scientific inquiry may be easy to accept for college students learning conceptual physics. Our goal as their instructors in these semester or year-long survey courses is to give them an introduction to, or first pass at, physics topics and help them to understand what physics is about. Mechanistic reasoning provides a way for those students to make sense of introductory topics and thus serves as an appropriate entry point for physics learning. We might also have the grander goal of helping them gain an appreciation for how science knowledge, and more specifically physics knowledge, is constructed; mechanistic reasoning can serve that purpose as well. Just as mechanistic reasoning was part of how Newton and his contemporaries developed their initial models of the physical world, so it is also part of how introductory students can make sense of the basic elements of those models. It is reasonable and appropriate to expect mechanistic reasoning from our introductory students.

It may be more difficult to accept that mechanistic reasoning should be included in our understanding of upper level physics expertise partly because our instructional goals for physics majors and graduate students are different than those described above. Unlike our students in conceptual physics, students at this stage in their physics learning need to know many things that cannot be directly understood using an intuitive sense of mechanism from experiences in everyday life. We rightly want these more advanced students to be able to solve complex problems involving multiple abstract physical concepts and sophisticated mathematical formalisms. Those formalisms are crucial to upper level physics understanding as they provide precise language for reasoning about physical systems. To familiarize students with those formalisms, we require multivariate calculus as a prerequisite for many advanced physics courses. In addition, the University of Maryland Department of Physics requires one undergraduate course and strongly recommends another graduate course in the mathematical methods of physics. Developing proficiency in using formal, mathematical language to model physical phenomenon is a major goal of upper level physics.

Given that making sense of ‘real’ physics requires extensive mathematics, it is appropriate to question whether mechanistic reasoning is part of expertise in advanced physics, or if it is only part of how students “get started” in understanding basic physics. Should we expect or hope to see evidence of mechanistic reasoning like that used by students in introductory science when we analyze upper level students solving heavily mathematical problems? Can we as educators and researchers understand the reasoning of experts in similar terms to how we understand novice’s reasoning, or is expert mechanistic reasoning so removed from that of novices that we cannot use the same language in talking about them?

To help answer those questions, this chapter analyzes graduate physics students’ solutions to a classical mechanics problem on a PhD qualifying exam. Application of the coding scheme identifies several elements of mechanistic reasoning in their mathematical problem solving. One implication of this result is that the coding scheme developed from characterizations of professional bioscience research and tested in elementary science discussions can also be successfully applied to the written work of physics graduate students. In doing so, the coding scheme gives insight into what mechanistic reasoning looks like throughout physics learning, including in upper level physics. The coding scheme is useful as an analysis tool across K-20 science inquiry and thus may help us begin to recognize some continuity from novice to expert reasoning.

More importantly, the result also speaks to the questions posed above. Evidence found in both the graduate students' written work and their interviews suggests that mechanistic reasoning is part of the fabric of sophisticated mathematical problem solving and how upper level students 'do' physics. Advanced students use mechanistic reasoning to supplement mathematical formalism and they use mathematics to express their sense of mechanism. This work provides case-study evidence that mechanistic reasoning is not limited to use in introductory or conceptual physics but is also a crucial part of graduate (even expert) physics understanding.

Context for Analysis

Problem Context

To explore mechanistic reasoning in advanced physics learning, we use student solutions to a classical mechanics problem on the August 2003, PhD qualifying examination from the University of Maryland Department of Physics. As one of the requirements of the department's Doctor of Philosophy of Science program, students must show "competence in basic [graduate level] physics as evidenced by passing a written qualifying examination." (UMD-DP, 2000) The exam consists of two parts given over two days. In each part students select four out of five problems to complete in four hours; questions on the first part test classical physics (mechanics, electricity and magnetism, and statistical physics) and those on the second part test quantum physics. At the end of each part, students turn in their written work for each problem to be graded by faculty members in the department. Graduate students are given as many as four opportunities to pass the exam, once when they enter in August and three times more after their first year in the physics program (August, January, and the following August).

The particular problem analyzed here comes from the classical part of the exam and tests student understanding of graduate level mechanics. Below is the problem scenario.

> A tube of total length l contains a right angle bend, as shown in figure [8], below. The tube is held rigidly in place. At time t = 0, a flexible chain of length l and total mass m is placed in the tube, as shown in figure [9]. The chain is released from rest at t = 0. The chain slides within the tube with no friction between the chain and the walls of the tube. Assume that the mass of the chain is uniformly distributed along its length, and let g denote the acceleration of gravity. Let $\xi(t)$ denote the horizontal displacement of the end of the chain at time t with $\xi(0) = 0$. See figure [10]. Let t_0 be defined as the time when the left end of the chain reaches the bend in the tube, $\xi(t_0) = l/2$.

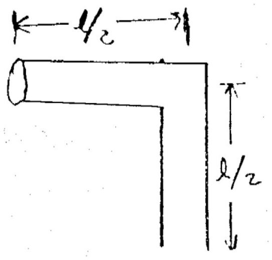


Figure 8

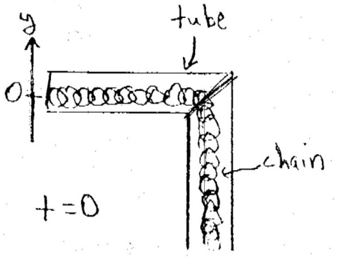


Figure 9

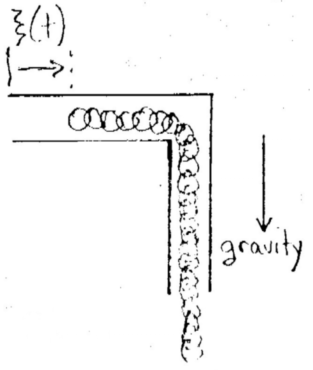


Figure 10

Figures 8, 9, and 10 are the actual figures given to students during the exam.

Given these conditions, students are asked the following questions.

(a) Taking the horizontal portion of the chain to be at a height of zero, what is the potential energy of the chain for $0 \leq t \leq t_0$ **and** what is the Lagrangian?

(b) What is the equation of motion for ξ(t) for $0 \leq t \leq t_0$?

(c) What is ξ(t) for $0 \leq t \leq t_0$?

(d) Now consider the case where friction between the tube walls and the chain is not negligible. At the instant that the left end of the chain reaches the bend in the tube, ξ(t) = l/2, it is observed that the speed of the chain is $\sqrt{\frac{gl}{2}}$. How much energy has been dissipated due to friction by this time?

A copy of the official solution to the problem is given in Appendix F.

Data Sources

We analyze two students' solutions to parts (a), (b), and (c) of the chain problem. The first solution studied is my own; I took the qualifying exam following my first year in the physics program after taking five graduate courses including classical mechanics, electricity and magnetism, quantum mechanics (I and II), and mathematical methods. The other student, Ben, took the exam before taking any graduate physics courses but after completing an undergraduate degree in physics (and receiving a secondary teaching certification) the preceding May. Both students received perfect scores on the first three parts of the problem and performed well in their graduate courses.

To analyze my own work, we use the written solution I constructed during the exam and turned in for grading (found in Appendix G). My written work includes several notes (to myself and the graders) that clarify my approach to the problem and describe my reasoning. Since the analysis described here was performed three years after I took the exam, those notes helped remind me of my thinking during problem solving. We use two sources of data to study Ben's reasoning. First, we look at the solution he turned in at the time of the exam. Copies of his work were obtained from the graduate director with Ben's permission (found in Appendix H). Early discussions with Ben revealed that the work he turned in was his "clean" finished solution; it did not include any extra information about why he solved the problem as he did or any incorrect paths he explored. To supplement this written solution, we interviewed Ben and asked him to "talk through his solution," reconstructing his reasoning from his written work as best he could remember. His interview took place three years after the original exam and was video taped and transcribed for analysis. The transcript of his interview can be found in

Appendix I. When referencing student work in the analysis below, we provide digital images of what the students actually wrote during the exam.

We recognize that the time separation between solving the problem and reflecting on the reasoning that generated the solution is not ideal; Ben or I might not accurately remember how we were thinking in the moment of the exam. There are two responses to this concern. The first is that Ben and I are both fairly confident in our reconstructions of our reasoning. Our written work provided us with cues to our reasoning; seeing what we had written jogged our memories of what we had been thinking at the time. The second response is that perfect alignment between our recollections of our reasoning and our in-the-moment reasoning is not crucial to the argument of this chapter. We seek to show that mechanistic reasoning plays a significant role in how upper level physics students make sense of rigorous mathematical problems. Ben's and my current explanations of the mathematical solution to the chain problem speak to that question just as much as our solution of that problem three years ago. Even if we are not accurately remembering how we reasoned about the problem then, how we reason about it now gives insight into how graduate students make sense of mathematical problems.

Coding Scheme Reveals Evidence of Mechanistic Reasoning

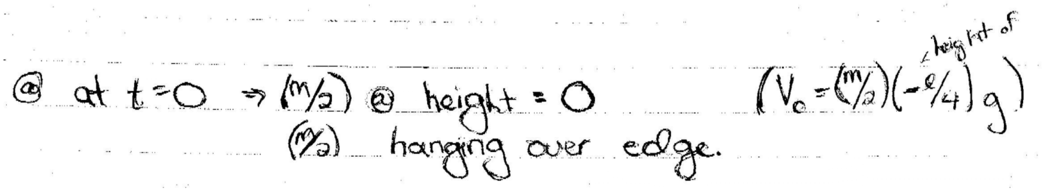
At the start of this analysis, it was not clear whether the coding scheme developed to identify mechanistic reasoning in student *discourse* about *conceptual* science topics would necessarily be able to identify mechanistic reasoning in students' *mathematical written work*. That is, it was not obvious that the framework would function as an analysis tool. It was possible that the framework would not be useful in this new context either because upper level students do not commonly reason mechanistically about mathematics or because their reasoning has changed or been refined in such a way that the framework could not capture it.

There is evidence elsewhere that rules out the first concern. Sherin (2006) presents several case studies to demonstrate that students' intuitive physics knowledge about mechanisms can influence their mathematical solutions to physics problems. He describes how third semester university physics students' "intuitive schematizations [of the physical world] can drive work with equations in a fairly direct manner" (Sherin, 2006, p. 553). He cites other work by Ploetzner and colleagues (e.g. Ploetzner & Spada, 1993) that "provides an account of the role of nonquantitative reasoning in problem solving" (p. 538). In addition to the research literature, our own experiences in advanced physics courses suggest that understanding the physical mechanism underlying a situation is crucial to solving heavily mathematical physics problems. For example, one key part of solving for the electromagnetic field in a waveguide is correctly reasoning about what physically happens to the field at the boundary and then translating that physical picture into a mathematical boundary condition.

The question then becomes whether the mechanism framework can usefully portray and describe that reasoning. Analysis reveals that the mechanism framework can be used successfully in this new context; we find evidence of the mechanism codes, and thus of mechanistic reasoning, in students' work. Below we provide examples of each that demonstrate the utility of the coding scheme. The examples show students using mathematics to express their sense of mechanism and give insight into how mechanistic reasoning manifests itself in upper level problem solving.

Identifying Set-Up Conditions

The first problem asks students to find the potential energy of the chain for *all time* (what I call $V_{\text{potenergy}}$). In my solution, however, I started by calculating the potential energy of the chain *at time t = 0* (what I call V_0). In doing so, I used mathematical formalism to precisely specify the starting conditions of the chain.



height of

@ at $t=0 \Rightarrow (m/2)$ @ height $= 0$ $\left(V_0 = (m/2)(-\ell/4)\, g\right)$

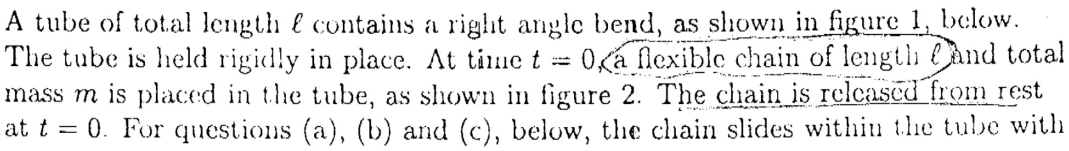
$(m/2)$ hanging over edge.

Figure 11

Even though it is not requested in the problem, I described the amount (mass) and location of each part of the chain at time t = 0. I translated the initial physical situation as depicted in Figure 9 into an exact mathematical description in terms of potential energy. Only after finding the potential energy at the starting time did I proceed to calculate the potential energy in terms of generalized coordinates that change in time.

Identifying Entities and Activities

The problem statement largely specifies the relevant entities and activities of the chain problem. However, it is worth noting that in my solution, I drew special attention to those parts of the problem statement.

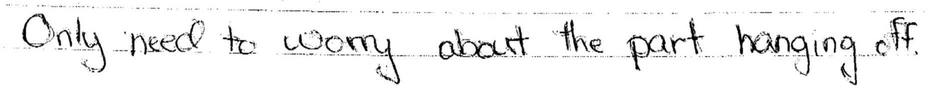


A tube of total length ℓ contains a right angle bend, as shown in figure 1, below. The tube is held rigidly in place. At time $t = 0$, a flexible chain of length ℓ and total mass m is placed in the tube, as shown in figure 2. The chain is released from rest at $t = 0$. For questions (a), (b) and (c), below, the chain slides within the tube with

Figure 12

Of all the information given in the problem, I circled and underlined the entities and activities, presumably because they were important to my thinking.

In my problem solution I also modified the given entity by breaking it into two parts: the part on the table at height h = 0 and the part hanging off the table (see *Identifying Starting Conditions* section above). Then, instead of considering the entire "flexible chain of length l," I chose to focus only on the part of it hanging over the side of the table.



Only need to worry about the part hanging off.

Figure 13

Ben similarly chose to only focus on the part of the chain that is hanging down. In his written work he constructed an integral for the potential energy (what he called U) that only has contributions from that part of the chain.

Figure 14

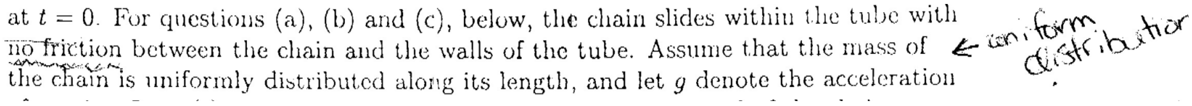
The limits on Ben's integral only cover the part of the chain that is hanging vertically. In his interview, he mentioned the chain on the table in passing, only to say that it does not contribute to the potential energy. For the rest of the discussion, he focused only on the part hanging off the table.

> **Ben:** And the problem said that the height was equal to zero [on the table] so potential energy is zero up here.
>
> …
>
> **Ben:** Each different bit of this chain *that's hanging down* here is going to contribute a different amount to the potential energy.

While I used words explicitly to identify my modified entity, Ben used a mathematical expression for potential energy (the integral) to denote that he was only considering part of the chain. Both methods provide evidence of mechanistic reasoning; only the chain-off-the-table is an important entity for calculating potential energy while the chain-on-the-table can be ignored. An important aspect of solving this problem involves specifying which entities affect the outcome and thus need to be mathematically modeled.

Identifying Properties of Entities: Mass Density

The problem not only specifies the entities but also some important properties of the entities; the flexible chain has a uniform distribution of mass. Again in my solution I especially noted that part of the problem statement.

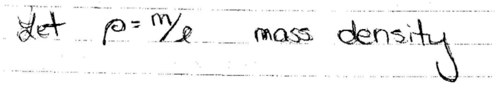


at $t = 0$. For questions (a), (b) and (c), below, the chain slides within the tube with no friction between the chain and the walls of the tube. Assume that the mass of the chain is uniformly distributed along its length, and let g denote the acceleration

← uniform distribution

Figure 15

In order to find the potential energy of the chain, students must translate this physical property of the entity into a mathematical statement. Both Ben and I did so in our solutions.



let $\rho = m/\ell$ mass density

Figure 16

I defined a property of the chain called the mass density in terms of other parameters in the problem. This mathematical expression more precisely specified the "uniform distribution" property of the chain given in the problem. Ben did the same thing and his definition gave him information about a small piece of chain that he later used to set up an integral for potential energy.

let $\lambda = \frac{m}{l} \Rightarrow \lambda dl = dm$

Figure 17

Ben described this step in his solution as follows.

> **Ben:** So I, I said on here, you know, define a linear mass density that is the mass of the chain over its length… And if that's true, then if we're talking about a little tiny piece of chain, you know, you just make this [the mass] infinitesimally small and that [the length] infinitesimally small.

Ben defines the entity property of the entire chain mathematically and then uses that expression to describe an entity property of one "little tiny piece of chain." Although the problem did not explicitly ask the students to describe the mass density of the chain (or the mass of a small piece of chain), using a mathematical expression to express the entity property is a necessary step in calculating the potential energy. Identifying entity properties mathematically is part of solving advanced physics problems.

Identifying Properties of Entities: Inextensibility

The uniform distribution of mass over the chain is not its only important property; the chain is also inextensible. However, when I first read this exam problem, the "coils" of the chain in the given diagram (Figure 9) made me think the problem was about a *spring* falling off a table.

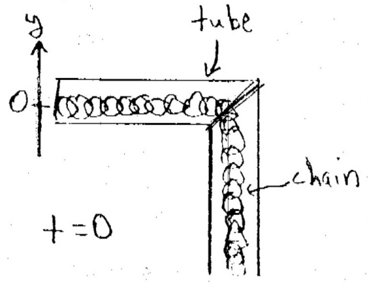


Figure 9

I recall being overwhelmed by this idea. Solving the problem of a falling spring would be very difficult, since springs are extensible. A correct solution to that problem would require accounting for all the internal forces and including the spring potential energy in addition to the gravitational potential energy.

It was only on rereading the problem that I realized the problem was about a chain rather than a spring.[14] In my written solution, I made two moves to remind myself not to think about the problem as though it were a spring before I began any mathematics. First, I wrote an explicit note at the top of my problem statement.

Part I, Problem 1

NOT spring

Figure 18

Second, I redrew the given diagrams.

---

[14] This realization may be why I circled the entity in the problem statement.

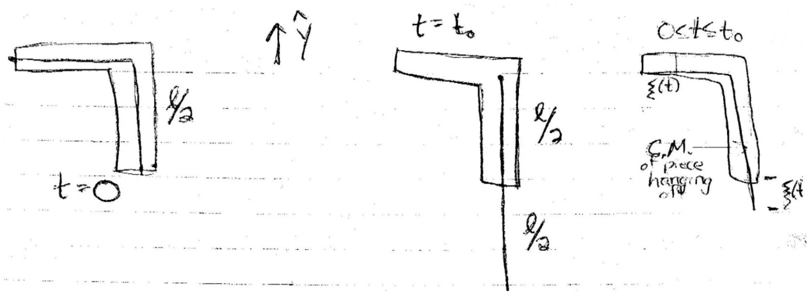


Figure 19

Notice that my diagrams are not the same as those provided in the problem; I purposefully used a line to represent the chain and left out the “coils” (or links) that cued my thinking of the problem as a spring.

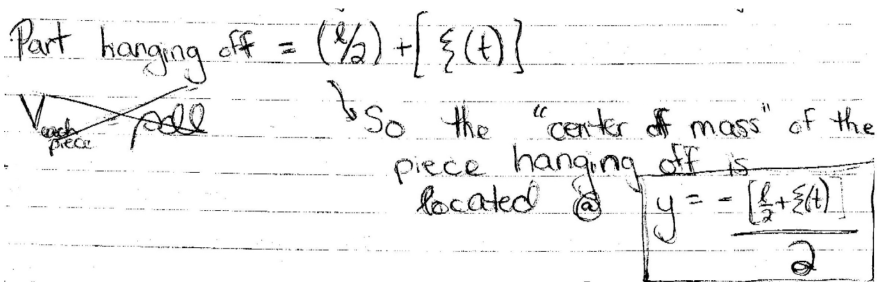
The explicit “not spring” reminders illustrate an important aspect of my mechanistic reasoning. Before beginning any mathematical formalism, I first identified which entity properties were relevant to the mechanism; the “link-ness” of the chain could be ignored because it does not affect how the chain falls off the table (hence the line in my drawing). In contrast, had the problem been about a spring as I had originally thought, the extensibility of the coils would be important to solving the problem correctly; the spring’s “springiness” would need to be modeled explicitly because that springiness would affect the potential energy and how the spring falls. My reminders indicate that the inextensibility of the chain is an entity property I consider especially relevant to the problem.

In my solution, I reminded myself to ignore the links in the chain not only because they were irrelevant but also because they distracted me by invoking entity properties that were not appropriate in the physical situation (springiness). In previous chapters, we described how it is productive for students and scientists to identify entity properties partly because it helps eliminate irrelevant ones from consideration. For example, the students in the falling objects discussion do not need to talk about what is on the cover of the book they are dropping because it does not affect the mechanism of falling. In solving the chain problem, the chain links actually diverted my attention away from thinking about gravitational potential energy and towards thinking about the restoring forces between the links. Identifying the chain as equivalent to an inextensible line is an important step in my solution because it helps me eliminate distracting properties (springiness) that do not affect the falling mechanism and not need to be modeled. Had I not done so, my mathematical solution to the problem would have been dramatically different (not to mention incorrect).

Identifying Organization of Entities

The problem asks students to find the potential energy of the chain for time $0 \leq t \leq t_0$. Potential energy is a function of both the mass of an object and its location; an object held 10 meters off the ground would have more potential energy than the same object held 5 meters off the ground. Thus an important step in this problem is precisely identifying the location of the chain; that location will dictate how much potential energy the chain has at any time.

In my solution, I treated the chain as though all of its mass is located at the center of mass. As such, I described the location of the entire length of chain with one expression, using parameters given in the problem and the generalized coordinate $\xi(t)$.



Part hanging off $= (\ell/2) + [\xi(t)]$

~~$V_{\text{each piece}}$ $d\ell$~~

So the "center of mass" of the piece hanging off is located @ $\boxed{y = -\frac{[\frac{\ell}{2}+\xi(t)]}{2}}$

Figure 20

Thinking of the chain as a point mass located in one place allowed me to use the single variable 'y' to capture all the relevant organization of the chain; I did not need to describe the entire extended object.

Ben does not describe the organization of the chain in the same way. Instead of thinking about the entire chain as effectively located at one point, he thinks about the chain as made up of many tiny pieces of mass each located at a different height.

> **Ben:** So I'm sure the way, I'm ve, quite sure the way, they way I went about this at the time, it's still the way I go about problems like this, is uh, each different bit of this chain that's hanging down here is going to contribute a different amount to the potential energy because it's a different distance away from our reference line.

Later:

> **Ben:** For the potential energy, you know the amount this bit [in the middle of the hanging part] contributes is, uh, different than the amount this bit [bottom of the hanging part] contributes to the potential energy… Because they're at different heights.

Thinking of the chain and its potential energy as many small pieces spread out over a distance led Ben to set up an integral. He defined a general length element (called l') representing the height of one of the bits of chain (called dm) and then integrated over the part of the chain that is hanging off the table.

$$U = -\int_{\ell=0}^{\ell=h'} (dm) g \ell \qquad \text{but } h' = \frac{\ell}{2} + \xi(t)$$
$$= -\int_{0}^{\frac{\ell}{2}+\xi(t)} (\lambda g \ell) d\ell' = -\frac{\lambda g}{2}\left[\ell'^{2} \Big|_{0}^{\frac{\ell}{2}+\xi(t)} \right]$$

Figure 21

In the interview, Ben described how the integral allowed him to "consider every point along that chain." For him, it was important to identify and account for the location of each piece of chain.

Ben and I produced equivalent solutions for the potential energy; our final answers for V (or U) were identical.[15] However, our descriptions of the entity organization in the chain problem were quite different; I described the extended body as located at a single point and Ben described each small piece of chain individually spread out over its length. The difference in our mechanistic reasoning is reflected in our mathematical approaches to the problem; I defined the height (and mass) of the center of the chain using algebraic expressions and Ben defined infinitesimal mass elements, selected appropriate limits, and integrated to explicitly account for every piece of the chain hanging off the table. The mathematical machinery Ben and I employed (i.e., integration vs. algebra) expressed our sense of mechanism in the chain problem, particularly our ideas about entity organization.

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[15] In fact the underlying justification for the center of mass argument is Ben's integration.

Chaining

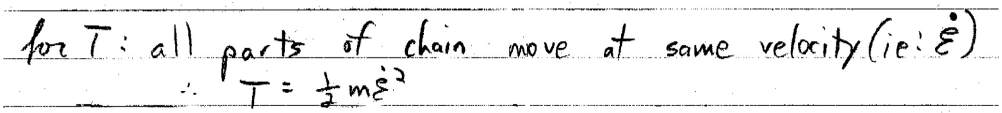
In order to construct the Lagrangian, students need to find both the potential and kinetic energy of the chain falling off the table. The kinetic energy of a point particle (or an object whose mass is rigid) is defined as

$$T = \frac{1}{2}mv^2 \text{ where}$$

m = mass of the particle

v = velocity of the particle

Calculating the kinetic energy of the chain involves deciding what mass and velocity are appropriate to use. Ben chose the velocity based on his understanding of the properties and activities of the chain.



for T: all parts of chain move at same velocity (ie: $\dot{\xi}$)

$\therefore T = \frac{1}{2}m\dot{\xi}^2$

Figure 22

In his interview he further explained his decision to use $\dot{\xi}$ for the velocity.

> **Ben:** If it's an inextensible, inextensible chain, every bit of that chain is moving at the same velocity… So you know kinetic energy is one half m v squared there by definition. You know, every bit of that chain is moving at the same velocity, so this [v] is just going to be constant of the length of the chain… And uh, you know, you can look at how fast ξ of t is changing, you know and that's going to be how fast this, this first little bit of chain is moving, which I just said is the same as how fast every bit of the chain is

> moving. So v here [in T] is just gonna be, you know, the first derivative of ξ.

Ben is reasoning mechanistically by chaining: using what he knows about the properties and activities of the chain to select the appropriate velocity for his kinetic energy equation. He knows an entity property of the chain: it is inextensible in that all the parts are connected and not stretchy. Given that property, he describes the activity of the chain: all parts of the chain must be moving at the same velocity. Since all points move together, he decides to model the velocity of entire chain with the velocity of one point. In his interview, Ben expresses his surprise at how easy this part of the problem was.

> **Ben:** I guess if you want the Lagrangian you need to know the kinetic energy also. So, I mean that's, I'm sure I remember thinking at the time, "Boy, it can't be that easy, can it?" But, I mean, it is.

Ben's chaining from entity properties he knows to the velocity he does not know is precisely what made solving for the kinetic energy straightforward to him. However, we can imagine another (correct) method for finding the kinetic energy that involves setting up an integral over the mass and velocity of each little bit of the chain in the same way Ben set up an integral to account for the potential energy of each part. This method would certainly be more difficult and time consuming to complete than Ben's argument. By chaining from physical properties of the situation, Ben is able to simplify the mathematics he needs to correctly solve for the kinetic energy. We do not suggest that Ben (or other students who made this same decision) consciously do this chaining for the purpose of making the problem easier. In fact, we imagine they might not even consider the integration method but rather just "see" that modeling the chain with one velocity is appropriate. Chaining appears to be a fairly automatic part of how graduate students approach problem solving.

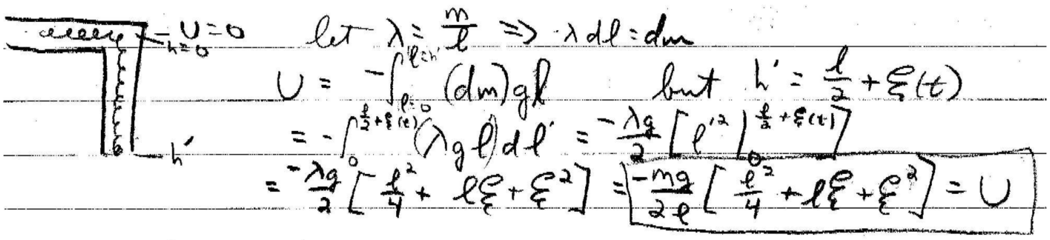
The chaining Ben does in this problem is different from the chaining we have discussed in other chapters. He chaining does not occur *in time*: he does not take what he knows about the properties of the chain at one time to reason about the velocity of the chain at another time. Instead, his chaining occurs in sequential reasoning steps: the properties of the chain at one time have implications for the velocity of the chain at the same time. This use of the term "chaining" is a departure from how it is used in MDC's framework. However, we feel it is an appropriate extension because Ben is still using what he knows about the physical situation to make claims about what he does not know.

Mechanistic Reasoning Supplementing Mathematical Solutions

We have seen evidence of mechanistic reasoning in upper level physics students' mathematical problem solving. We now present two episodes in which students' mechanistic reasoning supplements their mathematical reasoning. In particular, we show students engaging in mathematics that is not technically correct or sensible but is nonetheless appropriate and effective for modeling the physical situations. In one case, the "fudged" mathematics gives the correct answer and in the other case it does not. Regardless of whether it gives them the right answer, mechanistic reasoning seems to underlie these students' mathematical moves.

Episode One: Mechanistic reasoning contributes to a correct mathematical solution

As discussed earlier, one approach to solving for the potential energy of the chain involves performing an integral over the entire length of the chain that is falling off the table. Ben solves the problem in this way.



let $\lambda = \frac{m}{l} \Rightarrow \lambda\, dl = dm$

$$U = -\int_{l=0}^{l=h'} (dm) g l \qquad \text{but } h' = \frac{l}{2} + \xi(t)$$

$$= -\int_{0}^{\frac{l}{2}+\xi(t)} (\lambda g l) dl' = \frac{-\lambda g}{2}\left[l'^2 \Big|_0^{\frac{l}{2}+\xi(t)} \right]$$

$$= \frac{-\lambda g}{2}\left[\frac{l^2}{4} + l\xi + \xi^2 \right] = \boxed{\frac{-mg}{2l}\left[\frac{l^2}{4} + l\xi + \xi^2 \right] = U}$$

Figure 23

Although Ben obtains the correct expression for potential energy (what he calls U), his mathematical solution is not technically correct. When he introduces the U integral, Ben's integration variable is dm (the mass) but his limits of integration are distances (l) along the chain. Ben notices this problem during the interview.

> **Ben:** So, I mean, looking at this now, I don't think my notation is, is, ex, totally correct here… So I have to somehow, now here I'm mixing things because when I integrated over the chain, l is just a kind of variable that will sweep out up and down here [the chain]… Now I mean, that's not technically correct, I can see that now, cause my infinitesimal is kind-of an m here.

Ben's integral also has the problem that he uses l both inside the integral and as an integration variable representing the length of the chain. To remedy this problem, in the next line he adds primes to the l's inside the integral. Again, he discusses this move in the interview.

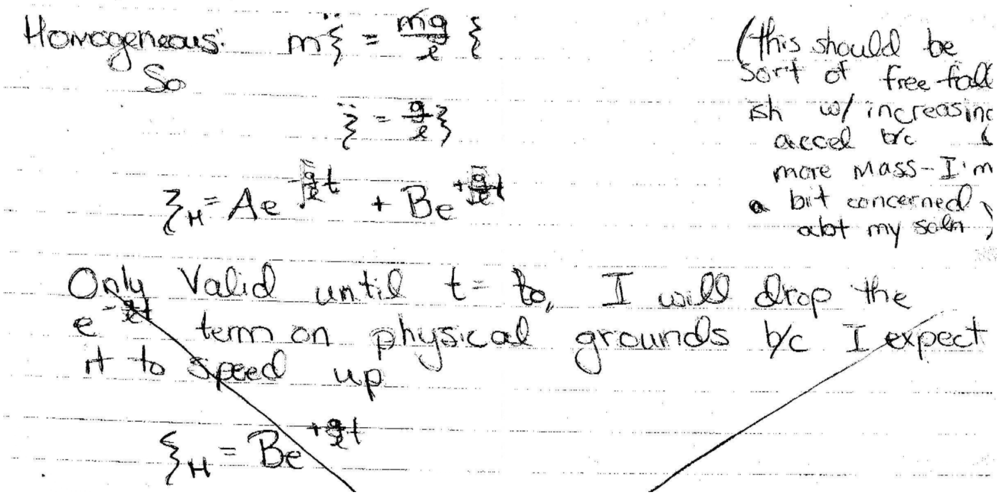
Interviewer: And that l [inside the integral] was the same l as you'd been using [to specify limits]? That's the same l as you were using for l, as it were?

Ben: Right, okay so, yeah, now at this point you'll see on my paper these little primes mysteriously appear here… Because, you're right, they're not the same l… technically speaking. Yeah, this l [in the limit] is distinct from these l's [in the integral]. These [in the integral] are just integration variables to help me sweep out, you know, this chain's length.

Ben's notation in this part of the problem is not technically mathematically correct; he mixes variables both in the limits and inside the integral. However, he is able to correctly solve for the potential energy because he is using the mathematical variables as place-holders to represent different physical properties of the chain. The limits of integration represent the *locations* of the beginning and end of the falling chain that he needs to "sweep out" while the mass and length inside the integral represent the *properties* of a representative small piece of chain. He does not need to obey the formal rules of integration because he is only using it to express his idea that the potential energy of every piece of the chain needs to be summed together to get the total potential energy. While his math might be incorrect, his physical mechanism for the falling chain underlies the formalism and helps him effectively keep track of the mixed variables. In this case, Ben's mechanistic reasoning supplements his mathematical moves and allows him to successfully solve the problem even with "fudged" mathematics.

Episode Two: Mechanistic reasoning leads to an incorrect mathematical solution

The problem scenario describes the target phenomenon generally: a flexible chain falls off a table with no friction. The first three parts of the problem ask students to describe the target phenomenon more precisely using mathematical formalism. In particular, in part (c) students have to find the position of the chain for any time t by solving a differential equation derived from the potential and kinetic energies of the chain. My first solution to the homogeneous equation reflects an incorrect attempt to model the target phenomenon mathematically.



Homogeneous: $m\ddot{\xi} = \frac{mg}{\ell}\xi$

So

$$\ddot{\xi} = \frac{g}{\ell}\xi$$

$$\xi_H = Ae^{-\sqrt{\frac{g}{\ell}}t} + Be^{+\sqrt{\frac{g}{\ell}}t}$$

(this should be sort of free-fall ish w/ increasing accel b/c more mass - I'm a bit concerned abt my soln)

Only Valid until $t = t_0$, I will drop the $e^{-\frac{g}{\ell}t}$ term on physical grounds b/c I expect it to speed up

$$\xi_H = Be^{+\frac{g}{\ell}t}$$

Figure 24

From my equation of motion, I directly solve for the homogeneous solution and obtain a superposition of exponentially increasing and decreasing terms. In reflecting on that solution, I grow concerned because it does not match my understanding of the mechanism at work: I expect the chain to speed up with increasing acceleration because more and more mass is coming off the table. I then incorrectly drop the exponentially decreasing term from my mathematical solution on "physical grounds." My steps in solving the problem mathematically are dictated by my mechanistic reasoning about what the target phenomenon should look like.

After applying boundary conditions (what I call B.C.'s), I discover that dropping the terms is not the correct method for solving the problem.

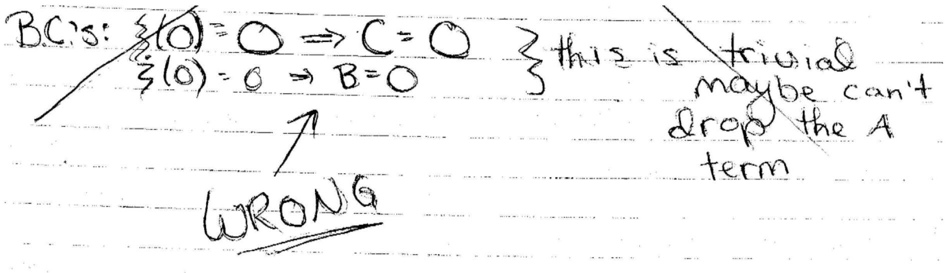


Figure 25

Application of the boundary conditions leads me to the conclusion that all terms in the complete solution (homogeneous and nonhomogeneous) are zero. I am uncomfortable with this solution as well, not because it fails match my understanding of the target phenomenon but because I end up with a mathematically trivial solution: I did not imagine that they would give a problem to which the solution was zero. I decide to resolve the differential equation keeping both the exponentially increasing and decreasing terms; this entirely mathematical method of solving the problem ultimately gives me the correct answer. In this case, using my physical description of the target phenomenon to check and supplement the mathematics leads me to an incorrect answer that I correct by temporarily neglecting my sense of mechanism about the problem.

Strictly speaking, dropping terms is not a legitimate mathematical move. However, dropping terms is commonly an appropriate move in physics. For example, in solving reflection and transmission problems in quantum mechanics we often leave out solutions representing waves moving in the "wrong" direction around potential wells. We modify the mathematical solutions derived from Schrödinger's equation using our understanding of the mechanism behind how the waves might plausibly be moving. My mistake in the chain problem is not so much in dropping the term but in misinterpreting the exponentially decreasing term as necessarily indicating a decreasing solution. Although in this case it is incorrect to drop terms, dropping terms based on physical considerations is generally appropriate (and even necessary) in solving physics problems. Mechanistic reasoning often supplements mathematical solutions.

Conclusion

In this chapter, we use the mechanism coding scheme to analyze student solutions to a graduate qualifying exam question on classical mechanics. The success of this methodology may in itself be somewhat surprising. At the start of the analysis it was not clear that the coding scheme developed from characterizations of professional bioscience research and tested in conceptual science discussions would capture the advanced reasoning of graduate students in problem solving. However, we find evidence of each of the mechanism codes in student written work. As such, it seems that the framework might begin to help us characterize how students make progress in mechanistic reasoning across K – 20 science education.

The analysis provides some insight into what mechanistic reasoning might look like in upper level physics learning. For example, students use mathematical expressions to more precisely define target phenomenon, starting conditions, and entity properties. As seen in Ben's decisions to integrate, students' choice of whether or not to apply advanced mathematical machinery (integration vs. algebra) reflects their understanding of the underlying mechanism at work, particularly the entity properties and organization. Finally, mechanistic reasoning may dictate the particular mathematical moves students make in solving problems; that reasoning may be particularly noticeable when students make moves that are mathematically invalid.

The excerpts from this analysis suggest that upper level students do in fact reason mechanistically when solving mathematically rigorous physics problems. In doing so, it provides further evidence that mechanistic reasoning is part of expertise in “doing” and learning advanced physics and is not just a way for students to “get started” in understanding basic science concepts. Mechanistic reasoning may thus be one element of continuity from naïve to expert physics understanding. It seems appropriate then to attend to the development of that reasoning as an integral part of expert physics understanding and not limit its scope to introductory science topics.

Chapter 8: Reflection on Current Work and Directions for Future Research

Introduction

The work presented in this dissertation is grounded in two assumptions. The first assumption regards student resources for science learning.

> Imagine a kindergartener and ask yourself whether she's likely to know about what its like to lift and drop rocks or books or tissue paper about how it feels to touch a candle flame or an ice cube; about what water does when she pours or drinks or swims in it. Does she know about seeing things through a window or her reflection in a mirror; about the sounds of hitting drums or guitar strings or just her abdomen; about walking and running, slipping and falling, or slipping and *gliding*? Could she predict what would happen is she were to step on a house of cards – if that's not something she's actually done – or what would happen if she were to pour a jar of ink onto a tablecloth, or if she were to try to use a bowling ball to play soccer? (Hammer & van Zee, 2006, p. 13)

From a very young age, students have lots of experience with the physical world. It must be the case then that our students are familiar with what kinds of things can happen and what kinds of things can cause other things to happen. As Sherin (2006) suggests: "Given that we [and our students], as humans, must function in the physical world, it is manifestly evident that we [and our students] must know a great deal about the behavior of that world" (p. 536). Students have knowledge readily available for thinking about science.

The second assumption follows from the first and speaks to the purpose of science inquiry in classrooms.

> Students start with sufficient understanding to engage in significant conversations that they can learn in and contribute to. (Greeno, 1992, p. 42)

and

> According to this view, we should try to change education in science and mathematics so that mathematical and scientific thinking are the main focus of activities in situations of learning, enabling students to develop the capabilities of scientific and mathematical thinking through elaboration, refinement, and modification of capabilities that they bring. (Greeno, 1992, p. 40)

Science classrooms should not always center on providing students with pieces of factual knowledge but rather should provide students with opportunities to practice and refine their thinking about knowledge they have already gleaned from their experiences with the physical world.

These two assumptions may be easy to accept in the abstract, but are more difficult to put into practice. Much of the challenge in enacting science inquiry grounded in these two assumptions is in defining what constitutes good scientific thinking and how to assess it in students. While many educators may accept the value of such inquiry, the continued ambiguity of "scientific thinking" makes it difficult for researchers, curriculum developers, and teachers to pursue it systematically. This work attempts to make our understanding of that thinking more articulate. We make progress in defining scientific thinking along one particular dimension – reasoning about causal mechanisms for phenomena.

Summary

Mechanism Framework

In this work we motivated our attention to mechanistic reasoning by describing the limitations of current characterizations of inquiry centered on controlled experimentation. We presented further arguments about the prevalence and value of mechanistic reasoning in professional science and in everyday causal thinking. Finally, we discussed the need to make the heuristic descriptions and examples of mechanistic reasoning found elsewhere in the literature more explicit.

The primary result of this work is the coding scheme itself. Using Machamer, Darden, and Craver's (MDC, 2000) account of bioscientists search for mechanisms, we developed a framework that provides a reliable means of analyzing student scientific discourse for evidence of mechanistic thinking. We drew on their definition of mechanisms as "a series of activities of entities that bring about the finish or termination conditions [from the set-up conditions] in a regular way" (MDC, 2000, p. 7) as well as their notion of chaining: reasoning about one stage of a mechanism based on what is known about another stage. Our framework consists of seven main codes derived from their characterization that identify aspects of mechanistic reasoning and can be used to systematically analyze narrative data for patterns in student thinking. Below we briefly describe each of the codes.

1. <u>Describing Target Phenomenon (DTP):</u> Students state or demonstrate the particular phenomenon or result they are trying to explain.
2. <u>Identifying Set-Up Conditions (SC):</u> Students identify the particular enabling conditions of the environment that allow the mechanism to run.

3. Identifying Entities (IE): Students identify objects that affect the outcome of the phenomenon.
4. Identifying Activities (IA): Students articulate the actions and interactions that occur among the entities.
5. Identifying Properties of Entities (IPE): Students articulate general properties of entities that are necessary for the mechanism to run.
6. Identifying Organization of Entities (IOE): Students describe how the entities are spatially organized, where they are located, or how they are structured.
7. Chaining: Backward and Forward (C): Students reason about one stage in the mechanism based on what is known about other stages in the mechanism.

The coding scheme allows us to be explicit and articulate about the instructional intuitions we have regarding the value of student thinking. Our ability to obtain precision and clarity with respect to mechanistic reasoning suggests that it is worthwhile and appropriate for educators to devote time to pinning down their understanding of productive science learning in other areas, perhaps with help from the history and philosophy of science.

Case Study Analysis

The mechanism framework provided us with a tool for analyzing student scientific inquiry. We described the results of that analysis for four case-studies. Application of the mechanism coding scheme allowed us to develop rich, in-depth descriptions of the students' inquiry; these descriptions captured both our intuitions about when students are doing well and revealed student abilities obscured by traditional assessments. We summarize the results of those descriptions below.

Case One: First Graders Discuss Falling Objects

Our coding of the first graders in a large group discussion about falling objects revealed young students engaging in sophisticated mechanistic reasoning; they are capable of constructing rich theoretical explanations that some education literature suggests is developmentally restricted from this age. It seems appropriate then that science inquiry should allow for and promote student abilities to do so by including subject matter that is rich with mechanistic possibilities.

The first grade students also transitioned quickly and fluidly between various levels of mechanistic thinking. This observation suggests the need to account for the variability of student reasoning in our research on and assessments of science learning. In particular, it is inappropriate to assume how students act or respond in one context will be the same as how they act or respond in other contexts. Thus researchers need to study student reasoning in a variety of situations: such as written work, students participating in class, students talking to their friends, and one-on-one interviews. Similarly, educators need to assess student reasoning based on performance on a number of tasks or else they risk misrepresenting the breadth of their students' abilities and ideas.

Case Two: Second Graders Discuss Collapsing Juice Boxes

The description of the second graders' small group discussion about collapsing juice boxes illustrated that students can be engaged in mechanistic reasoning that is valuable and productive for understanding science even when the products of that reasoning are incorrect. So we saw again that students are capable of mechanistic reasoning, which leads support to our initial assumption. We also found that a teacher's reactions to the correctness of an idea can nudge students out of productive mechanistic reasoning. We suggested that such reasoning may be an instructional target worth pursuing in its own right, rather than merely using it as a method for teaching and learning correct content.

The analysis also clarified that the quality of mechanistic reasoning is independent of whether the result of that reasoning is correct. As such, reasoning can and should now become the subject of research in and of itself. We can begin to systematically study reasoning, its development, and its dynamics to gain insight into what curricular materials might promote such reasoning.

Case Three: College Students Discuss Electrostatics

Applying the coding scheme to the discussion of electrostatics that occurred among college students in an introductory physics tutorial revealed several productive relationships between informal empirical investigation and mechanistic reasoning. This finding suggests that scientific inquiry should not be limited to controlled experimentation. Even when the students are not selecting variables to test or performing rigorous data analysis, they can nonetheless make significant progress in understanding and constructing models for novel physical phenomenon. As such, theoretical reasoning supported by informal observation should be given a more prominent place in our conceptions of inquiry and our science curricula.

Case Four: Graduate Students Solve a Classical Mechanics Problem

The analysis of the independent work (written and interview) of graduate students on a classical mechanics exam question suggested that mechanistic reasoning plays a crucial role in solving heavily mathematical physics problems. In addition, the mechanism coding scheme was able to capture their reasoning, suggesting some continuity between what we observed in novices (first graders) and what we observed in experts (graduate students). This possibility is discussed in more detail below.

Reflections on the Current Work

From Intuitions to a Coding Scheme to a General Language

In looking back over this dissertation, I am reminded of my experiences in the physics education research group at the University of Maryland that led me to begin this work. When I entered the group after leaving a traditional physics undergraduate program, I had difficulty "seeing" all the good stuff in video of student science discussions that others in the research group so readily saw. I grew frustrated because while it seemed to natural to others in the group, when I watched episodes of student reasoning I did not even know where to look for the good stuff, much less what to see. Others in the research group tried to help me but they struggled when trying to be articulate about what they were seeing. What they saw seemed to be grounded in their intuitions: intuitions that I did not yet share. It took me over a year of listening to our group analyze student science conversations before I was finally able to develop my own intuitions about what productive inquiry looks like. My frustration with this experience led me to seek a more precise language for talking about student reasoning so that others might not find themselves floundering as much when learning to watch video.

I found that more precise language in a philosophy of science course about mechanisms in professional science taught by Darden (of Machamer, Darden, and Craver, 2000). In retrospect it is somewhat surprising that a framework developed from descriptions of professional research would be able to identify corresponding elements in students' discussions of science. First, Machamer, Darden, and Craver set out to characterize the mechanisms that exist in the world whereas we were trying to identify times when students reason about and construct understanding of those mechanisms. Second, MDC study the work of scientists with extensive content knowledge in their fields whereas we were studying student reasoning discussing topics in areas where they are not experts. Third, whereas we studied students constructing knowledge in the moment, MDC look at historical episodes of discovery. Finally, MDC's work centers on the mechanisms studied by biologists, geneticists, and neuroscientists while we study how students learn physics concepts. So in retrospect, it was by no means guaranteed that our analysis would be possible much less fruitful. And yet, the framework both "works" and does work for us.

Now that the framework has been developed, I am pleased that it has provided a language not only for me but also for others in our research group to talk about mechanistic reasoning. When others who are not a part of our group ask us what kinds of good things we see in a particular student science discussion, we can now use the language of the mechanism framework to articulate our instructional intuitions. The coding of entities, activities, and chaining helps us describe the good stuff that was formerly described only by our sense of goodness. For those who have not yet developed intuitions about mechanistic reasoning, systematic coding provides a readily accessible avenue for developing them.

In this sense, the framework has done its job; it has helped us develop and be clear about our intuitions regarding student mechanistic reasoning. However, now that I have analyzed several video cases, I believe that systematically applying the coding scheme may no longer be necessary (at least for me). At this point, I do not need to code every single line of every single student in a class discussion to identify moments of mechanistic reasoning. My experience in applying the coding scheme to other pieces of data has helped me sharpen my focus; I know both where to look and what to see in student science discussions. For me, the power of the framework now lies in the language and terminology it provides, more than in the graphs or patterns of codes it generates.

A Perspective on Continuity: Progress in Physics Learning

At this point, it is appropriate to step back from the specifics of each case and think about the "bigger picture" of this work. What might all the cases taken together indicate about student mechanistic reasoning?

The cases presented here involve almost the largest possible breadth of students: first graders all the way up to graduate students. Unlike education research that focuses on one particular age group or grade level, this work spans K-20 science learning; the same framework is able to capture similar mechanistic reasoning in all ages of students. When the cases are taken together, we begin see continuity between graduate level learning and elementary school science: part of what students are able to do in elementary school finds its way to graduate school.

So what does it mean that we find mechanistic reasoning as a thread that runs throughout K-20 science learning? Let us first consider what it does *not* mean. The fact that these cases show sophisticated mechanistic reasoning throughout the grade levels does not mean that educators should take that reasoning for granted in their students; it would be inappropriate for teachers to assume that just because students can reason mechanistically that they necessarily will. In fact, as instructors in college courses we have all observed instances when students are doing the exact opposite of mechanistic reasoning; instead of making sense of the physical situation they memorize and pattern match equations to problems.

An Example of a Non-Mechanistic Approach to Science

Consider the following example from a group study session in which college students are trying to estimate the pressure difference between the top and bottom of their dorm room. Solving this problem is fairly easy if one thinks about the mechanism for the pressure difference: the weight of the air in the room exerts an extra pressure on the bottom of the room that is not on the top. All the students need to do is to find the weight of a column of air the height of their room. Instead, they students do something that is physically non-sensible; they randomly apply a formula solely because it includes a relevant variable (P for pressure).

S1: Well pressure's supposed to be higher at the bottom, isn't it?

S2: Hmm?

S1: Pressure is supposed to be higher at the bottom.

S2 I think there's more at the bottom, because the thing, because the gravitation.

S1: And, there's pressure pushing down on it.

S2: Um-huh.

S1: OK.

S2: Pressure's equal to the radius times the moles of the gas times the temperature divided by the volume. So, what we need to do, we know the pressure find the volume from this. Density is equal to...

S1: Are you using PV equals N R T?

S2: Huh?

S1: Are you using P V equals N R T?

S2: Yeah, or yeah

S1: Or.

S2: Or P equals R times N T...

S1: Over V.

S2: Over V.

S1: We know the pressure.

S2: We know the pressure. But we need to take the density to volume. Density is equal to...

S1: Oh, we have the density.

S2: Yeah, yeah, but that doesn't matter we need the volume.

S1: Oh, what did I just say.

S2: Density is equal to volume over what mass, or something?

S1: Density equals mass over volume.

S2: Hmm?

S1: Density is equal to mass over volume.

S2: Is equal to mass over volume.

S3: It's over, it's over.

S2: OK. So, if let's say it's equal to mass over volume, then [to another student] yeah. No I just found the formula to do it. So, this is equal to mass over volume, then the mass is equal to. So, basically we just found the formula that P is equal to the radius times the moles times the temperature over the volume. So, if we have the density we can find the volume.

S1: Is R the radius?

S4: I don't think R is the radius.

S2: It's not? The radius of the...

S1: R isn't radius. R is...

S2: Or, whatever R is.

S4: Some number.

S1: It's not radius.

S2: Is it a constant?

S3: Yeah, it's a constant. It's a constant.

What these students are doing is ridiculous; though they start with a sensible idea that pressure should be higher at the bottom of the room than the top, they quickly move to using PV=nRT which has no physical relevance to the problem. Unlike those in the cases presented in this dissertation, they are not engaging in any (much less sophisticated) mechanistic reasoning about the phenomenon in question. They are not trying to identify physical causal entities and activities (nor are they chaining) that affect the pressure in the room. This example is not an isolated case; we have all seen other students engaging in this non-sensible behavior instead of reasoning about problems mechanistically. However, even though students sometimes do not engage in mechanistic reasoning, we have no reason to suspect that they cannot do so. In fact, we have evidence to the contrary: we see them doing so from a very young age.

Supporting Continuity in Mechanistic Reasoning

Our experiences with student discussions like those above suggest that it is not appropriate to assume that just because mechanistic reasoning can appear across grade levels it necessarily will. These college students (and others) may have learned from other experiences in science that this kind of ‘plug-n-chug’ problem solving is how you are supposed to do science or that its how you get good grades in science classes. Thus even though they are capable of the kind of mechanistic reasoning we see in young students, they may (tacitly) decide not to use it. If we want to see more of the continuity in mechanistic reasoning across K-20 education, we need to be explicitly attentive to and encouraging of it lest we actually suppress it in our students. There are two ways this suppression might occur, making it less likely that we will see mechanistic reasoning in upper level science learning.

The first is epistemological: if we do not support student's efforts at mechanistic reasoning, we may in fact send students the message that mechanistic reasoning is not appropriate or valuable for science learning. Part of science teaching must involve helping students recognize that the thing they are doing in first grade *is* science and that it is the kind of thing they should continue doing throughout their school science careers. We need to be explicit with students that mechanistic reasoning is one of the right things to do in learning science, as opposed to the physically non-sensible activity we saw the college students do above.

The second way we might suppress students' mechanistic reasoning is merely by failing to give them opportunities to engage in it. Like any skill, from integrating a contour integral to doing a flip on the balance beam, learning to productively engage in mechanistic reasoning takes practice. As Greeno (1992) suggests, we suspect that "its [scientific thinking] growth will depend mainly on opportunities to think" (p. 40). Unless our classrooms provide such opportunities, students' ability to reason mechanistically may not develop but instead stagnate.

Progress in Science: Progress in Mechanistic Reasoning

The continuity we observe in the reasoning of first graders and graduate students helps us think about how mechanistic reasoning might develop or progress if we are purposefully attentive to it. One possibility for development would be for students to gain access to richer stores of entities and activities so that their mechanistic explanations can go to a deeper level. For example, instead of relying on entity properties of “conductor-ism” to account for the mechanism of static electricity, students might show refinement in their mechanistic thinking by reasoning about what entities and activities underlie that property (namely electrons jumping). Progress in mechanistic reasoning might also manifest itself in students’ more precise identification of entities and activities, as in the case when Ben and I use mathematical expressions to describe entity properties or organization. Another type of progress might involve students becoming aware of their transitions into and out of mechanistic reasoning. For example, while the first graders probably did not consciously or deliberately shift between describing target phenomenon and chaining, Ben and I both show awareness of and control over our decisions about when to use mechanistic reasoning (in calculating potential energy) and when not to (in using Lagrange’s equation to find the equation of motion). Coordinating mechanistic reasoning with other strategies (e.g. constraint based reasoning, mathematics, experimentation) might also indicate development in science learning.

This analysis gives us a way to conceptualize progress in science learning, and in particular physics learning. Instead of thinking of progress in science learning as the accumulation of more conceptual facts, we might begin to think of progress as the refinement of mechanistic reasoning abilities. Our ability to identify similarities in the mechanistic reasoning of students throughout K-20 education helps us think about how that reasoning is changed and refined (or can be changed and refined) through experiences with science inquiry.

Directions for Future Research

Analysis of the Effects of Systematic Attention to Mechanistic Reasoning

In this work we have suggested that it is appropriate (and possible with the mechanism framework) for educators and researchers to explicitly attend to and systematically promote mechanistic reasoning in student discourse. One avenue for future research would be to explore the effects of such explicit attention on students' science learning. What would happen if educators were intentional about recognizing and promoting mechanistic reasoning in their classrooms? It may be that the idea of mechanistic reasoning as appropriate and productive for science would become more firmly established in students' epistemologies such that they would use it automatically. In that case, college professors might be able to take that reasoning as an existing foundation on which they can build conceptual understanding. It may also be that students would develop and access richer collections of resources for making sense of physical situations. Future research could explore these possibilities for what the continuity in mechanistic reasoning might look like if it received explicit attention in science teaching.

Analysis of Student Resources for Science Learning

The mechanism framework we developed provides a research tool for analyzing the phenomenology of student reasoning during inquiry; it allows us to be articulate about what we see students doing and helps us precisely describe student behavior. These rich descriptions of student behavior are interesting and valuable in and of themselves, but they also suggest questions for further research. In particular, seeing how students behave during inquiry naturally prompts questions about why students act as they do. For example,

1. Why do the students in the falling objects discussion (chapter four) switch from the lowest to the highest levels in the mechanistic framework when they do?
2. Why do the students in the electrostatics discussion (chapter six) start talking about their observations and shift to thinking about the mechanism underlying those observations?
3. Why did I "see" the chain falling off the table in terms of its center-of-mass while Ben thought about it in terms of an integral? (chapter seven)

These questions all arise from studying the data through the lens of the mechanism framework; we could not speculate about why the students in the falling objects discussion transitioned between levels without first identifying what those levels are and when students move between them. Although these questions come out of the precise descriptions of student behavior, further work outside of phenomenology is needed to answer them. Below is an example of the kind of analysis that might shed light on these kinds of questions.

A Transition in Explanation: Juice Box Discussion

Consider the following example from the episode of inquiry presented in chapter five. Second grade students are discussing with their science enrichment teacher why empty juice boxes collapse when you suck on their straws. The students give three different explanations for the phenomenon: the inside-pusher model, the outside-pusher model, and the imbalance of pushes model. In the inside-pusher model, air inside the box holds the sides out until the air is removed. The outside pusher model describes how the air outside the box pushes the sides in when the passive resistance of the inside air is removed. Finally, the imbalance of pushes model involves both the inside and outside air actively pushing against one another until the outside air wins when the inside air is removed.

Coding the conversation with the mechanism framework reveals an interesting transition in one student's explanation. In the excerpts below we have edited the transcript by removing teacher comments (replaced with ellipses) so that the student's ideas, which are given in several turns at talk, are one continuous explanation. Early in the discussion, Leah explains her reasoning for why the sides cave in when there is less air inside the box as follows:

> **Leah:** Because the air, it blows um, the uh sides (Holding sides of box and moving her hands out away from the box.) It blows the sides… Um. I think that um as you s, um, drink the juice the air comes out too, and some air, a little bit of air comes out too. And the more, the less air there is in the juice box, the more the sides go in.

Leah initially expresses the inside-pusher model for the phenomenon; the sides of the box cave in when there is less air in the box because air inside the box blows out to hold its shape. The coding scheme identifies evidence of mechanistic reasoning in Leah's comments; she describes an entity (air), its location (inside the box), and its activity (blowing the sides). She then chains from those elements to the observed phenomenon.

After another student gives the outside-pusher model, Leah changes her explanation.

> **Leah:** Um. I, I think since there's no, there's um air inside and then we suck up, out a little, um and the air uh is also like pushing, pushing in the sides [Pointing to the sides of her box.] …from the outside…. And, uh while the um air is coming in [into our bodies as we suck it out of the box] from the inside [of the box], the ou, the air from the outside is push, push, pushing also to um, pushing the sides also to make it cave in.

Leah now describes the outside-pusher model: there is air inside the box (she does not say it is pushing) and when it is removed, the air outside pushes on the sides to make them collapse. Here she identifies the same entity (air) with the same activity (pushing the sides) only it now has a new location (outside the box).

As educators, we might have hoped that on hearing that air pushes on the box from outside, Leah would add the new idea of air outside pushing to her original idea of air inside pushing to come up with the correct, balance of pushes explanation. However, she does not. We would like to be able to make sense of *why* Leah changes her mechanism for the juice box collapsing in the way that she does instead of changing to the imbalance of pushes model. One possible way to explain her transition as evidenced in her verbal behavior (phenomenology) is to consider what sorts of elements are acting in her mind (ontology).

The mechanism behind the (incorrect) inside-pusher model involves one entity in one location engaging in an activity to produce the entire phenomenon - air pushes on the inside of the box to support it. The box's collapse results largely from property of the box – without anything to hold the sides out, the box naturally falls in. In the language of diSessa (1993), Leah initially invokes a general piece of knowledge (a cognitive element called a p-prim) about *support* in which an object (juice box) is held in place (sides held out) by another object (air) in its path. This same general mechanism helps make sense of other situations as well. For example, a glass of water sits on a table because the table *supports* its weight; without the table, the glass would naturally fall to the ground.

The (incorrect) outside-pusher explanation also involves one entity in one location engaging in an activity to produce the entire phenomenon - air pushes on the outside of the box to collapse it against an inside resistance. As with the inside-pusher model, there is only one active agent; the inside air serves only to resist and does not actively push. Here, Ben has applied *Ohm's* p-prim, which diSessa (1993) describes as "**an agent** that is the locus of an **impetus** that acts against a **resistance** to produce some sort of **result**" (p. 126). This sense of mechanism allows Ben to make the claim that less resistance (inside air) with the same impetus (outside push) produces more result (sides go farther in). Although not appropriately applied here, Ohm's p-prim accounts for other phenomenon such as Ohm's law of electric circuits (V = I*R) where voltage (V) is impetus/effort, current (I) is result/effect, and resistance (R) is resistance.

In contrast to both the inside- and outside-pusher mechanisms, the correct explanation requires two entities in two locations both engaging in an activity *against one another* to produce the phenomenon – air inside pushes out against air outside pushing in and the outside "winning" causes the box to collapse. In addition to needing two active entities, the ideas of *dynamic balancing* and *overcoming* (diSessa, 1993) are also required for the mechanism to run. In order for the box to collapse "two opposing forces 'try' to achieve mutually exclusive results" but one force is greater and "wins over the others, and the winner's 'intended result' is achieved" (diSessa, 1993, p 135-138).

Considering the cognitive elements (p-prims or resources) that give rise to inside-pusher, outside-pusher, and imbalance of pushes mechanisms gives insight why Leah might have shifted from inside- to outside-pusher instead of shifting to the correct explanation. Leah's transition from the inside- to outside-pusher model does not require changing the overall sense of the mechanism; in both her explanations there is one active causal entity responsible for the phenomenon. However, a transition to the correct explanation would have involved not only recognizing that air exists and pushes on both sides of the box but also incorporating the (less obvious and thus perhaps more challenging) idea of two forces acting independently in opposition to *balance* one another until one overcomes the other. Such a transition is non-trivial; it is similar to the shift required to understand normal forces. A table does not just prevent (or resist or support) objects from falling to the ground; the table actually pushes back up on the object to balance gravity that is pushing down.

Thinking about the cognitive elements that underlie Leah's explanations helps us make sense of why Leah changes her explanation for the juice box collapsing in the way that she does; her transition only requires changing the entities in her existing mechanism whereas the correct transition requires thinking about an additional piece of mechanism: balancing. This explanation for Leah's transition gives an example of the kind of analysis that might follow and build on the work presented in this dissertation.

A Shift from Phenomenology to Ontology

The mechanism framework is a phenomenological coding scheme: it is used to identify evidence of student mechanistic reasoning during scientific inquiry. An appropriate direction for future work involves a shift from analyzing student behavior to speculating about is happening in students' minds that gives rise to that behavior. As in the analysis above, understanding what cognitive elements exist in students' minds (resources) will help us answer questions about the development and dynamics of mechanistic reasoning. Possible questions to pursue include:

1. Do new mechanisms that students reason about develop from old ones? If so, how and why do students transition between the new and old ones?
2. How does students' understanding of mechanisms develop? What conceptual resources do students have for thinking about physical phenomena (e.g. p-prims)? How do students use these resources to understand mechanisms?
3. How does students' understanding of mechanistic explanations develop? What do the epistemological resources for mechanistic reasoning look like? How do students' learn when it is appropriate to reason about mechanisms and when other types of explanations (i.e. intentional, constraint-based) are more appropriate?

These questions represent a shift in focus from phenomenology to ontology. That is, now that we have a framework for reliably identifying evidence of mechanistic reasoning (phenomenology), we are in a better position to answer questions about how that reasoning develops and becomes activated during scientific inquiry (ontology).

Concluding Remarks

In this dissertation we used the framework we developed from the philosophy of science to describe both the abundance and value of mechanistic reasoning in student inquiry. This reasoning is continuous with how laypeople reason about causal situations in the everyday world. For example, the other day I wanted to send a fax but was concerned because there was a “Low Toner” error message on the machine in my office. However, by reasoning about the mechanism of how the fax machine works (scanning the image, calling the recipient’s number, transmitting the information, printing the scanned image on the recipients machine), I quickly figured out that my concern was silly; low toner on my machine could not affect the image received at the other end. Mechanistic reasoning is also continuous with the work of professional scientists. For example, some current work in molecular genetics is focused on how changes in the structure of the ribosome affect the mechanism of ribosomal frameshifting (e.g. Meskauskas, Harger, Jacobs, & Dinman, 2003). That mechanistic reasoning, which we have identified across K-20 education, connects to both everyday experience and research science gives credence to Einstein’s suggestion that “the whole of science is nothing more than a refinement of everyday thinking.”

Appendix A: Summary of Mechanism Coding Scheme

Mechanism Code	**Description of the Code**
Describing Target Phenomenon (DTP)	Students state or demonstrate the particular phenomenon or result they are trying to explain.
Identifying Set-Up Conditions (SC)	Students identify the particular enabling conditions of the environment that allow the mechanism to run.
Identifying Entities (IE)	Students identify objects that affect the outcome of the phenomenon.
Identifying Activities (IA)	Students articulate the actions and interactions that occur among the entities.
Identifying Properties of Entities (IPE)	Students articulate general properties of entities that are necessary for the mechanism to run.
Identifying Organization of Entities (IOE)	Students describe how the entities are spatially organized, where they are located, or how they are structured.
Chaining: Backward and Forward (C)	Students reason about one stage in the mechanism based on what is known about other stages in the mechanism.

Table 3

Appendix B: Transcript of the Falling Objects Discussion

Teacher: What, what happened when you dropped the book and the piece of paper at the same time, at the same height? Huh, what happened? (Students raising hands.) Okay, Ebony why don't you go ahead and begin.

Ebony: To me, first, the paper fell first.

Jorge: No way, no!

Student: Whoa!!

Brianna: The book fell first.

Ebony: No, to me the paper fell first.

Students: No!

Student: It fell at the same time.

Ebony: No, the book, um - the paper fell - the paper fell first to me!

Henok: ⌈Yeah, but not to me!

Ebony: ⌊To me it fell, the paper fell first (Voice trailing off.)

Jorge: Yeah, but did the book fall first, just like the paper?

Ebony: No, the papers fell first.

Henok: The book fell first.

Ebony: No, the paper – to me.

Allison: To ⌈Ebony – to Ebony the paper fell first.

Student: ⌊To me, not to you

Brianna: And to all of us the book might of fell first to us.

Students: Yeah.

Jorge: Our paper - our paper goes slowly. It's, it's, it's a little bit ["out of practice"?].

Student: [Inaudible comment.]

Rachel: With me and Julio twice the book and the paper tied - ⌈twice.

Ebony: ⌊went at the same time.

Rachel: They both tied twice.

Allison: What do you mean tied?

Rachel: ⌈They both

Ebony(?): ⌊They went both at the same time.

Rachel: They both went down

Autumn: They both fell down at the same time.

Julio: ⌈They both fell down at the same time.

Allison: ⌊Same with me, same with me, same with me, same with me!

Students: [Inaudible discussion and laughter.]

Teacher: So, what I'm hearing is that we have one person that said when he did it, that -

Brianna: the ⌈paper fell

Teacher: ⌊- that when he dropped at the same time, from the same height -

Brianna: the paper fell first

Teacher: - that the paper fell first. Now do you mean it hit the ground first, or it just started to fall first?

Ebony: It hit the ground first.

Teacher: So, you're saying the paper hit the ground first, and then the book hit the ground. (Ebony nodding his head in affirmation.) Then we have two other friends who are saying that the book and the paper hit the ground at the same time.

Rachel: ⌈Twice!

Students: ⌊Yeah! Twice!

Teacher: Twice. You did it twice and that's what you noticed.

Allison: Yeah, me too!

Teacher: Okay.

Students: [Inaudible discussion.]

Student: And then we did it.

Teacher: What happened with it when the rest of you did it?

Diamond: Oooh.

Autumn: The book fell first.

Brianna: Yeah, the book fell first, yeah.

Diamond: Um - the paper, when we - the book and the paper –

Student: [Inaudible comment.]

Diamond: - the book fell first –

Teacher: Mmm hmm.

Diamond: - but Henry (Points to Henry) keep putting the paper so it could fall first.

Teacher: How did, how was Henry putting the paper so it could fall first?

Brianna: He's dropping the paper first, and ⌈then the book.

Diamond: ⌊He did like this. (Raises and lowers her arm.)

Henry: No!

Diamond: Uh hm. And I told you to stop.

Henry: I didn't do that.

Diamond: Yes you did!

Henry: No, I didn't. (5 second pause)

Jorge: [I think both of 'em??]

Teacher: How could this be that we all did the same thing – we dropped the paper and the book -

Brianna: and it was all different!

Allison: ⌈[Inaudible comments.]

Teacher: ⌊- at the same place, at the same time. How could it be that we got all these different results? One person found out the paper hit the ground first, and then the book. We have two other friends that found out the book and paper fell down at the same time.

Rachel: Twice.

Teacher: Twice, two times. And, then some other friends are saying, "Well, no the book hit the ground first, and then the paper."

Student: ⌈Yeah.

Allison: ⌊[??] My group went around two times. My group went around two times.

Teacher: How could it be that we all – we got ⌈different results

Allison: ⌊and with

Teacher: - when we did the same thing?

Allison: When one of - when our group went around once, the book hit the ground first. But, then, the second time we went around - with me they fell at the s, same time. And, with Ebony, ⌈the paper fell first.

Ebony: ⌊the paper

Allison: And then with Eveen –

Ebony: The book fell first

Allison: - they didn't get - have time to get a turn.

Teacher: Okay. Wh - why do you think that is? Why did that happen?

Ebony: ⌈Cause we did it twice.

Teacher: ⌊Do you have an idea?

Teacher: ⌈Rachel has -

Rachel: ⌊Forces of gravity?

Henok: Yeah.

Teacher: - Rachel has an idea.

Rachel: Forces of gravity.

Allison: Yeah!

Diamond: What are forces of gravity?

Rachel: ⌈Gravity is what -

Allison: ⌊Gravity, gra – you know how when we jump we always land back on the ground.

Rachel: Exactly. It's what keeps us down on the ground. (Patting the ground.)

Student: Yeah.

Autumn? ⌈Like ground magnets.

Ebony: ⌊And no gravity. No gravity is when you're like in space and you can never ever really fall down. [??]

Julio: You know, you just float in the air. (Ebony nods in agreement.)

Allison: Gravity – see how when I jump (Stands up and jumps.) I'm just landing at the same place on the ground that - because gravity, gravity is just pulling me down.

Teacher: Okay.

Rachel: We're not all going to.

Teacher: Oh, we're not all going to [jump?]. They already, they already showed us. (Students jumping.)

Students: [Inaudible comments.]

Teacher: You can sit down. (7 second pause)

Students: [Laughter.]

Teacher: Okay, so, so what you're saying is that a for - what is a - you're saying the force of gravity -

Rachel: is pulling it down at different times.

Teacher: So, you're sayin' the force of gravity is pulling the book down at a different time than the paper.

Student: ⌈Yeah.

Rachel: ⌊Yeah, probably. And, sometimes it's pulling it down at the same time, or pulling the paper down

Alison or Brianna?: Before the ⌈book.

Brianna?: ⌊And then the book, ⌈and then the paper [??]

Rachel: ⌊Before the book and then the book's pulling it down before the paper. Gravity's pulling the book down before the paper.

Ebony: You said that.

Teacher: Why would gravity – why would gravity (3 second pause) How do I phrase this. Why, why would gravity sometimes make the book come down first, and then the paper. But the, the same gravity at other times make things come down at the same time. Or you're saying that gravity sometimes makes the paper come down before the book.

Autumn: ⌈I am not [???] this. [??]

Teacher: ⌊Why does - why does gravity do all the - I'm trying to think. (2 second pause) How could gravity make - how could the same force of gravity - give us three different results?

Henry: Ooh, ooh, ooh. I know.

Allison: Maybe -

Teacher: Can we have Henry share? Go ahead.

Henry: Uh cause it’s the, c - cause it’s um, if you drop the book first, then it goes [first?/like this?] but if you drop the paper then the paper will go down. (Voice trailing off.)

Teacher: Are you saying if you dropped the book first –

Henry: Mmm-hmm.

Teacher: - and then the paper, that the book will hit first?

Henry: No, if you drop them in, in the same time, they both will, I’m saying they both will fall down.

Teacher: They both will fall down. ⌈We’re -

Henry: ⌊I think.

Teacher: Okay. So if we, if we drop them, I’ll go ahead and drop ‘em, you’re saying they both will fall down.

Henry: No.

Student: They won’t. (Teacher drops the book and the paper simultaneously.)

Brianna: Oh. The book fell first.

Students: [Inaudible comments.]

Henry: No, I said if you - if you drop ‘em at the same time, maybe they might fall on the same time - on the floor.

Students: [Inaudible comments.]

Teacher: Let’s go ahead - let’s go ahead and just - I’m going to do this a few times - I’m going to do it five times. And, let’s watch and see what happens, okay? I’ll go ahead - I have the book and piece of paper.

Diamond: The paper’s gonna fall second and the book’s gonna fall first.

Teacher: Well, we’ll see. Some people said that that’s what they found out, other people that they saw that they hit at the same time, and then we had two people that said that, “Well the paper hit first.” Let’s see what happens, okay? You guys watchin’?

Student: Yeah. (Teacher drops the book and the paper simultaneously.)

Brianna: The book fell first! Yeah!

Allison: ⌈I knew it!

Diamond: ⌊I knew it!

Teacher: Let’s try it a few different times, because we got –

Student: ⌈One, two

Teacher; ⌊- a lot of different types of results. Are they about the same height? (Teacher holds the book and the paper up.)

Students: Yeah. (Teacher drops the book and the paper simultaneously.)

Brianna: The book fell first again!

Diamond: I knew it!

Student: [Inaudible comment.]

Teacher: Alright, we’ll do it three times. (4 second pause.)

Student: [Inaudible comments.] (Teacher drops the book and the paper simultaneously.)

Brianna: The book fell first!

Diamond: I knew it!

Students: [Inaudible comments.] [Laughter.]

Henok: See, Ebony?

Teacher: But, you found out something different.

Ebony: The book - the paper fell first.

Teacher: How could that be?

Ebony: I don’t know. (Ebony shrugs his shoulders.)

Jorge: Three times it falls down.

Allison: ⌈The gravity -

Autumn: ⌊You probably just dropped the paper first.

Allison: - the ⌈gravity probably -

Ebony: ⌊No.

Jorge: No the book fall ⌈down first.

Allison: ⌊- the gravity probably had uh - the gravity probably just pulled the paper a little more than it pulled the the um book.

Ebony: Maybe it’s tired. [Laughs.]

Teacher: So you’re saying that the gravity ⌈maybe -

Student: ⌊[Inaudible comments.]

Autumn: Maybe the book is tired.

Henok: I know!

Allison: Yeah. Maybe the book's tired. [Laughs.]

Students: [Laughter.]

Teacher: [Laughs with the students.] Let's come back to Allison's idea. Allison said, "well, maybe the gravity – the time when Ebony did the gravity pulled the paper down more than the book that time."

Ebony: Yeah. Maybe the gravity's tired. [Laughter.]

Students: [Inaudible comments.]

Allison: Yeah, maybe the gravity's tired!

Autumn: ⌈Maybe the gravity's tired.

Teacher: ⌊We're going to do something different now with the piece of paper, watch this.

Students: [Inaudible comments about gravity being tired.]

Allison: [Discussing with Ebony about gravity pulling one faster using hand gestures to represent each object.]

Teacher: When you go back to your seat this is what you're - you are going to do with your piece of paper. (Crumples up the piece of paper.)

Brianna: Ball it up.

Ebony: This is the book. [Discussing with Allison about gravity pulling one faster using hand gestures to represent each object.]

Teacher: You're going to make it into a ball.

Brianna: Yeah!

Students: [Laughter.]

Teacher: Not right now.

Student: Not yet ⌈Nancy.

Teacher: ⌊Nancy not yet sweetie. You're going to make into one ball, and you just need to crumple it one time. You don't need to keep doing it just one time.

Henok: ⌈Oh yeah.

Teacher: ⌊Then you're going to try the same thing. What will happen when you drop the book, and now the crumpled piece of paper –

Brianna: Crumpled

Teacher: - at the same time from the same height?

Students: [Inaudible comments.]

Student: Drop it.

Jorge: Oh yeah, I know, I know –

Student: Drop it.

Jorge: I know.

Teacher: What do you think will happen?

Autumn(?): Drop it! Drop it! ⌈Drop it!

Jorge: ⌊The book - um, the book the book and the paper will fall first.

Brianna: At the same time.

Jorge: Yeah.

Diamond: The book and the paper ⌈will fall at the same time.

Jorge: ⌊When you crush it. When you crush it like this and it will fall down first.

Student: Nancy.

Jorge: Remember, I did that while at home.

Diamond: It gonna fall at the same time. [Laughter.]

Jorge: I used to do that all the time.

Teacher: Autumn and Nancy, I'd like you to be with the group. We'll go back to our seats in a just few minutes, okay? Jorge what do you mean that it will fall first? What is the "it"?

Jorge: The um, the book and the paper will fall first, the um, the same time.

Teacher: And you're saying you did this at home when you knew that. Go ahead now Diamond.

Diamond: The book and the paper gonna fall at the same time.

Jorge: [Yeah?] If we crush it like -

Teacher: Why do you think that? That now the book and the paper will fall at the same time.

Allison: Because -

Diamond: When you ball ⌈it up -

Allison: ⌊now the pap -

Diamond: - it's almost ⌈like a ball -

Allison: ⌊- now, now, ⌈now the

Diamond: ⌊- and the ball falls first too, the same time as the book.

Allison: Now, now the paper has a little more weight because it's all crumpled.

Jorge: Yeah. Like crumpled. Like -

Allison: So it has a little more weight.

(Another teacher removes Jorge from the room.)

Teacher: So All - Allison has an idea. She thinks that now maybe with the crumpled piece of paper it has more weight. You guys are going to go ahead and test this out. You should probably go ahead back to your seats.

[Students talking inaudibly – Transcript resumes a few minutes later.]

Teacher: Be careful where you walk. Keep it there. Henry, keep, just keep it there. Okay. [??] We'd like for you to join us, on the carpet. Keep it there okay. [Teacher giving instructions to individual students.] Is everybody here with it? Make sure that you can see everybody just like before. You need to be able to see every, see everybody or part of that person so that you'll be able to also hear them. I want to know what happened when you dropped the book and now the crumpled piece of paper the same time from the same height. So what happened guys when you dropped the book and the crumpled piece of paper? What happened this time? (Students raising hands.) Brianna, Brianna will go ahead and begin. Remember, we just want to talk one at a time. (6 second pause)

Brianna: They will fall at the same time. (5 second pause) 'Cause they both got the same strength together.

Teacher: So Brianna has an idea. She said, well, she found out that they fell at the same time because they both have the same strength together? (Teacher looks to Brianna for confirmation.)

Brianna: Strength together yeah.

Teacher: Before, we said that the book had more strength than the piece of paper. How could it be that now they have the same strength? We are going to talk about Brianna's idea and then we'll go to the next one. How could it be that now they have the same strength?

Rachel: I can answer that.

Teacher: Okay.

Henok?: [I could too?]

Rachel: Um. Now that it's crumpled up, there's - the piece of paper has more strength because -

Brianna: And the book too. ⌈[Because they have, same strength all together??]

Rachel: ⌊[No??] No, I said. The piece of paper has more strength because it's all crumpled up and it used to be, um, really light but now it's, um, it has more strength. It probably has as much strength as the book since all the, um, paper is crumpled up together. (Picks up book and paper, drops them separately.)

Teacher: Do you want to comment on that? No, okay, do you have a different idea? Save that. Julio, I know you wanted to add to that before about the strength. How could they have the same strength now?

Julio: Um, crumpled up paper um is kind-of heavy. (7 second pause)

Student: [Inaudible comment.]

Brianna: If it's balled up it's still not heavy it's the same size.

Brianna: It's just a little bit like, if you need the heaviest.

Students: [Inaudible comments.]

Autumn: Why are you doing that? (Brianna picks up the crumpled paper and uncrumples it.)

Students: [Laughter.]

Brianna: It's still at the same size. It still feels -

Students: [Laughter.]

Brianna: - it still feels um –

Student: Can I see?

Autumn: It’s not heavy.

Brianna: It still feels –

Student: [Inaudible comment.]

Allison: My, my dad could probably ⌈throw that –

Brianna: ⌊it still feels [??] light. ⌈It’s still light.

Allison: ⌊- My, my dad could probably throw it up to the ceiling and he wouldn’t, and he wouldn’t say it’s light.

Brianna: It’s still light.

Student: It’s not heavy.

Student: It is not.

Students: [Inaudible comments.]

Teacher: So are you disagreeing with Julio? ⌈Is that your – okay.

Brianna: ⌊Mmm-hmm.

Teacher: So you’re saying that it’s, it’s - this is ⌈still light even when it’s balled up?

Student: ⌊still light

Student: I know it’s not heavy.

Student: But it’s just balled up at the same time because it’s crumpled up –

Students: [Inaudible comments.]

Teacher: All right Diamond go ahead.

Diamond: Um, the piece of paper, it was, it was light the first time, and it had more [“pages”?] when its balled up. But it don’t look - it looks like the book have a lot of pieces of paper cause when I dropped it, um the piece of paper and the book fell at the same time. But, the, first the book and the paper, like the one [??] (Brianna gives Diamond the book and the crumpled piece of paper.) ‘Cause I balled it up – (4 second pause)

Allison: Can you show us what happened?

Ebony: And you ⌈crunched the book up too?

Student: ⌊like

Allison: Can you show ⌈us what happened?

Diamond: ⌊No, I [??]

Brianna: [??] the book up.

Allison: Can you show it?

Diamond: [I put it like this and I dropped it?] (Holds up the book and the crumpled piece of paper and releases them both at the same time.)

Brianna: See it fell at the same time.

Diamond: It fell at the same time.

Teacher: Why do you - why do you think that is that it fell?

Diamond: Because the piece of paper was like [big?/this?] the first time (Uncrumples the piece of paper.), like this, and then it balled up. (6 second pause)

Teacher: So, you're thinking it's the change in -

Allison(?): In shape.

Teacher: In the shape? And that's ⌈what caused the difference?

Student: ⌊Yeah.

Allison: ⌊Because then you change the shape. [At first it's a?] rectangle. Then, it's a sphere.

Brianna(?): It's a rectangle.

Teacher: Okay.

Diamond: Now, it's a sphere. (5 second pause)

Students: [Inaudible comments.]

Teacher: Go ahead and put it in the middle there. Go ahead. You wanna share with the group? Go ahead.

Diamond: Now - because now the piece of paper ⌈can roll.

Henry: ⌊If, if the book is the same like heavy, and and you go in the same time like, like at first at the same time the book will fall [like same time?] like this. (Uncrumples the paper.)

Student: [Inaudible comments.]

Henry: It will fall it will fall like that – 'cause look. If you put it in front ⌈of [??]

Brianna: ⌊The, the book will fall first.

Henry: Because if it, if ⌈it goes like this, then it will go like that.

Diamond: ⌊Oooh. I was not done what I was sayin'.]

Brianna: The book. The paper -

Diamond: I was not done what I was sayin'.

Henry: [??] will fall [last?/fast?]

Students: [Inaudible comments.]

Brianna: Yeah. And the book will fall first.

Diamond: I was not done what I was saying.

Student: [Inaudible comments.]

Diamond: I was not done what I was saying.

Ebony?: Hey now.

Diamond: 'Cause the piece of paper was balled up, it don't go like this no more (Shows a rocking motion with her right arm.)

Brianna: No, yeah. It don't, yeah. ⌈It just drops, kind of like the booklet.

Students: ⌊It just [??]

Allison: Henry, can ⌈I see the paper?

Diamond: ⌊Cause it just goes, cause it just goes straight like the book.

Student: [Inaudible comment.]

Allison: No, uh, just, just the paper.

Ebony: [For me and ?]

Allison: Because - see, now the paper (Drops the crumpled up paper.) doesn't keep going like this (Shows same rocking motion with her hand.)

Brianna: It just ⌈goes straight.

Allison: ⌊[Autumn, Autumn?] I need the paper.

Brianna: It goes - it just goes straight like ⌈the book.

Allison: ⌊Um, it just goes, "Ehhh," (Drops her hand with the paper straight down from over her head.) and then it [goes like?]

Brianna: Straight, it just goes straight like ⌈the book like fall.

Allison: ⌊It just goes. It doesn't, doesn't go like this (Rocking motion with her hand.) [it just?], it just goes "Ehhh," (Drops her hand straight down in front of her.) and then it rolls a little.

Brianna: Yeah, like –

Ebony: When me and Allison, and Eveen did it, it keep on going at the same time. ⌈[Going together?]

Allison: ⌊Yeah, every time, that Eveen, Ebony, and me did it, dropped the piece of paper and the book, it just went. This is the paper (Holds up her clinched left fist.) this is the book (Holds up her right hand next to it flat out.) It went, "Eh, Eh, ⌈Eh, Eh, Eh" -

Brianna?: ⌊It just goes at the same time.

Allison: - every ⌈single time we did it.

Diamond: ⌊The book - and ⌈the piece of paper.

Autumn: ⌊Let me see it. Let me see it.

Brianna: Diamond. (Takes book from Diamond.)

Student: If it goes [??]. It, it rolls by.

Diamond: Can you pass it to me again?

Rachel: ⌈I –

Autumn: ⌊When, when the paper's like this, (Flattens out the paper.) straight like this straight, it just goes like that. (Drops the paper.)

Allison: ⌈I, I know why. I know why.

Autumn: ⌊Like that, it just went crooked. It just goes crooked.

Allison: Because - I need to ⌈see the paper.

Autumn: ⌊Let me ball it back up. Let me ball it back up.

Allison: 'Cause this is thicker and - where's the book?

Student: [Inaudible comment.]

Student: Thicker than the ⌈book. Thicker than the book.

Allison: ⌊and this this is thinner –

Students: [thicker?]

Allison: [??] because, because when its like this, it can be used as a bookmark. But when it's like this –

Brianna: [Laughter.] Bookmark.

Autumn: It can't be a bookmark!

Allison: - it, the book would be like - would have to squish them.

Brianna?: I know.

Students: [Laughter.]

Teacher: May I go ahead and see those two things. It sounds like -

Autumn: I want to go home.

Teacher: - a, a lot of you guys are talking about the shape. That they change because when it was like this (Flattens out the paper.) -

Student: ⌈It, it could be a bookmark.

Teacher: ⌊most of you found out -

Allison: ⌊It could fit in my book.

Students: ⌊It could [??]

Teacher: It would go like - the paper would go like this. But when the paper's like this, (Balls up the paper.) it falls straight down. And that's what you mean.

Brianna: ⌈Yeah. And it [??]

Student: ⌊Like the book, like the book.

Teacher: This is what I'm going to challenge you guys to do at home. You're going to choose two things at your house that you're going to get to do the same experiment with.

Students: [Inaudible comments.]

Allison: Anything?

Teacher: Any two things. If you want you can bring it to school.

Appendix C: Transcript of the Juice Box Discussion

Teacher: I am wanting you to watch your box and your friends' boxes as you suck on them.

Erin: [??] air

Ben: [??] but its still full of air.

Kristen: But the, when we drink it, it comes, it goes in.

Eleanor: Well I know what happens.

Teacher: What?

Student ?: [Inaudible comment.]

Eleanor: You're also sucking out a little air because, so the

Students: [Laughter.]

Teacher: [Laughing] It's squirting out all juice.

Eleanor: No so so the, the, these sides, the long sides of the boxes get, well, they sort of go in a little. [Motioning in with flat hands like a slow motion clap.]

Teacher: Is that what the rest of you are noticing, is that the sides go in a little bit?

Students: Yeah. Uh-huh. Mm-mm.

Student ?: [goes like this??]

Teacher: And that's what I'd like to hear you talk about. I wanna hear your thinking about why the ins, sides should be going in like that.

Student ?: Because [the amount of ???]

Erin: Woah. [Apparently spills juice on the table.]

Students: [Laughter.]

Teacher: Let me get you a tissue. [Gets up from the table.]

Eleanor: Like this. [Sucks in on her juice box.]

Erin: Yeah, if you still have juice in that [??]

Students: [Inaudible comments.]

Kristen: It's like oxygen, oxygen.

Ben: No, it's like an, an inhaler.

Eleanor: Yeah.

Chandra: Like inhale.

Student ?: [??It's not an inhaler.]

Students: [Laughter.]

Students: [Sucking on their juice boxes. Some cleaning up their spilled juice with the tissues from the teacher.]

Teacher: Um, so again, if you haven't figured out by now, what I want you to do is talk for the tape recorder and so we can each hear each other, why are the sides -

Erin: [There… orange juice??] [Inaudible comments while she cleans up her spilled juice.]

Students: [Inaudible comments and laughter.]

Teacher: - Why are the sides going in?

Chandra: My box is like –

Student ?: Because you are sucking it in.

Chandra: It's like –

Teacher: One at a time.

Chandra: - pushing in the front. [Apparently pushing on the box with her fingers.]

Teacher: Now you can't push it with your fingers because then you're gonna to get wet like Erin did.

Erin: I didn't push it with my fingers I blew air into it.

Teacher: Oh you blew air into it. But try to drink most of it, all the juice out of it first. [pause] Um, Kristen?

Kristen: Um. I think why its going in because you're um sucking on the straw to get the um, the juice. And um, the air goes in, um, I don't know.

Teacher: And that's what we're here to do. Think about it, get other ideas from others. Leah?

Leah: I think as the juice comes out, um, you're also sucking out a little bit of air. And so, um, um the less air there is the uh more it goes in.

Teacher: The less air there is where?

Leah: In the juice box. [Pointing to the juice box.]

Student ?: [Inaudible comment.]

Teacher: In the juice box. Then finish the sentence again.

Leah: Um. The more the sides go in.

Teacher: The more the sides go in. [pause] Could I ask you why? Why you think that? Why should they go in, if there's less air inside?

Students: [Laughter.]

Leah: Because the air, it blows um, the uh sides [Holding sides of box and moving her hands out away from the box.] It blows the sides.

Teacher: Time out here a minute. I'm anticipating that the sounds of our cart, our cartons doing that is going to show up on the, on the tape recorder and make it hard to hear everybody. So having done it once or twice or three times or four times, just let it park. You can hold onto it. But let's be sure we can hear everybody. So, and don't forget, how do you sit on a stool, young lady.

Students: [Laughter.]

Teacher: Thank you. Um, tell us again then. [Looking at Leah.]

Leah: Um. I think that um as you s, um, drink the juice the air comes out too, and some air, a little bit of air comes out too. And the more, the less air there is in the juice box, the more the sides go in.

Teacher: Anybody want to add to that? [Students raising their hands.] Do you have the same idea or do you think there's another explanation? Ben?

Ben: When we first got it, there was stuff in it. There was juice in it. And when we drank it, the only thing that was left in it was air. And –

Teacher: Keep going.

Ben: - when we sucked the, when we um drank all the ju, juice. And, and, and the only thing that was left in it was air and its only, its only a juice box with air.

Student ?: And juice.

Teacher: Is that the case now for mine. Look at your's, they're different aren't they? [Ben nods his head.] So is there –

Student ?: [??Very different.]

Teacher: - so is there air inside everybody’s juice box now?

Students: Yeah. Mm-mm. [Nodding.]

Teacher: We’ve drunk all the juice out of it.

Students: Yeah. [Nodding.]

Teacher: So are you kind-of agreeing with Leah?

Ben: No.

Teacher: Can I hear more? What makes it cave in when you suck on the straw?

Ben: Everything [??around] -

Student ?; [?Your breath.]

Ben: - The air pushing. [Pushes his hands forward in front of him.]

Teacher: Tell me w, which air. Where is the air that’s pushing?

Ben: Outside. [Pushing in on the sides of his juice box with his hands.]

Teacher: Outside. And its pushing what?

Ben: Pushing the sides in. Because there’s not much [?] -

Erin: Woah. [Apparently squirts juice on Ben who wipes it off his arm. Erin gets up from the table to get tissues.]

Students: [Laughter.]

Ben: - every time you drink it there’s less, there’s less stuff inside it.

Erin: [To teacher.] Where’s the paper?

Teacher: [Gets up from table.] Right here.

Students: [Inaudible comments.]

Teacher: (talking to Erin) Try not to squeeze it.

Erin: [Inaudible comments.]

Teacher: [Returns to the table with Erin.] You gotta, you might want to finish it and it won't do that.

Erin: I did finish it. I thought I finished it.

Teacher: Okay just wipe it up so you're fine. Um, so Ben keep going and let's see how well the rest of us were listening to this. So there you talked about air, I think outside pushing.

Ben: Yeah pushing it. [Pushes in on the sides of his juice box.]

Teacher: Like you're doing it with your hands. But if I do it this way, [Sucks on his juice box.] you're saying that it’s the air that's pushing on it.

Ben: Mmm-mmm.

Teacher: Why should it do that? Why is the air on the outside pushing?

Ben: 'Cause there's less stuff inside, and where there's less stuff inside, it's easier to push.

Teacher: I hear that. Other thoughts? Eleanor?

Eleanor: Um. I sort-of agree with Ben but I sort-of don't because I think air from, I don't think the air from the outside is pushing because I think the air from inside us [Pointing to herself.] is sucking and since the straw is in, would be in the juice, it it since the straw would be, is in the ju, juice, you'd be sucking up juice. And that, and then there is more air in it so when you finish it there is all air.

Teacher: Mmm-mmm.

Eleanor: 'Cept a little, except there might be some little drops of juice. And so when you're sucking it in, since the juice box, when we didn't, when it wasn't well, when it hadn't had. Okay, when there wasn't anybody sucking out of it, when they were full, it was all the si, it was, the juice was inside it so that

Teacher: Like these. [Holding up a full juice box.]

Eleanor: Yeah, yeah. So that the sides couldn't, that so that the sides couldn't suck [?it.] So that orange juice or the apple juice couldn't get out of it. And since it was, wasn't like um. It wasn't like -

Teacher: (To another student.) Did you lose your straw?

Eleanor: - it was, since it wasn't like this [Holding up her sucked in juice box.]um, a, like a flat orange juice box.

Teacher: Mmm-mmm.

Eleanor: juice box. [Pause]

Teacher: What'd you do just now?

Eleanor: I blew it up.

Teacher: You blew it up.

Eleanor: Mmm-mmm. And -

Teacher: Why, what happens, what happens when you blow it up?

Eleanor: More air comes [?in.]

Teacher: And what happens to the, to the box itself?

Eleanor: But when you're sucking on it, when you're sucking out juice [??] since juice was everywhere in the box so there wasn't much air in it. If you suck out some juice it will go in because the juice I think was probably up against this, every side -

Teacher: Okay.

Eleanor: - and the top and the bottom and this side and this side and this side and this side [Pointing to all the sides of the box.]

Teacher: Okay.

Eleanor: Then if you suck it, the, it goes in because the less juice there is in there, the m, the less juice there is in there, the more the sides go in.

Teacher: The less juice, the more the sides go in.

Students: [Inaudible comments.]

Teacher: We've certainly seen that.

Eleanor: [?? be it.]

Teacher: Can I hear Chandra? I wanna to give everyone a chance to get on tape here. What's your thinking on this?

Chandra: Um.

Teacher: Why are the sides caving in? [Eleanor gets up from her seat to get a paper towel.]

Chandra: It's like when, when we had the the juice inside the the the juice carton

Teacher: Mmm-mmm. Like that. [Points to a full juice box.]

Chandra: - it was all full and it didn't [even/need to??] cave in.

Teacher: Full of what?

Chandra: Full of juice.

Teacher: All right. Then?

Chandra: And um then -

Teacher: When you drank all the juice what happened?

Chandra: [??] we drank all the juice. And the, the less juice there was in there. Its like we were sucking, and [when/then?] we sucked in some air.

Teacher: And where'd that air come from?

Chandra: [Pointing to her juice box.] Inside the, the juice carton.

Teacher: Okay. But I'm still trying to get a sense of why if you suck air from inside the carton, why should the sides cave in?

Student ?: I don't know.

Chandra: [?So when you suck in] air, suck in some air with the juice [5 second pause] you're sucking in some air [?] cave in.

Students: [Inaudible comments.] Sucking in.

Teacher: Do you understand why that might happen?

Kristen: (To Eleanor.) Still [?] juice in there. [Pointing to Eleanor's juice box.]

Teacher: Why should it cave in? Why shouldn't it just stay this shape it is? [6 second pause.] Do you wanna th, we'll just go around the table, take your time. Erin?

Erin: Um, I think because since you sucked out the air, it's like, it caves in because there's not any air so it has no, nothing's pushing it in from the inside [Pointing towards her box with her index fingers.] to make it like [?squa], like -

Teacher: Like that?

Erin: - like its normal shape. Yeah.

Teacher: Nothing's inside there so -

Erin: There's not mu, not as much is inside so it's, it, there's not mu, as much pushing out so it caves in.

Teacher: Oh. So you mean right now there's air in there pushing out to make it the box shape.

Erin: I think so. [Nods her head.]

Teacher: And then what happens when I suck? What's -

Erin: You take some of the air out so -

Teacher: - and so why should the sides. (To Kristen who is blowing paper across the table using her straw.) Kristen, that's taking us off our task here. Why should the sides then cave in? [2 second pause] If there's not as much air on the inside? [4 second pause] I mean, is there anything pushing - [Points to the outside of his juice box with several fingers.]

Erin: No -

Teacher: - the outside in?

Erin: - there's nothing pushing.

Teacher: There's nothing pushing.

Erin: So when -

Teacher: Nothing pushing where, on the inside or the outside?

Erin: Inside.

Teacher: Inside. So why, if there's nothing pushing on the inside, why should the outsi, why should the box's sides cave in? [3 second pause] Hunter, be thinking, I wanna, I'm gonna call on you soon 'cause I want to hear your ideas on this too.

Erin: 'Cause uh, there's not as much air in [this/it?].

Teacher: Okay, so there's less air in the inside that way.

Erin: Yeah.

Teacher: But I don't understand why that makes the sides have to go in. [5 second pause]

Erin: Maybe its pressure I don't know.

Teacher: What's that? Pressure?

Erin: It's something that's hard to explain. Um. [4 second pause] It's something that's [6 second pause] like, it's hard to explain.

Teacher: Okay. Let's try, as a group and individually. You had your hand up Leah.

Leah: Um. I, I think since there's no, there's um air inside and then we suck up, out a little, um and the air uh is also like pushing, pushing in the sides [Pointing to the sides of her box.] So -

Teacher: From the outside.

Leah: - from the outside.

Teacher: 'Cause I notice you've got your fingers, [Models Leah's actions with her hands.] you're pretending you're air -

Leah: Mmm-mmm. [Nodding her head.]

Teacher: Like pushing.

Leah: Mmm-mmm. And, uh while the um air is coming in from the inside, the ou, the air from the outside is push, push, pushing also to um, pushing the sides also to make it cave in.

Teacher: [Looking at Ben.] Is that the idea you had expressed? Is that it's the air outside that's pushing? [Pointing his fingers together towards each other.]

Ben: [??It was.]

Teacher: That's what you said. Hunter, what do you think? What's your thought on this?

Hunter: Um. What I was thinking was when it's empty there's air inside -

Teacher: Okay.

Hunter: - and if you suck up, and there's like air pushing on the sides. And there's air pushing um, wait. Inside there's air pushing on the sides to make it come out. And outside, um there's air pushing on the outside. Um -

Teacher: Pushing. So the air outside is pushing which way?

Hunter: Um it's, um the sides in.

Teacher: Pushing the sides in. And then -

Hunter: And then if we take some of the air out it won't be equal so, um, the sides start to go in.

Teacher: Equal. That sounds like a math term. What do you mean by that?

Hunter: Um.

Teacher: What's not equal?

Hunter: They both um, the amount of air is the same.

Teacher: By the amount the same you mean on the inside and on the outside?

Hunter: Yeah. [Nodding his head.]

Teacher: Interesting. [3 second pause] I have a big, I'm gonna, [Gets up from the table and brings back a large orange juice carton.] I have a big juice box here. This is orange not apple. But I've already drunk it. [Shakes the carton.] I did this at home. It's got kind of a different opening in it. So I want to show you something so that we can continue our talk. [Gets up from the table and returns with a small vacuum cleaner.] This is a little vacuum cleaner. It's gonna be kind-of loud [?] won't bother us.

Appendix D: Electrostatics Tutorial

Working from a model: Static electricity

You probably associate “electrostatics” with physics class, but you probably also have lots of experience with “static electricity” at home. Of course, it’s the same stuff!

In this tutorial, you’ll work with materials you could get at the supermarket, or may even already have at home. And you’ll see that you can use the model we’ve started to develop in lecture to make sense of what happens.

What happens when you rub?

Using our model of electrostatics, what might rubbing do? It often helps, in thinking about how something happens, to think about situations when it *doesn’t* happen, or when you think it might not.

Rub a foam plate with cloth (or on your sweater, etc) and see that it gets a charge. (You could tear paper into tiny bits and see that the plate picks them up; try bringing it near the little ball that’s hanging from a string at your table.)

Have you ever noticed an electric charge (sparks?) when you rub your hands together? How about if you rub someone else’s hands? Try it if you’re not sure, and then suggest an explanation.

Make a prediction for what would happen if you were to rub two foam plates together. If they had no net charge to begin with, would either one have a net charge as a result of rubbing?

> You should have two foam plates at your table. Try rubbing them together and see if they get charged. Does the explanation you tried in part B fit with what you observe?

What if instead of rubbing foam plates together, you peeled apart two pieces of tape?
Set them up as follows:

Get a piece of tape (2 or 3 inches) and fold over a little bit of one end. Stick the tape to your desk with the folded end sticking out over the edge of the desk. Write the letter "B" on the tape. Now get another piece of tape and fold the end in the same way. Put the second tape directly on top of the first and write the letter "T" on it.

Pull both tapes off the desk together. Get rid of any excess charge by running it lightly over your lower lip (or on your nose). Then hold the folded ends of the two tapes in your opposite hands and pull the two tapes apart.

Does your explanation above fit with what you observe in this case? If not, try to reconcile the contradiction.

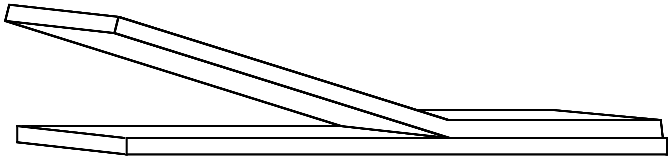
✯ *Please check with your TA before you continue.*

Representing charge

According to our model of electricity, everything is loaded with positive and negative charges (protons and electrons), but in nearly identical numbers. If you wanted to represent *all* the charges around in a drawing, you could draw lots of pairs of "+" and "–" symbols everywhere, but that would get tedious. So it's customary to draw "+" and "–" symbols only to show that there's more of one or the other. (You could draw a couple of pairs to remind yourself what's going on, though.)

Also according to our model, the amount of charge can be distributed in different ways in an object: Different parts of an object may be charged differently. So we use "+" and "–" symbols to show where on the object there's an excess of which kind of charge.

A bottom (B) piece of tape and a top (T) piece of tape are separated halfway as shown below. Use "+" and "–" symbols to indicate the parts of the tapes that are charged and the type of the charge on a diagram like the one below.



Suppose you were to take one of the foam plates and rub it with a piece of cloth. Draw a diagram in the space to the right showing the charge on the

plate and on the cloth. (Can you tell whether the plate is + or –? If not, just pick one!)

If you earn $500 and $150 is deducted in taxes, the amount of money that you take home ($350) is called your "net" income. The word "net" is used similarly to describe the relative amounts of charge on an object. (We also sometimes use the word "total.") If there is more positive charge than negative charge then the object is said to have a "net" positive charge. If an object has the same amount of both types of charge, then it is common to say that the object has a "net" zero charge. (We also sometimes say it has "no charge," but that could be misleading!)

In part A, was the sign of the net charge on the pair of tapes taken together positive, negative, or zero? Explain how you know.

In part B, would the net charge on the plate and cloth taken together be positive, negative, or zero? Explain how you know.

Check that the drawings you made in parts A and B are consistent with your answers above.

Another way to separate charge

Notice that in our model, we never *make* charge (electrons and protons); we pull pairs of charge apart from each other. Rubbing was one way to do that. In this section, you'll find another way.

You should have at your table an aluminum pie plate with the foam cup attached. This is a version of a device called an "electrophorus"—a fancy name for a simple thing. It's a device for holding charge. The following instructions will show you how to put a net charge on the electrophorus; at the end of the tutorial we'll ask you to use the model of + and – charges to explain why these instructions work.

To charge the electrophorus:

1. Rub a foam plate with cloth so that it has a net charge (and let's suppose it's negative).
2. Set the foam plate on the table, and, holding the electrophorus by its handle (the cup), bring the aluminum plate very close to the foam plate.

3. Holding the two plates close together, touch the top of the aluminum plate with your finger. If things work well, there'll be a tiny spark. (Even if there isn't, the electrophorus still might be charged.)

Verify that the electrophorus is charged after steps 1-3. (Later we'll ask you to explain how touching the plate can result in its being charged.)

Charge the electrophorus and set it on the cup as a stand. Now find the pith ball at your table.
(In place of a pith ball, you might have a tiny ball of aluminum foil, also hanging from a string.)

> *Make a prediction for what will happen if you let the pith ball touch the plate. Use a diagram to explain why that's your prediction.*

> *Try it: Touch the bottom of the plate to the pith ball. If it doesn't come out as you predicted, try to figure out why not. Revise your diagram if you need to.*

✯ *Please check with your TA before you continue.*

(At any point during this tutorial, especially now with that pith ball, you might make your own discovery of some interesting phenomenon. As long as you can reproduce it—make it happen reliably when you do specific things—you could use it to further your thinking. We're just picking some things we know about and expect will give you reproducible results. So feel free, if you find something else that's interesting and reproducible, to go figure it out. Use the model!)

Charge the electrophorus again, and, holding it by the cup, touch it to the pith ball and hold it near.

> *Make a prediction for what would happen if you were now to touch the pith ball with a foil-covered straw, still holding the plate near by. Draw a diagram of the charges, to explain your prediction.*

Try it! If something different happened, same deal: Try to figure out why not.

Would the same thing happen if you used a plastic straw, with no foil covering it? How about if you touched it with your finger? Explain.

D. Try to explain those instructions for charging the electrophorus. Draw a series of sketches showing what happens at each step, in terms of + and – charges. Check your thinking with each other and with your TA.

Appendix E: Transcript of the Electrostatics Discussion

Erin: Is it hard? [the pith ball]

Claire: No. [Shaking her head] It looked hard but its not. It's like –

John: Styrofoam.

Claire: - feels like styrofoam yeah.

[Audrey picks up a Styrofoam plate and rubs it on Erin's sweater.]

Claire: Oops. [Laughter]

John: [Inaudible comment.]

Erin: [Inaudible comment.] Yeah, on camera, they got you.

Audrey: I think it has charge.

Claire: Bring it near the ball to see if it worked. [Audrey brings the plate near the pith ball.]

Erin: No.

Claire: A little bit.

John: Your sweater sucks.

Claire: Here, try the, try the cloth. [Passes Audrey the cloth.]

Audrey: Which side should I do it on? Like that? [Rubbing the plate.]

Claire: I don't think it really matters.

John: [Inaudible comment to Claire.]

Audrey: [?The sides too?]

Claire: [In a mocking tone.] I think rubbing creates static electricity.

Erin: [Laughter.] You're good. [Pause as Audrey continues to rub the Styrofoam plate and then holds it up to the pith ball.] Is it doing anything? [They do not see any attraction between the plate and the pith ball.]

Claire: Let's go with the little pieces of paper approach.

Audrey: Yeah.

Claire: How about we use this extra tutorial?

Audrey: How about, that sounds like a good idea.

[Laughter.]

Claire: All right, we'll use notebook paper. [Laughter.] [??] yet. [To John]

[Inaudible comments by Erin and John.]

Claire: I'm kidding. [Laughter as they look at the camera.]

John: There's the [?].

Claire: And I'm sitting here with the microphone right in front of me. "Let's tear up the tutorial." [Audrey laughter.]

John: [Inaudible comment. Laughter.]

Audrey: You're gonna set the whole building on fire. Oh great, if there is a fire they'll think I did it.

Claire: Do you think he watched that last semester like before this semester?

Audrey: Maybe.

Claire: All right, we'll try it with these little pieces of paper. [Puts the pieces of paper on the table and Audrey holds the charged Styrofoam plate to them.]

Erin: Yeah I saw. [the paper jump up]

Claire: Oh, it definitely works.

Audrey: Oooh-wahhhh. [waving the plate over the paper.]

John: Maybe that was a fluke.

Claire: Must be windy in here or something.

Audrey: Okay. That's great.

Claire: Okay.

Erin: Alright, that was fun. [Pause to read next question.] Sparks when you rub your hands? I haven't.

Audrey: No.

Erin: Like if you touch something metal I have.

Audrey: Yeah but not just your hands together. [Rubbing her hands]

John: Your hands.

Claire: When you rub your hands together, is there a spark? [Rubbing her hands]

Audrey: Shk-Shk-Shk [Rubbing her hands together making "spark" sounds.]

Erin: [Laughter.]

Audrey: I wonder wait, why –

John: It's just so damp in here, so I mean its not going to work that well.

Claire: It’s hot too.

Audrey: So why, I don’t get this. What’s the rational explanation for why there’s no sparks between our hands. Is it ‘cause they’re moist?

John: Because -

Claire: Because of moisture.

John: - there’s so much moisture in the air and its a conductor so… [Motions with his hands.]

Claire: The air and in your skin. Its mostly in your skin. [Audrey nodding.]

Claire: [To Audrey] But why does, is it just moisture?

Erin: So moisture prevents -

Claire: ‘Cause they’re –

Erin: it?

Simultaneous conversations:

John: Because it’s, it’s a conductor so like its not going to let charge build on your hands because its [?] a conductor so it [?can easily jump off and disappear]. [Pointing to his fingertips.]

Erin: Okay.

John: Before it actually builds up enough so that you’d see a spark.

Claire: I mean they’re neutral, our hands are neutral. No matter how much you rub your hands the papers aren’t going to [?jump to them.]

Audrey: So what happens when you scuff your feet on the carpet and then you touch the door nob?

Claire: I guess it stays in your body.

Audrey: Does it carry through our body?

Claire: Yes. But I guess its just, it must be too moist.

Return to Group Discussion:

Erin: Mmm-Mmmm.

Audrey: What about two plates?

Erin: Didn’t we say yeah, like –

Claire: I think that, that -

Erin: - that rubbing causes.

Audrey: Maybe it has to be two different things.

Claire: Because they may have the same - [Rubbing two Styrofoam plates together.]

Audrey: Maybe that's why. They have different materials.

Claire: Well maybe. We'll see.

Audrey: 'Cause yeah. 'Cause if I rub my hand –

Claire: Oh no that worked. [Rubbing to plates together picked up paper.]

Audrey: Did it?

Claire: Well one piece moved.

Audrey: Does it still have charge [?from] before.

Claire: Maybe.

Claire: Well also I don't think you're going to get two different charges from you hands really.

Audrey: It should all be balanced then.

John: But why, why wouldn't you get two charges on your hands if you can get two different charges on other things?

Audrey: Well I can, if I take my hand and rub on her sweater then I can touch something spark. I don't think you can do two things that are made out of the same thing.

Claire: [Simultaneously with Audrey] Well your whole body is [?only one thing]. Like this is a plate and you can charge this [Styrofoam plate]. But, but your whole body is kind-of like a conductor really.

Claire: [To John] Yeah that's true. Because well it could go back to like what you [Audrey] said before with like it travels through your body.

John: But like, I mean, if you touch someone's hand, [?it's fine], you shock each other.

Audrey: Yeah.

Claire: You can create a charge maybe but it doesn't stay there?

John: I think, I think [?it distributes].

Claire: Can you create a charge though?

John: I don’t know if I can get like two different charged hands.

Audrey: No. I don’t think you can. I don’t think just from your hands. [Rubbing her hands together] I think, I think what makes the charge is two different substance things. ‘Cause if you figure you walk around and then shock somebody, the charge is -

Erin: It’s the floor. Yeah.

Audrey: - probably created from the carpet on your feet and then you carried it through.

Claire: But what about the –

Audrey: Like if I rubbed on her sweater and I touched you I might shock you but I don’t think you can rub two like things together it makes any sort-of –

John: Right.

Claire: What about the tape? Why? Like the tape we did in lecture. Then why did that get staticy that’s two of the same thing.

Audrey: I don’t know.

John: Those are two separate objects. These are not, like you have two hands but they’re not separate objects, its all connected. [pointing from one hand across his body to the other]

Claire: But if you rub somebody else’s hand you still don’t get it.

Audrey: So, but that would work with the plate thing though ‘cause they’re two separate plates and they’re made out of the same thing.

Claire: Yeah. [Rubbing two plates together.]

Audrey: So I guess maybe if they’re…

Claire: [Holds the rubbed plates to the pieces of paper.] No.

Erin: It’s not working.

John: I gotta think its because there’s moisture then –

Claire: I definitely think moisture with the hands.

Audrey: Yeah.

Claire: But I don’t know why it doesn’t work with the plates.

John: If one of them is not charged to being with then –

Claire: No. Because –

John: Yeah. [?] see.

Claire: If, if they had no net charge to begin with, would either one of them have a net charge as a result of rubbing? [Reading from the tutorial.] We said in lecture that if you take an uncharged balloon and rub it against uncharged hair, you get a charge.

Audrey: Its still, ‘cause it like concentrates the -

John: Yeah ‘cause it transfers them [??]

Claire: It concentrates the ions?

John: Yeah its, its like a transfer. Like they just rub it and like excite, excite the s, like [Laughing at his inability to get the words out.] excites electrons and they jump off the balloon.

[3 second pause]

Audrey: That sounds good. [Sounds not convinced.]

John: I’ve got a speech impediment. [Laughter.]

Erin: So there is a charge created when it rubbed –

Audrey: So is there a net charge to begin with? They’re both neutral until you start changing up the, I guess the balance of how they’re spread out. [Wiggling her fingers.]

[7 second pause while they write on their tutorials.]

Erin: So charge is still created?

Claire: Yeah.

Erin: But, if the charge was there, wouldn’t we be able to pick these [pieces of paper] up?

Audrey: I don’t know.

John: Yeah I don’t see why -

Claire: Why if you rub the plates aren’t they excite, like, if you rub things together we say that electrons get excited and whatever a charge. But like, why wouldn’t it work with plates?

Audrey: I thought it did work with plates?

Claire: It didn’t.

John: It worked cloth to plate, but not plate to plate.

Audrey: Is that [??] Oh.

Erin: [?Yeah and it didn't move the] [Pointing to pieces of paper.]

Simultaneous Conversations:

John: Maybe it has to be two different objects. 'Cause its balloon to head, cloth to plate.

Claire: But tape to tape remember?

John: But it was on a desk.

Claire: I'm pretty sure if you just took the tape [Laughter as she pulls her hand apart like she's holding tape.]

John: I tried. [Laughter.]

Audrey: Maybe it has to be -

Audrey: Well if you rub two things that are the same [rubs her hands together], there's nothing making them change like their plus minus normal balance.

Return to Group Discussion:

Claire: The tape desk interaction. [Laughter.]

Audrey: The stupid tape. [Pounds the table.]

John: Could be.

[3 second pause]

Audrey: Well we didn't rub the tape together we just stuck it together and pulled it apart. 'Cause like Syran Wrap, that already has like static in it.

Claire: From rubbing against itself when you pull it. [ERIN nods her head.]

Erin: So.

John: Maybe foam's not a good conductor. [Putting finger quotes around conductor.] Or Styrofoam.

Claire: No because why is, why is it a good conductor when you rub it with something else?

John: Mmmm. [Shrugs his shoulders.]

Erin: So is there a charge but not enough to move stuff? Or something? I don't know.

Claire: Maybe it could have a small charge.

Audrey: What happens if you rub two balloons together? Can you stick it on the wall?

Claire: I don’t know.

John: I think you can rub balloons [??]

Claire: I don’t think it would work.

Audrey: Because you clothes stick to themselves too like. [Laughter.]

Claire: Yeah.

Audrey: Have you ever like took a shirt out, a shirt out of the dryer and went to like shake it to fold it and its like kcreeer [Strange sound as she scrunches up her body to show the shirt.].

Claire: Yeah.

Audrey: You can like hear it [Laughter] like crackling.

Claire: The only place I’ve seen sparks from static electricity was in my sheets coming out of the dryer.

Audrey: Really?

Claire: [Nods her head.]

[5 second pause.]

Claire: All right, I have no idea.

Audrey: Alright. Next. [They all flip over their tutorial.]

Claire: The joy of tutorial.

Audrey: I know.

Claire: It confuses you. [Laughter.]

Audrey: No, no, uh closure.

Audrey: Oh, here’s the tape thing.

[26 second pause as they read the tutorial, flip between pages and write.]

Audrey: Well if you play along with their little game then you say the hands are the same material. ‘Cause then they’re like okay what about the plates? And you’re like well yeah that makes sense. And they say well what about the tape?

Claire: Well we pretty much did that. We just did –

Audrey: Yeah.

Claire: Yeah. We did play along we just didn't know we were. [Laughter.]

Audrey: So we just walked through all of that now we're on part three. We just made up like every [??]

Claire: The tape is charged for the same material. Why doesn't it work with the plates? I don't know. Let's go to the next question.

Audrey: Now we're ready f - Oh we gotta, wa – we gotta do our, our TA check. [in finger quotes.]

Claire: Oh.

Audrey: Before we're allowed to continue.

John: Are, aren't we supposed to go in [??] fix [???]

Erin: Yeah. Um.

Claire: Yeah.

Audrey: We're reconciling.

Erin: So the two pieces of tape did get a charge, but not plates.

Audrey: So.

Claire: So we're pretty much saying it depends on the material. That we need to look at the properties of the materials.

John: [?How good] a conductor I guess. [?Something like that] I don't think tape's a very good conductor though.

Claire: No.

John: I'm just guessing. [Laughter.]

Audrey: It's probably better than foam though I guess, since it was able to generate [shakes her hand.]

Claire: No well if you think about something that might get staticy, I would think Styrofoam.

John: What are we [?]

Claire: Styrofoam's really good with static. Like that's why this [the pith ball] is made out of it for sure. [5 second pause.] Like if you rub this [rubbing plate with cloth], we know that this gets staticy. [holding plate to pieces of paper that do not move.] Okay.

Audrey: Not when you do it. [Laughter.]

Claire: Apparently, um, that’s not right either.

[Laughter.]

John: Well we saw it earlier so –

Claire: Yeah, but I mean does the cloth get staticy too?

Audrey: I would assume it was, it was. If it was hot and dry enough, just like sheets and the sweater come out of the dryer.

Claire: Yeah.

Audrey: If it’s hot and dry. Like this room sucks right now.

Claire: This room is like hot and wet. [Laughter.]

Audrey: It is. You have to like get the s–

Claire: That’s why they run the dehumidifier in here so we can get some static goin’ on.

Audrey: [Inaudible comment.]

Claire: Um.

John: [??] section it is you took.

Claire: I know.

Erin: I know. We have to go up four flights of stairs. I’m really mad about that. [Laughter.]

Claire: I know.

Erin: That’s a lot.

Audrey: Do they have a elevator?

Erin: You need a breather to go up one. I know. [Laughter.]

Claire: Alright.

John: Yeah.

Audrey: So basically we’ve decided we can’t reconcile it.

Erin: [? We haven’t done it yet.]

Claire: We basically don’t understand yet which is why we need to do the check.

Simultaneous Conversations:

Erin: We need the TA.

Audrey: - to go on and do the rest. Yup. That's how it always ends up working. Oh no, 'cause if we ask her she's –

Erin: We – Can you come over here? [To TA] We don't understand. [TA comes over.]

John: So what was our predict [?], did we actually end up with a prediction?

Claire: A prediction for what? What would happen with the plates?

John: For C. Yeah. Would they both [?] charge?

Claire: We -

Return to Group Discussion:

Erin: We have help.

TA: You guys can keep talking. If you're s - keep working.

Claire: Well [Sigh.] We're, we've kind-of reached a point where we don't really know where to go.

TA: Okay.

Claire: Because we, we're thinking that maybe when you rub two like things together it won't get a charge but then with the tape you got a charge.

TA: Mmmm-hmmmm. Okay.

Claire: And things stick to themselves. So we're kinda stuck.

TA: Okay.

Claire: 'Cause we don't know why –

TA: Okay, how do you mean things stick to themselves.

Claire: Things stick to themselves like –

Audrey: Saran Wrap. Tape.

Claire: Saran wraps sticks to itself. Or like clothes like, like materials can stick together.

Audrey: Static cling.

TA: Okay. If I just have two things hanging in my closet, do they stick together?

Claire: No. They're not charged.

TA: So how do you – Right. So there’s no charge on them. So those two things aren’t sticking together. [Putting her hands together and taking them apart several times.]

Claire: Right. Though, but -

TA: My hands aren’t sticking together.

Audrey: I guess if they rubbed together.

Claire: It, it we, we can’t. We’re having trouble determining what properties a material has to have so that when its rubbed together it becomes charged.

TA: Okay.

Claire: And what has to rub against what to charge it.

TA: Okay. Okay. So what are, what are the things you’ve thought of? You’ve thought of this idea that two of the same things won’t –

Claire: - can.

TA: - can?

Claire: Can and sometimes don’t.

TA: Okay so they can and the instances when they can would be [?]?

Claire: Tape, t, tape, the tape. And like static cling.

TA: Okay. Okay. Let’s look at the tape. [To another group.] Can I steal this from you guys? Okay. [Tearing off pieces of tape to show the group.] So in class what you guys we kind-of doing was, was something like this where you had one piece of tape on top of the other.

Claire: Mmmm-hmmm. [TA sets up tape experiment.]

TA: What um, what two things are touching there? In that situation?

Claire: The tape to the tape and the tape to the table.

TA: Okay so. [Inaudible comments.] Is the tape the same on both sides? [Students shake their heads no.] If I put the tape down like this instead, so, so I had the two slick sides together, would those charge?

Claire: No. [Mostly silence and confused looks from the students.]

TA: We could try it and see. I’m not sure if like -

Audrey: So [?there it goes, there really is] two different. [TA is putting like sides of the tape together and apparently they are still attracting.]

Claire: They must have been already charged. [Laughter from all students.]

TA: Um.

Claire: No, 'cause there's no friction.

TA: Okay. Do we think friction matters then? That's another idea that maybe friction could matter. [Erin nodding her head.] Am I making friction here? [TA rubs her hands together.]

Erin: Yeah. [Nodding their heads.] Are my hands charging?

Erin: No. [Shaking their heads.]

Audrey: They're wet.

Claire: Moisture.

John: Yeah.

TA: They're wet. Okay. [Rubs the back of her hands together instead of the palms. Laughter from the students.] My palms aren't sweaty, I mean this side of my hands aren't sweaty as far as I know. Okay. So one, one thing that you guys brought up was this idea that they're the same, and you said that the tape was an example of when that didn't work. [Students nodding.] But now maybe we're seeing that's not the case. That maybe these are two thing, two different things. 'Cause you've got this side of the tape which is obviously different from this side.

Claire: Okay. [Silence from the group.]

TA: So now, now what do we, what do you guys think?

John: [Starts saying something but is cut off by TA.]

TA: What would be a reason that if two things were the same electrons wouldn't go back and forth?

Claire: 'Cause they have the same electric –

John: It would be balanced [??]

Audrey: - distribution.

TA: Everything's balanced, right so –

John: [Inaudible comment.]

TA: So if I was a little electron on this plate, and, and I start rubbing these together, would I have any reason to want to come over here?

Claire: No ‘cause it’s the same. [Silence from other students.]

TA: ‘cause it’s exactly the same. These two things look the same to me. So it’s like, you know, if I’m standing in the middle of like two Snicker’s bars. And I, you know, I could equally as well have that one as that one. But if it was like a Snicker’s bar and green beans –

Claire: Yeah. [Audrey laughter.]

TA: Which side are we going to go to? So maybe that’s why. So that’s a, that could be an explanation for why.

Claire: Okay. [Other students nodding.]

TA: So that, that was a good idea [pointing to John], that that they, they look the same to them. Can you think of anything else maybe that you might have done last semester that’s could be a similar kind of thing? [Students laughing and looking lost.] What about with heat flowing? With heat moving back and forth between two objects.

John: Yeah. [Nodding his head.] If it’s the same temperature then heats not going to flow. It stays there.

TA: But if one is, has a higher temperature than the other, what’s gonna happen?

John: Heat goes to the other one.

TA: Heat’s gonna flow.

Claire: Okay. [Students nodding their heads.]

TA: Okay. So yeah, those are all, those are all good ideas. And I think it was, it was good that you guys were coming up with those contradictions. So now maybe you can go back to the clothes thing and think about why do you s, why do you get charge between clothes.

Claire: ‘Cause they may not be exactly the same material.

TA: Mmm-hmm.

Claire: They may not be the same texture.

TA: Mmm-hmm. When do you notice, well I don’t know if you guys do laundry, like, when do you most notice the static?

Audrey: Out of the dryer.

John: Dryer.

TA: When you pull it out of the dryer. So what's it been doing while it was in the dryer?

Audrey: Rubbin' everything else. Like dry [??]

Claire: Rubbing. Mmm-hmm.

TA: Rubbing everything else. Rubbing on to the sides of the, you know, on to the sides of the thing. The dryer sheet. Yeah. [Students laughter.]

Claire: Mmmm-hmmm.

TA: So you guys are doing a really good job. [Walks away]

Claire: Okay so we were right and wrong. [ERIN laughter.]

Audrey: So, and we just checked with our TA, so -

[15 second pause to write and read the tutorial.]

Erin: So unless they're two different objects -

Audrey: Like two different surfaces I guess we should say.

Erin: Yeah.

Claire: Unless they provide two different environments for the electrons –

Erin: They will not conduct charge.

Claire: So they could be like different by like a tiny bit, and it will work.

Erin: Okay.

[25 second pause while they write on their tutorials]

Claire: Okay.

[45 second pause to read the next section]

Claire: How do we know if the top or the bottom one [tape] is –

Audrey: These ones probably aren't charged right [picture of two tapes halfway together]. 'Cause they're not, is this like after its already been stuck together and you're pulling it? [pulling apart her hands]

Claire: Yeah.

Audrey: Okay. So –

Claire: So basically one is plus, one is minus, but does it matter which -

Erin: Which piece? [?]

Claire: Probably not as long as we're consistent. [Audrey nodding her head]

Audrey: ‘Cause we don’t know which one it is. [Erin nodding her head]

Claire: Right.

Audrey: Right now.

Audrey: So does that just mean that the inside surfaces that touch are different? Or like the entire piece of tape is now [?]

Claire: Well, when we did the tape thing -

[Interruption from course instructor trying to learn names.]

Claire: [Pulls two pieces of tape off the table and away from each other, then brings both sides near each other] No see, but both sides stick.

Audrey: So you think it goes like, it goes through the –

Claire: Like slick to slick still touches, still is attracted [ERIN nodding]. So it must charge the whole thing.

Audrey: Okay. Sounds good to me.

John: Why are they, why, you [Audrey] have opposite. Or you have negatively attracting?

Claire: They attract to each other. This is the tape thing that we did in lecture.

John: Right, so they [?]

Claire: What? So one’s plus, one’s minus.

John: Okay.

Claire: Right.

John: Yeah. Sorry.

Erin: So like along this whole surface of this top one would be plus?

Claire: I think the whole piece.

Audrey: Once you open it, right like, this part down here [Unpulled apart section of tape] isn’t charged yet right? ‘Cause you haven’t like taken it apart to make the – [Pulling her hands away from each other.]

Claire: So, can, alright. Am I wrong in thinking of it like the actual electrons go to the other one?

Erin: That’s what I thought. They like jump from one piece of tape to the other one.

Audrey: I thought that when we like -

Claire: To the other so that like the whole piece has more positives, and this whole piece has more negatives.

Erin: Has more negatives, right.

Audrey: Okay.

Claire: Is that right?

Erin: That's what I thought.

Audrey: What was the thing we were talking about in class where we had that equal distribution of pluses and minuses. And all the positives moved to one side. [Moving her hands from right to left in front of her.] That's how it stuck to the wall.

Claire: Yeah.

Audrey: So it wasn't like removing charges from something. Well that was –

Claire: But did we even, that was like a, that was like a hypothesis. Was that even shown to be? Because that wouldn't even makes sense because that would mean that when you are holding that balloon, something with a negative charge is going to stick to this side and something with a positive charge is going to stick to this side. 'Cause if you pull all the positives to the right, the left side is going to be negative. It's gonna be polar. Does that happen?

John: I think the negative [?one] just gets more electrons, I think. [?And that's why]

Clare: Like the actual electrons leave one object and go to another.

John: Right. Right. [Erin nodding her head] And I think its just, its due to like them getting excited, [?like us], you know what I'm saying.

Claire: Yeah.

John: Like they'll get excited so they'll jump up and [moving his hand up step levels]. 'Cause they need ener, it takes energy for them to just transfer, you know.

Claire: To go.

John: So they'll have to get excited and they'll go. But they would probably –

Audrey: So if you rub ‘em then you’re making the heat energy. [rubbing her hands together]

John: Right. Exactly. You’re making the [?] -

Audrey: And now that makes them “Wahohohoho.” [Shaking her hands and body] [? Together.]

Claire: Yeah. You create energy and that energy is used to excited the electrons and allow them to like transfer to the other.

John: Transfer.

Audrey: Then they’re about at the same [? Both sides], like –

Erin: [Reading] Take one of the foam plates.

Claire: Take one of the foam plates and rub it with [?]

Audrey: Here’s the plate. [Drawing on the tutorial.]

Claire: How could we tell if it’s positive?

Erin: Can you tell where the plates [Reading] – I don’t think you can tell.

Claire: I don’t think you can tell.

John: Is there a [rule] that dictates which plate has which [? charge]?

Audrey: There’s probably a way to test it, like somehow but –

Claire: I’m sure it depends on the material.

Erin: There’s no way, there’s no way to tell.

Claire: But I don’t think we know right now.

Erin: Yeah.

Audrey: Right. That’s what I’m sayin’. All right that’s plus that’s minus. [Drawing on her tutorial.]

John: I mean, I’d say the plate, just guessing, I’d say the plates positive but I don’t have a reason for that. I’d say that –

Claire: I was going to say the plate was negative, but that was just guessing. [Laughter.]

John: I like, I would say that, it just seems to me that electrons. This [the cloth] looks like it could hold electrons to me. [Laughter.]

Claire: ‘Cause its soft. There’s room for them. [Laughter.]

John: It’s soft. [Rubbing the cloth against his face.] Yeah.

[Laughter from group,]

Audrey: They'd slide off the plate.

Claire: It's roomier.

John: It's quilted, you see.

Audrey: It's like toilet paper. [Laughter from group.]

Claire: Alright we'll make the plate positive. Alright?

John: Thank you. Appreciate that. [Laughter.]

Audrey: Okay to total's interchangeable with net so that answers our question from the homework. [Reading.]

Claire: Oh. I was trying to do my homework. I got through the first two problems but then the third one when you need to like learn something.

Erin: Yeah that's –

Audrey: Me too.

[Laughter.]

Erin: I know.

Audrey: Like a formula or something.

Erin: Um. A bunch of us are meeting at four today after our lab in the course center.

Audrey: And that's gonna to be our homework time. We're gonna be there at four.

Erin: If you wanna work on the homework with us.

Claire: After lab? [Erin and Audrey nodding.] Yes, I can do that.

Audrey: [?] we should try to get a group together.

Claire: [??] Ooh. I have to remember. I have to hand mine in early.

Audrey: Are you going away to run or something?

Claire: [Nodding her head.] Probably this weekend so I have to either hand it in like tomorrow or Thursday morning.

Audrey: Thursday morning sounds good. [Laughter.]

Claire: Yeah. Especially because I need to kinda learn something tomorrow to finish my homework.

Audrey: I know. Oh my god. We've had one day of tutorial. Alright.

Erin: I know. I don’t know how they expect us to do the homework and not teach us anything.

Claire: Alright.

[10 second pause as they read the tutorial.]

Audrey: [Reading.] Net charge on the pair of tapes. Well together they would be –

Claire: Same thing as force. Like force.

Audrey: -It would be like zero.

John: I mean together they should be in equilibrium right?

Audrey: Yeah.

John: For part, for like, for this part ‘cause the tape is still -

Claire: They should, they should be.

John: They should be, together. Because you’re not – [Touching his fingertips together.]

Claire: Neither one was charged when it was by itself. [Pulling her hands apart from one another.]

John: No they were charged but they were balanced. They say “no charge, that would be misleading.” [Quoting from the tutorial.]

Claire: They were neutral. [Laughing.] I obviously didn’t read carefully enough.

Erin: How are we supposed to know? How are we supposed to know if one is [??]?

Audrey: Well.

Erin: There’s no way to know.

Audrey: No. There probably is a little bit different. [???] I think they’re tryin’ to -

Claire: They weren’t charged in relation to each –

John: Like they attract.

Audrey: Their net charges probably.

John: They have, they’re net charge for the two of them is zero. Like they each have the positives and the negatives. [Moving his hands back and forth in front of each other.]

Claire: But their net charge is still zero.

John: Not when they’re apart. No there’s like a [??]

Audrey: ‘Cause as much as one lost by that one [? Gained] by.

Claire: Okay. Say, say you could count the, the charge as like plus four or minus four, you know.

John: Right.

Claire: So if these two objects are, [Picks up a plate and a cloth and holds them together.] you know, whatever they haven’t touched, they’re not static.

John: Alright.

Claire: You rub ‘em. [Rubs plate and cloth together.] This one loses four this one gains four.

John: Right.

Audrey: So then, together -

Claire: There’s still [?a/no] net charge of zero.

John: Right, but, yeah. It’s -

Claire: And initially there’s a net charge of zero, but was there any charge at all?

John: Initially there’s be a net charge of zero but it’s equally distributed. So –

Claire: Yeah.

John: - one of them [???] On the whole system there’s still a net charge of zero, but whenever it’s –

Audrey: Conservation of charge. [Laughter.]

Erin: Oh yes.

Claire: We’re learning. Okay. So in part A –

Audrey: So do we think that –

Claire: - the net charge was zero, because neither one. They were both neutrally charged.

Audrey: ‘Cause in theory they, yeah.

John: Yeah. [Erin nods her head.]

[5 second pause.]

Erin: What you said. What one gains the other loses so the bal, its always balanced.

Claire: But wait. No they’re not the same charge. They’re just neutral.

Audrey: Right. That’s [?right].

Claire: Okay. [All writing on their tutorials.]

John: Yeah. It's not. Because if they were the same charge they'd repel.

Claire: Right.

John: And same with B then. [Referencing part B of the tutorial.]

Audrey: Yeah.

John: And the charge [?just doesn't]

Audrey: I think they're just trying to throw us 'cause its two different materials but its still only just shifting the way its – [Moving her hands from side to side.]

[4 second pause while students write in their tutorial.]

Claire: [?] part B, are they asking about after its been rubbed?

John: I'm just going to explain it as if it's [?]

Claire: As, yeah.

[4 second pause while students write in their tutorial.]

Audrey: 'Cause it's zero before like the other one. And it's zero after still. [Erin nods her head.] [8 second pause for writing in tutorial.] I think it's getting like, warmer in here. My face.

Claire: I know. I'm like sweating.

Audrey: Yeah. [6 second pause.] Yeah. They were consistent 'cause we have one until giving it away plus or minus [??] [Responding to a tutorial question.] Like anybody's gonna draw three pluses and one minus or something. Like here's another positive charge to put on the plate. [Pulls a "charge" out of her back pocket and slams it on the table.]

Claire: But how do we know that?

Erin: How do we know –

Claire: Well because we d, they would just fly off into nowhere. They'd have to be conserved.

Erin: Mmm-hmm.

Claire: Conservation of –

Erin: Charge.

Claire: Charge?

Erin: Yeah. [Audrey laughter.]

Claire: Is it? That’s an actual theory.

Erin: I thi, I read that in the book.

Audrey: I think, I think I saw that in the book.

Erin: Yeah.

Claire: It’s like the little conservation thing that keeps things simple.

Erin: Mmm-hmm.

Audrey: Yeah. Momentum. Energy. Charge. Water.

Claire: [?] Follow the ongoing theme in this class.

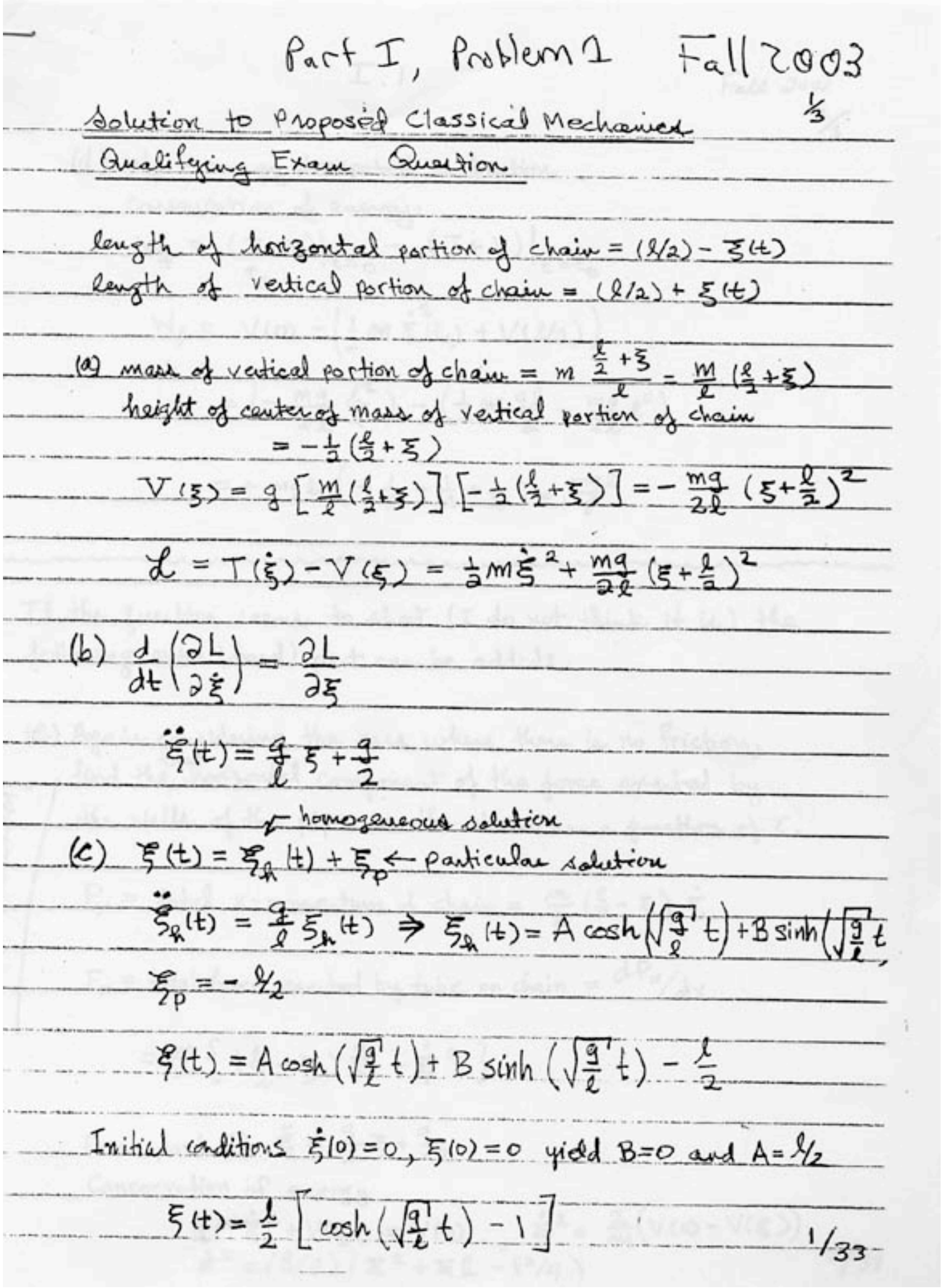
Audrey: We never make charge. [Reading.]

Claire: How would they be consistent with our answers from part A?

Audrey: ‘Cause they’re balanced. If you add the two of them together you get zero.

Claire: Okay.

Appendix F: Official Solution to Qualifier Problem



Part I, Problem 1 Fall 2003

$\frac{1}{3}$

Solution to Proposed Classical Mechanics Qualifying Exam Question

length of horizontal portion of chain = $(\ell/2) - \xi(t)$

length of vertical portion of chain = $(\ell/2) + \xi(t)$

(a) mass of vertical portion of chain = $m \frac{\frac{\ell}{2}+\xi}{\ell} = \frac{m}{\ell}\left(\frac{\ell}{2}+\xi\right)$

height of center of mass of vertical portion of chain

$$= -\frac{1}{2}\left(\frac{\ell}{2}+\xi\right)$$

$$V(\xi) = g\left[\frac{m}{\ell}\left(\frac{\ell}{2}+\xi\right)\right]\left[-\frac{1}{2}\left(\frac{\ell}{2}+\xi\right)\right] = -\frac{mg}{2\ell}\left(\xi+\frac{\ell}{2}\right)^2$$

$$\mathcal{L} = T(\dot{\xi}) - V(\xi) = \frac{1}{2}m\dot{\xi}^2 + \frac{mg}{2\ell}\left(\xi+\frac{\ell}{2}\right)^2$$

(b) $\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\xi}}\right) = \frac{\partial L}{\partial \xi}$

$$\ddot{\xi}(t) = \frac{g}{\ell}\xi + \frac{g}{2}$$

(c) $\xi(t) = \underset{\uparrow \text{ homogeneous solution}}{\xi_h(t)} + \xi_p \leftarrow$ particular solution

$$\ddot{\xi}_h(t) = \frac{g}{\ell}\xi_h(t) \Rightarrow \xi_h(t) = A\cosh\left(\sqrt{\frac{g}{\ell}}\,t\right) + B\sinh\left(\sqrt{\frac{g}{\ell}}\,t\right.,$$

$$\xi_p = -\ell/2$$

$$\xi(t) = A\cosh\left(\sqrt{\frac{g}{\ell}}\,t\right) + B\sinh\left(\sqrt{\frac{g}{\ell}}\,t\right) - \frac{\ell}{2}$$

Initial conditions $\dot{\xi}(0) = 0$, $\xi(0) = 0$ yield $B = 0$ and $A = \ell/2$

$$\xi(t) = \frac{\ell}{2}\left[\cosh\left(\sqrt{\frac{g}{\ell}}\,t\right) - 1\right]$$

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I.1 Fall 2003

2/3

(d) W_f = energy dissipated in friction

Conservation of energy:

$$W_f = \underset{t_0}{(T+V)}\Big|_{t=0} - (T+V)\Big|_{t=t_0}$$

$$W_f = V(0) - \left(\frac{1}{2} m \dot{\xi}^2(t_0) + V(l/2)\right)$$

$$= \left(-\frac{mg}{2l}\frac{l^2}{4}\right) - \left(\frac{1}{2} m \frac{gl}{2} - \frac{mg}{2l} l^2\right)$$

$$= + mgl\left(-\frac{1}{8} - \frac{1}{4} + \frac{1}{2}\right) = \frac{mgl}{8}$$

If the question seems to short (I do not think it is) the following extra (hard) part can be added:

not needed

(e) Again considering the case where there is no friction, find the total horizontal component of the force exerted by the walls of the pipe on the chain as a function of ξ.

P_x = total x-momentum of chain = $\frac{m}{l}\left(\frac{l}{2} - \xi\right)\dot{\xi}$

F_x = total force exerted by tube on chain = dP_x/dx

$$= \frac{m}{l}\left\{\left(\frac{l}{2} - \xi\right)\ddot{\xi} - \dot{\xi}^2\right\}$$

From part (b) $\ddot{\xi} = \frac{g}{l}\xi + g/2$

Conservation of energy

$$\frac{1}{2} m\dot{\xi}^2 + V(\xi) = V(0) \quad , \quad \dot{\xi}^2 = \frac{2}{m}\left(V(0) - V(\xi)\right)$$

$$\dot{\Xi}^2 = (g/l)(\Xi^2 + \Xi l - l^2/4)$$

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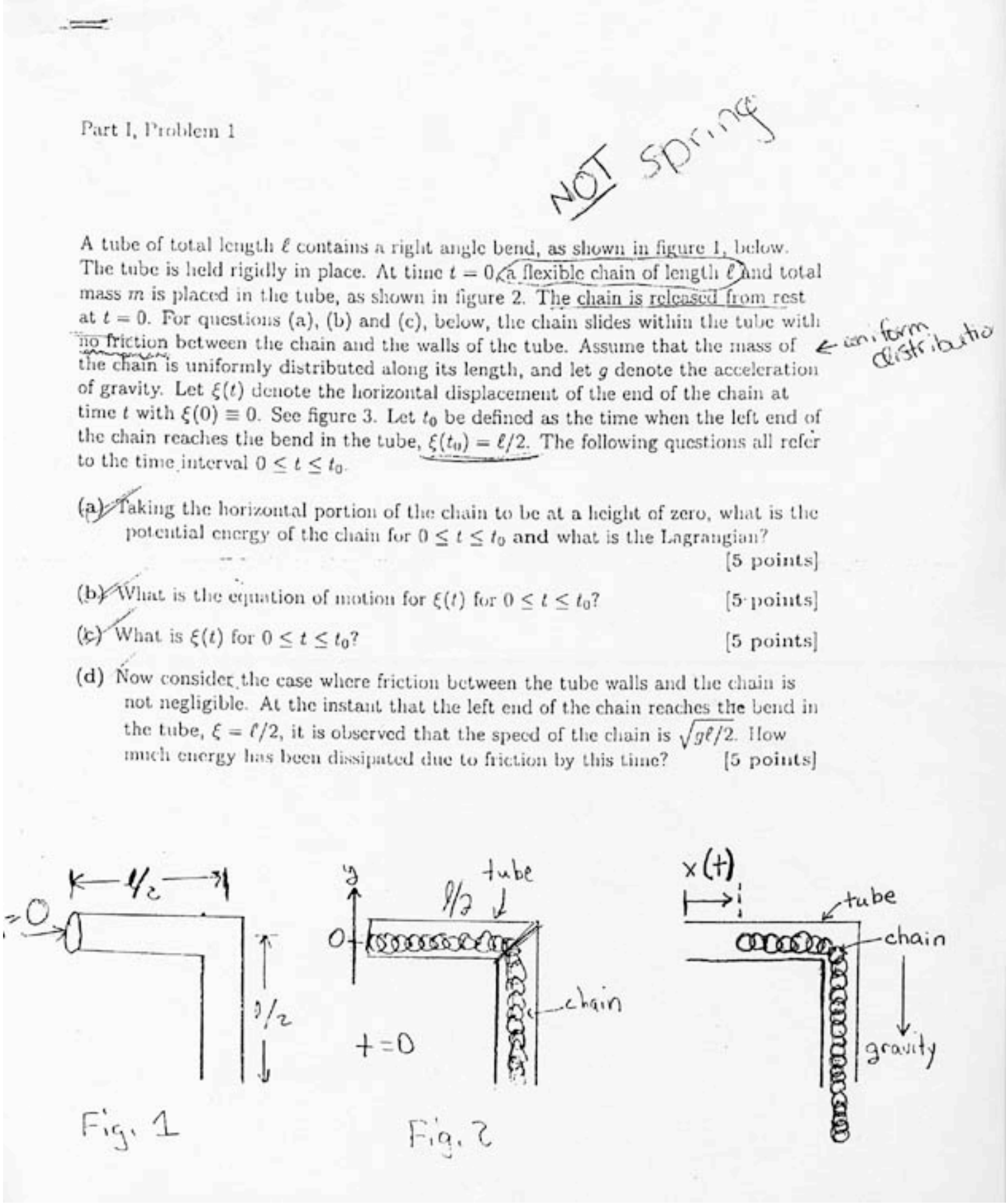
Appendix G: My Solution to Qualifier Problem



Part I, Problem 1

NOT spring

A tube of total length ℓ contains a right angle bend, as shown in figure 1, below. The tube is held rigidly in place. At time $t = 0$, a flexible chain of length ℓ and total mass m is placed in the tube, as shown in figure 2. The chain is released from rest at $t = 0$. For questions (a), (b) and (c), below, the chain slides within the tube with no friction between the chain and the walls of the tube. Assume that the mass of the chain is uniformly distributed along its length, and let g denote the acceleration of gravity. Let $\xi(t)$ denote the horizontal displacement of the end of the chain at time t with $\xi(0) \equiv 0$. See figure 3. Let t_0 be defined as the time when the left end of the chain reaches the bend in the tube, $\xi(t_0) = \ell/2$. The following questions all refer to the time interval $0 \le t \le t_0$.

← uniform distributio

(a) Taking the horizontal portion of the chain to be at a height of zero, what is the potential energy of the chain for $0 \le t \le t_0$ and what is the Lagrangian? [5 points]

(b) What is the equation of motion for $\xi(t)$ for $0 \le t \le t_0$? [5 points]

(c) What is $\xi(t)$ for $0 \le t \le t_0$? [5 points]

(d) Now consider the case where friction between the tube walls and the chain is not negligible. At the instant that the left end of the chain reaches the bend in the tube, $\xi = \ell/2$, it is observed that the speed of the chain is $\sqrt{g\ell/2}$. How much energy has been dissipated due to friction by this time? [5 points]

Fig. 1

Fig. 2

#4

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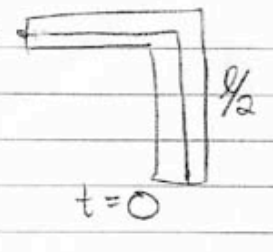
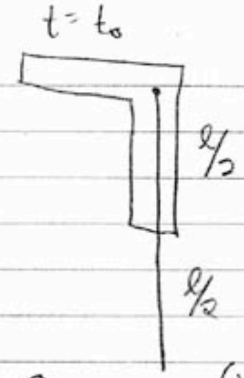
①



$\uparrow \hat{Y}$



@ at $t=0 \Rightarrow (m/2)$ @ height = 0 $\quad \left(V_0 = (m/2)\left(\overset{\text{height of}}{-\ell/4}\right) g\right)$

$(m/2)$ hanging over edge.

Let $\rho = m/\ell$ mass density

Only need to worry about the part hanging off.

Part hanging off $= (\ell/2) + [\xi(t)]$

$\cancel{V_{\text{each piece}} = \rho d\ell\ell}$

So the "center of mass" of the piece hanging off is located @ $\boxed{y = -\frac{\left[\frac{\ell}{2}+\xi(t)\right]}{2}}$

The mass thats hanging off is $\boxed{m = \rho\left(\frac{\ell}{2}+\xi(t)\right)}$ $\quad \rho = \frac{m}{\ell}$

$$V_{\text{pot. energy}}(t) = mgh_{\text{off}} = -\frac{mg}{\ell}\left(\frac{\ell}{2}+\xi(t)\right)\frac{\left(\frac{\ell}{2}+\xi(t)\right)}{2}$$

check @ $t=0$ $V_{PE} = -\frac{m}{2\ell}\left(\frac{\ell^2}{4}\right) = -\frac{m\ell}{8}$

$$\boxed{V_{P.E}(t) = -\frac{mg}{2\ell}\left(\frac{\ell}{2}+\xi(t)\right)^2} \quad *$$

✓ check $t=t_0$ $-\frac{mg}{2\ell}\ell^2 = -\frac{mg\ell}{2}$

#4

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①

Now need to know the kinetic energy to get the Lagrangian.

I think I can just use the motion of the C.M. of the whole thing (since its moving all together. To that end I'll just use $\xi(t)$ to model position. $(T = \frac{1}{2} m \dot{\xi}^2)$

So

$$\boxed{\mathcal{L} = \frac{1}{2} m \left(\dot{\xi}(t)\right)^2 + \frac{mg}{2\ell}\left(\frac{\ell}{2} + \xi(t)\right)^2 = T - V}$$

ⓑ E.O.M.: $\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\xi}}\right) - \frac{\partial \mathcal{L}}{\partial \xi} = 0$ b/c I've already included constraint

So

$$\frac{\partial \mathcal{L}}{\partial \dot{\xi}} = m\dot{\xi} \Rightarrow \frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\xi}}\right) = m\ddot{\xi}(t)$$

$$\frac{\partial \mathcal{L}}{\partial \xi} = \frac{mg}{\cancel{2}\ell} \cdot \cancel{2}\left(\frac{\ell}{2} + \xi(t)\right) = \frac{mg}{\ell}\left(\frac{\ell}{2} + \xi(t)\right)$$

So

$$\boxed{m\ddot{\xi} - \frac{mg}{\ell}\left(\frac{\ell}{2} + \xi\right) = 0}$$ E.O.M. for $\xi(t)$

ⓒ Now solve the above eqn. Hm. Looks like non-homogeneous ODE.

#4

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(1)

$$m\ddot{\xi} = \frac{mg}{\ell}\left(\frac{\ell}{2}+\xi\right) = \frac{mg}{\ell}\left(\frac{\ell}{2}\right) + \frac{mg}{\ell}\xi = \frac{mg}{2} + \frac{mg}{\ell}\xi$$

Homogeneous: $\cancel{m}\ddot{\xi} = \frac{\cancel{m}g}{\ell}\xi$

So

$$\ddot{\xi} = \frac{g}{\ell}\xi$$

$$\xi_H = Ae^{-\sqrt{\frac{g}{\ell}}t} + Be^{+\sqrt{\frac{g}{\ell}}t}$$

(this should be sort of free-fall ish w/ increasing accel b/c more mass - I'm a bit concerned abt my soln.)

Only Valid until $t = t_0$, I will drop the $e^{-\frac{g}{\ell}t}$ term on physical grounds b/c I expect it to speed up

$$\xi_H = Be^{+\frac{g}{\ell}t}$$

Then Particular $\xi_p = C$ = constant

$$\xi_{TOT} = Be^{+\frac{g}{\ell}t} + C$$

Plug in: $m(\ddot{\xi}_{TOT}) = B\left(\frac{g}{\ell}\right)^2 e^{+\frac{g}{\ell}t} = \frac{mg}{2} + \frac{mg}{\ell}\left(Be^{+\frac{g}{\ell}t} + C\right)$

$$B\left(\frac{g}{\ell}\right)^2 e^{+\frac{g}{\ell}t} = \frac{mg}{2} + \frac{mg}{\ell}Be^{+\frac{g}{\ell}t} + \frac{mg}{\ell}C$$

BC's: $\xi(0) = 0 \Rightarrow C = 0$
$\dot{\xi}(0) = 0 \Rightarrow B = 0$ } this is trivial

maybe can't drop the A term.

WRONG

#4

4/5

①

$$\xi_H = Ae^{-\sqrt{\frac{g}{l}}t} + Be^{+\sqrt{\frac{g}{l}}t}$$

$$\xi_p = C$$

$$\Bigg\}\ \xi_{TOT} = Ae^{-\sqrt{\frac{g}{l}}t} + Be^{+\sqrt{\frac{g}{l}}t} + C$$

Plug in: $m(\ddot{\xi}_{TOT}) = mA\left(\sqrt{\frac{g}{l}}\right)^2 e^{-\sqrt{\frac{g}{l}}t} + mB\left(\sqrt{\frac{g}{l}}\right)^2 e^{+\sqrt{\frac{g}{l}}t} = \frac{mg}{2} + \frac{mg}{l}Ae^{-\sqrt{\frac{g}{l}}t} + \frac{mg}{l}Be^{+\sqrt{\frac{g}{l}}t} + \frac{mg}{l}C$

$m\overset{\xrightarrow{}0}{\ddot{\xi}_p} = \frac{mg}{2} + \frac{mg}{l}\xi_p \Rightarrow \frac{mg}{l}\xi_p = -\frac{mg}{2} \Rightarrow \xi_p = -\frac{l}{2} = C$

Now BC's: $\xi(0) = 0 = A + B + C$

$\dot{\xi}(0) = 0 = -\sqrt{\frac{g}{l}}A + \sqrt{\frac{g}{l}}B \Rightarrow A = B$

So $-2A = C = -\frac{l}{2} \Rightarrow A = +\frac{l}{4} = B$

So

$$\boxed{\xi(t) = \frac{l}{4}e^{-\sqrt{\frac{g}{l}}t} + \frac{l}{4}e^{+\sqrt{\frac{g}{l}}t} - \frac{l}{2}}\quad 0 \le t \le t_0$$

check $\xi(0) = \frac{l}{4}e^0 + \frac{l}{4}e^0 - \frac{l}{2} = 0$ ✓

~~$\xi(t_0) = l/2 \overset{?}{=} \frac{l}{4}e^{-\sqrt{\frac{g}{l}}\sqrt{\frac{l}{g}}} + \frac{l}{4}e^{+\sqrt{\frac{g}{l}}\sqrt{\frac{l}{g}}} - \frac{l}{2} = \frac{l}{4}(e^{-1} + e^{+1}) - \frac{l}{2}$~~

↑ Not sure how to check this

What actual time is t_0: ~~$x_0 = \overset{\to 0}{v_0 t} + \frac{1}{2}at_0^2$~~

~~$\left(\frac{l}{2}\right) = \frac{1}{2}g(t_0^2)$~~ ← WRONG b/c a not const.

~~$\sqrt{\frac{l}{g}} = t_0$~~

$\dot{\xi}(t_0) = \sqrt{\frac{g}{4l}gl} = -\frac{l}{4}\sqrt{\frac{g}{l}}e^{-\sqrt{\frac{g}{l}}t_0} + \sqrt{\frac{g}{l}}\frac{l}{4}e^{+\sqrt{\frac{g}{l}}t_0}$

$\xi(t_0) = g = \frac{lg}{4l}e^{-\sqrt{\frac{g}{l}}t_0} + \frac{lg}{4l}e^{+\sqrt{\frac{g}{l}}t_0}$

$g = \frac{g}{4}(e^{-1} + e)$

$4 = \sqrt{e^{1} + e^{-1}}$

#4

①

5/5

ⓓ So since my $T = \frac{1}{2} m \dot{\xi}^2$

$$V = -\frac{mg}{2\ell}\left(\frac{\ell}{2} + \xi\right)^2$$

$$E = \frac{1}{2} m \dot{\xi}^2 - \frac{mg}{2\ell}\left(\frac{\ell}{2} + \xi\right)^2$$

If there was no energy dissipation, then

$$E(0) = E(t_0)$$

$$-\frac{mg}{2\cancel{\ell}}\left(\frac{\cancel{\ell}}{2} + 0\right)^2 = \frac{1}{2} m \dot{\xi}^2 - \frac{mg}{2\ell}\left(\frac{\ell}{2} + \frac{\ell}{2}\right)^2$$

$$\hookrightarrow \quad -\frac{mg\ell}{8} = \frac{1}{2} m \dot{\xi}^2 - \frac{mg}{2\cancel{\ell}}(\ell^2)$$

$$-\frac{mg\ell}{8} + \frac{4mg\ell}{8} = \frac{1}{2} m \dot{\xi}^2$$

$$\frac{3}{4\cancel{8}} \cancel{m} g\ell = \cancel{\frac{1}{2}} \cancel{m} \dot{\xi}^2$$

$$\boxed{\sqrt{\frac{3}{4} g\ell} = \dot{\xi}}$$ ← w/out friction

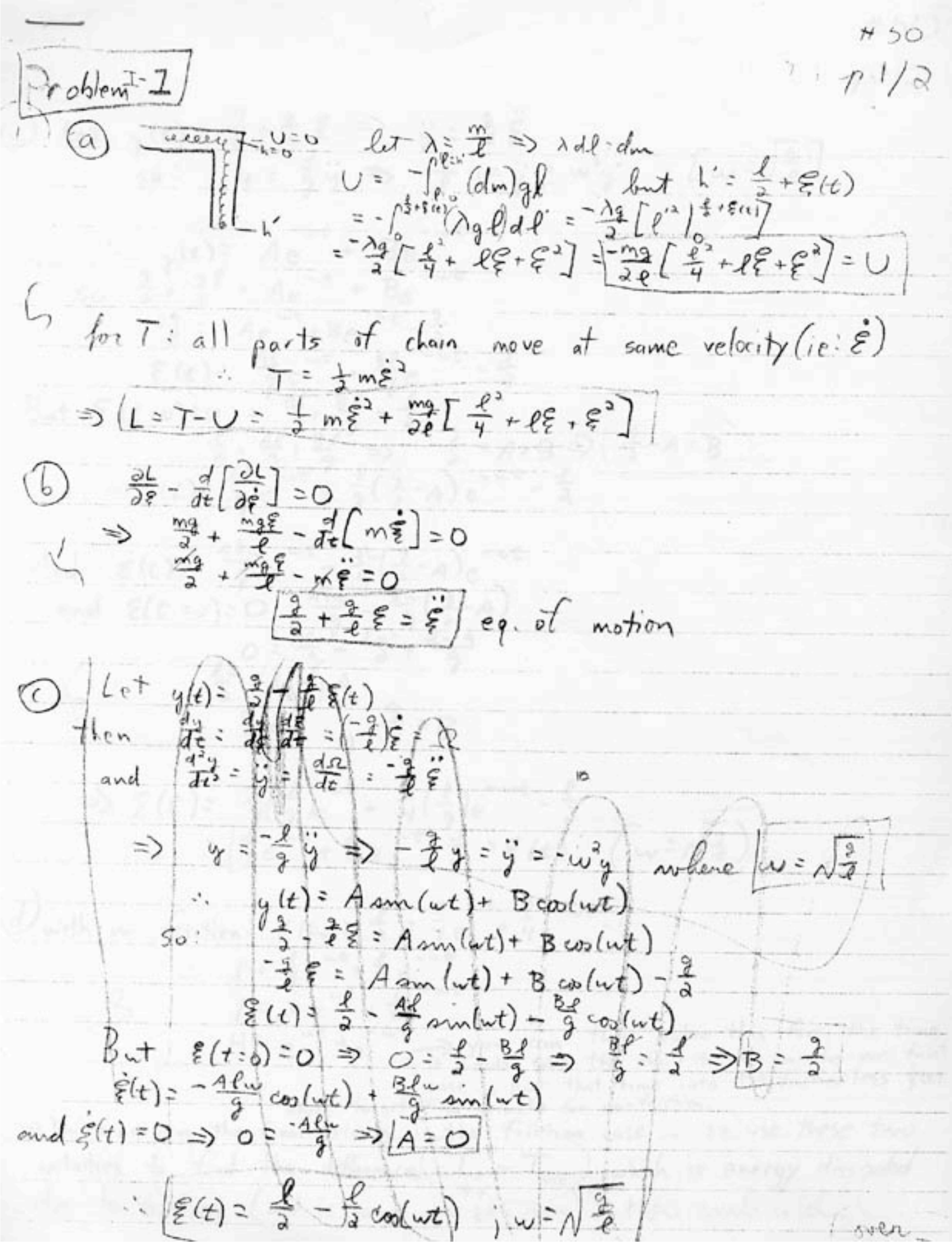
$$\dot{\xi}_{\text{w/ frict}} = \sqrt{\frac{g\ell}{2}} = \sqrt{\frac{2g\ell}{4}}$$

$$\Delta KE = \frac{1}{2} m \dot{\xi}^2_{\text{w/ frict}} - \frac{1}{2} m \dot{\xi}^2_{\text{w/out}}$$

$$= \frac{1}{2} m\left[\frac{2g\ell}{4} - \frac{3g\ell}{4}\right] = -\frac{1}{2} m\left(\frac{1}{4} g\ell\right) = \boxed{\frac{1}{8} mg\ell}$$

✱ ✱ ↑ KE_{lost}

Appendix H: Ben's Solution to Qualifier Problem



\# 50

p 1/2

Problem I-1

(a) $U=0$, $h=0$ ... h'

let $\lambda = \frac{m}{\ell} \Rightarrow \lambda\, d\ell = dm$

$U = -\int_{\ell=0}^{\ell=h'} (dm) g \ell$ but $h' = \frac{\ell}{2} + \xi(t)$

$= -\int_0^{\frac{\ell}{2}+\xi(t)} (\lambda g \ell) d\ell' = \frac{-\lambda g}{2}\left[\ell'^2\Big|_0^{\frac{\ell}{2}+\xi(t)}\right]$

$= \frac{-\lambda g}{2}\left[\frac{\ell^2}{4} + \ell\xi + \xi^2\right] = \boxed{\frac{-mg}{2\ell}\left[\frac{\ell^2}{4} + \ell\xi + \xi^2\right] = U}$

for T: all parts of chain move at same velocity (ie: $\dot{\xi}$)

$\therefore T = \frac{1}{2} m \dot{\xi}^2$

$\Rightarrow \boxed{L = T - U = \frac{1}{2} m \dot{\xi}^2 + \frac{mg}{2\ell}\left[\frac{\ell^2}{4} + \ell\xi + \xi^2\right]}$

(b) $\frac{\partial L}{\partial \xi} - \frac{d}{dt}\left[\frac{\partial L}{\partial \dot{\xi}}\right] = 0$

$\Rightarrow \frac{mg}{2} + \frac{mg\xi}{\ell} - \frac{d}{dt}\left[m\dot{\xi}\right] = 0$

$\frac{\cancel{m}g}{2} + \frac{\cancel{m}g\xi}{\ell} - \cancel{m}\ddot{\xi} = 0$

$\boxed{\frac{g}{2} + \frac{g}{\ell}\xi = \ddot{\xi}}$ eq. of motion

(c) Let $y(t) = \frac{g}{2} + \frac{g}{\ell}\xi(t)$

then $\frac{dy}{dt} = \frac{dy}{d\xi}\frac{d\xi}{dt} = \left(-\frac{g}{\ell}\right)\dot{\xi} = \Omega$

and $\frac{d^2y}{dt^2} = \ddot{y} = \frac{d\Omega}{dt} = -\frac{g}{\ell}\ddot{\xi}$

$\Rightarrow y = -\frac{\ell}{g}\ddot{y} \Rightarrow -\frac{g}{\ell}y = \ddot{y} = -\omega^2 y$ where $\boxed{\omega = \sqrt{\frac{g}{\ell}}}$

$\therefore y(t) = A\sin(\omega t) + B\cos(\omega t)$

So: $\frac{g}{2} - \frac{g}{\ell}\xi = A\sin(\omega t) + B\cos(\omega t)$

$-\frac{g}{\ell}\xi = A\sin(\omega t) + B\cos(\omega t) - \frac{g}{2}$

$\xi(t) = \frac{\ell}{2} - \frac{A\ell}{g}\sin(\omega t) - \frac{B\ell}{g}\cos(\omega t)$

But $\xi(t=0) = 0 \Rightarrow 0 = \frac{\ell}{2} - \frac{B\ell}{g} \Rightarrow \frac{B\ell}{g} = \frac{\ell}{2} \Rightarrow \boxed{B = \frac{g}{2}}$

$\dot{\xi}(t) = -\frac{A\ell\omega}{g}\cos(\omega t) + \frac{B\ell\omega}{g}\sin(\omega t)$

and $\dot{\xi}(t) = 0 \Rightarrow 0 = \frac{-A\ell\omega}{g} \Rightarrow \boxed{A = 0}$

$\therefore \boxed{\xi(t) = \frac{\ell}{2} - \frac{\ell}{2}\cos(\omega t) \; ; \omega = \sqrt{\frac{g}{\ell}}}$

over

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p2/2

(c) Let $y(t) = \frac{g}{2} + \frac{g}{\ell}\xi \Rightarrow \ddot{y} = \frac{g}{\ell}\ddot{\xi}$

so: $y = \frac{\ell}{g}\ddot{y} \Rightarrow \frac{g}{\ell}y = \ddot{y} = \omega^2 y \quad [\omega = \sqrt{\frac{g}{\ell}}]$

$$\therefore y(t) = Ae^{\omega t} + Be^{-\omega t}$$

so $\frac{g}{2} + \frac{g\xi}{\ell} = Ae^{\omega t} + Be^{-\omega t}$

$$\frac{g\xi}{\ell} = Ae^{\omega t} + Be^{-\omega t} - \frac{g}{2}$$

$$\xi(t) = \frac{A\ell}{g}e^{\omega t} + \frac{B\ell}{g}e^{-\omega t} - \frac{\ell}{2}$$

But $\xi(t=0) = 0 = \frac{A\ell}{g} + \frac{B\ell}{g} - \frac{\ell}{2}$

$$\frac{\ell}{2} = \frac{A\ell}{g} + \frac{B\ell}{g} \Rightarrow \frac{g}{2} = A + B \Rightarrow \left(\frac{g}{2} - A = B\right)$$

$$\therefore \xi(t) = \frac{A\ell}{g}e^{\omega t} + \frac{\ell}{g}\left(\frac{g}{2} - A\right)e^{-\omega t} - \frac{\ell}{2}$$

And $\dot{\xi}(t) = \frac{A\ell\omega}{g}e^{\omega t} - \frac{\ell\omega}{g}\left(\frac{g}{2} - A\right)e^{-\omega t}$

and $\dot{\xi}(t=0) = 0 = \frac{A\ell\omega}{g} - \frac{\ell\omega}{g}\left(\frac{g}{2} - A\right)$

$$0 = \frac{A\ell\omega}{g} - \frac{\ell\omega}{2} + \frac{\ell\omega A}{g}$$

$$\frac{\ell\omega}{2} = \left(\frac{2\ell\omega}{g}\right)A$$

$$\frac{g}{4} = A \; ; \; \frac{g}{4} = B$$

$$\Rightarrow \xi(t) = \frac{g}{4}\left(\frac{\ell}{g}\right)e^{\omega t} + \frac{g}{4}\left(\frac{\ell}{g}\right)e^{-\omega t} - \frac{\ell}{2}$$

$$= \boxed{\frac{\ell}{4}e^{\omega t} + \frac{\ell}{4}e^{-\omega t} - \frac{\ell}{2} = \xi(t) \quad \left(\omega = \sqrt{\frac{g}{\ell}}\right)}$$

(d) with no friction: $\xi(t_0) = \frac{\ell}{2} = \frac{\ell}{4}e^{\omega t} + \frac{\ell}{4}e^{-\omega t} - \frac{\ell}{2}$

$$\therefore \ell = \frac{\ell}{4}e^{\omega t} + \frac{\ell}{4}e^{-\omega t}$$

3

$$1 = \frac{1}{4}e^{\omega t} + \frac{1}{4}e^{-\omega t}$$

$4 = e^{\omega t} + e^{-\omega t}$ → you can then solve this for the time it would take the chain to fall in the no-frict case ... put that time into the friction-less $\dot{\xi}(t)$ above to get final velocity for no-friction.

→ You're given the final velocity in the friction case ... so use these two velocities to find the difference $(T_{\text{no fric}} - T_{\text{fric}})$ ... which is energy dissipated due to friction (ΔU is same in both cases) How much is this!

Appendix I: Transcript of Student Interview about Qualifier Problem

Interviewer: So what I guess I would like for you to do is actually just to through your solution on the board.

Ben: Okay.

Interviewer: [Laughter] And um, just talk me through what you did and why you did it, I guess, and why it seemed reasonable to you. If you can remember why it seemed reasonable to you at the time or if -

Ben: Uh-huh.

Interviewer: Why it now seems reasonable to you to do it that way.

Ben: So do it the same way I did it here?

Interviewer: Um –

Ben: Is what I should do?

Interviewer: Yes. But if, I mean, you said to me that there were some sort of supplemental things that went into that. So if you remember those, or, do you see what I'm saying?

Ben: Yeah, yeah, okay.

Interviewer: Yeah, I mean, if there is additional information that you feel is relevant to how you did the problem then that's fine.

Ben: So I guess I started by drawing a picture there (draws on board) and – You know can this thing even hear me with my voice like this?

Interviewer: Yeah.

Ben: Okay. And the problem said this was height equal to zero (writes h=0 next to top), so potential energy is zero up here (writes V=0 on board). And there's the chain.

Interviewer: So it actually does, oh it does say height equals zero there. Okay. And so why did, why is potential energy zero there?

Ben: Because that's where they defined the h equals zero point.

Interviewer: Okay. And that just by definition means the potential energy is zero there?

Ben: Right. Because the only thing that has physical meaning is a change in potential energy.

Interviewer: Okay.

Ben: A difference in potential energy between two points.

Interviewer: Okay.

Ben: So you can call the zero point wherever you want.

Interviewer: Okay.

Ben: So what, problem one says find the potential energy of that chain?

Interviewer: Um, I think it asks you, yes, what is the potential energy and then what is the Lagrangian.

Ben: Okay. So I'm sure the way, I'm ve, quite sure the way the way I went about this at the time, its still the way I go about problems like this, is uh, each different bit of this chain that's hanging down here is going to contribute a different amount to the potential energy because it's a different distance away from our reference line.

Interviewer: Okay.

Ben: So you have to somehow sum up all these little parts.

Interviewer: Okay.

Ben: And well, that's gonna be an integral.

Interviewer: Okay.

Ben: So, the, the thing that always goes thr, through my mind is pick out a little representative element –

Interviewer: Okay.

Ben: You know, so something like that (boxes a piece of chain)

Interviewer: Um-hm.

Ben: And just try to write, you know, what the contribution to the potential energy would be for that little part right there.

Interviewer: Okay.

Ben: And then you can worry about integrating over all the -

Interviewer: The little points.

Ben: Little bits of potential energy.

Interviewer: Okay.

Ben: So, I guess, thinking about this representative element here was what I was doing in the first few lines here.

Interviewer: Okay.

Ben: So I, I said on here, you know, define a linear mass density that is the mass of the chain over its length (writes eqn on board)

Interviewer: Um-hm.

Ben: And if that's true, then if we're talking about a little tiny piece of chain, you know, you just make this (mass) infinitesimally small and that (length) infinitesimally small. You could say dl times lambda is dm (writes ldl=dm).

Interviewer: Okay. And why did you, why were you wanting to find the mass? Or the, why, why were you doing this?

Ben: Why was I doing this? (points to infinitesimal equation)

Interviewer: Mm-mm.

Ben: Because I need to some, I'm thinking in the back of my mind I need to somehow integrate over, you know, the little contributions to the potential energy from each point along this chain. (writes integral dU over chain)

Interviewer: Okay. And the mass matters in contributing to the potential energy?

Ben: Right, right.

Interviewer: Okay.

Ben: Um, U is mgh. (writes U = mgh on board)

Interviewer: Okay so you're thinking for each individual point, that contributes to the total U by some factor mgh.

Ben: Right.

Interviewer: Okay.

Ben: Right. And, you know, I'm thinking in the back of my mind I want to do an integral I need infinitesimals here (in integral equation) –

Interviewer: Okay.

Ben: So that's why I'm concerned about talking about little tiny pieces of mass.

Interviewer: Okay.

Ben: [Laughter drinking water.] So, I mean lookin' at this now, I don't think my notation is, is ex, totally correct in here.

Interviewer: Okay, it's okay.

Ben: But, I'll just copy what I have here (writes U = in front of dU integral)

Interviewer: Okay.

Ben: There. Um, the total potential energy here, I have to integrate all the U's –

Interviewer: Okay.

Ben: - over the chain. So like I said U is m (writes dm), g, h (writes l). So I have to somehow, now here I'm mixing things because when I integrated over the chain, l is just kind of the variable that will sweep out up and down here (pointing to the hanging part of the chain)

Interviewer: Right.

Ben: That was the, the way I gonna go from here to here (chain at table to chain bottom).

Interviewer: Okay.

Ben: So, l from zero (writes bottom limit l=0) to l equals to what I call h prime (writes l=h' upper limit), you know, down here.

Interviewer: Okay.

Ben: At the bottom of the chain. Now, I mean, that's not technically correct, I can see that now, cause my infinitesimal is kind-of an m here –

Interviewer: Okay.

Ben: And so this is really, I'm just kind-of noting to myself, I gotta somehow sweep out (pointing to hanging chain), you know, consider every point along that chain, and here that's my notation for how I'm going to do that (gesturing up and down on the integral in the same way he did it over the chain).

Interviewer: Okay.

Ben: So then, what did I do? Let's see here. Because I guess I have written on this paper "but h prime equals l over 2 plus x of t." (writes but h'=l/2 + x(t)) So that must have been, I guess I was concerned that ultimately the question was gonna to ask me to solve the Lagrangian and find the equation of motion in terms of this function (writes x(t)) that they gave me in the problem.

Interviewer: Right.

Ben: So I guess I was concerned that, you know, I, I have to somehow work in the problem's given notation into the way I'm doin' this problem.

Interviewer: Okay.

Ben: And so I guess that's, I was gonna replace what I naturally called h prime with this equation here (points to h' equation).

Interviewer: Okay.

Ben: And that makes sense 'cause (back at diagram) its like, the chain started out half here and half here (pointing on table and off) –

Interviewer: Okay.

Ben: And whatever extra distance it goes down is what they defined as x –

Interviewer: Okay.

Ben: And so to sweep out however much chain is here you gotta go from zero to (points to h' equation) wherever.

Interviewer: So the U is also gonna be changing with time?

Ben: Yes because the uh, the chain is, the chain's gonna be moving –

Interviewer: Okay.

Ben: - in this event.

Interviewer: Okay.

Ben: So if the chain moves more of its hanging down further and U's gonna change.

Interviewer: Okay.

Ben: It's kinda, yeah, I mean, the thing that went through my mind there was we want to find the equation of motion for this chain so we have to allow the potential energy of it to change.

Interviewer: Okay.

Ben: If you want it to move in time.

Interviewer: Right.

Ben: Right.

Interviewer: Okay.

Ben: So yeah, um, let's see. On the next line I guess I wrote, I called this negative too (puts negative in front of U integral) because I'm below my reference point. (points to drawing vertical part).

Interviewer: Okay.

Ben: So potential energy has to be negative.

Interviewer: Mm-hmm.

Ben: If I'm calling this way (points down) negative.

Interviewer: Okay.

Ben: So the next line it seems I wrote I'm integrating from zero to l over to plus x of t (writes limits on integral on board).

Interviewer: Okay.

Ben: And I did this little substitution here (pointing to dm equation and writing ldl in integral)

Interviewer: Mm-hmm.

Ben: So uh, lambda dl in for dm. So I've got lambda g l dl. (writes lgldl in integral).

Interviewer: Okay.

Ben: Yeah okay so that's -

Interviewer: And that l was the same l as you'd been using? [T pointing to diagram] That's the same l as you were using for, l as it were?

Ben: Here? (pointing to h' equation)

Interviewer: Yeah.

Ben: Right, okay so, yeah, now at this point you'll see on my paper these little primes mysteriously appear here (writes primes on the l's on the board).

Interviewer: Okay.

Ben: Because, you're right, they're not the same l.

Interviewer: Okay, okay.

Ben: Technically speaking. Yeah, this l [in limit] is distinct from these l's [in integral]. These [in integral] are just integration variables to help me sweep out, you know, this chain's length.

Interviewer: Okay.

Ben: This [in limit] is a given parameter of the problem.

Interviewer: Oh, I see, I see, I see.

Ben: Okay, so now I'm just thinkin', I mean this seems to have led me to the right answer, but I want to try to understand why I put those limits on there.

Interviewer: Mm-hmm.

Ben: Like, so l prime is apparently my coordinate locating myself along this length of chain (pointing to part of chain hanging off).

Interviewer: Okay.

Ben: So l prime equals zero up here –

Interviewer: Mm-hmm.

Ben: And I'm gonna sweep out 'til l prime, which is the same as h prime –

Interviewer: Mm-hmm.

Ben: - equals where it started (pointing to l/2 in upper limit), half and half –

Interviewer: Mm-hmm.

Ben: - plus however extra long its moved. So yeah, I, I can see this, these limits of integration (pointing to limits) are gonna let me sweep out (pointing to diagram), at any given time (points to t in upper limit), however much of the chain is hanging here (pointing to chain off table in diagram).

Interviewer: Okay.

Ben: So then, okay. So that's great, now that's just an integral you can do that.

Interviewer: Right.

Ben: And work, work, work and you get to the answer that I came up with.

Interviewer: Okay. Okay. Great. And, I'm trying to think. Hmm. Okay, no, no, no, I'm good. Go ahead. Great.

Ben: Okay. Okay. So that's, uh, U and I guess if you want the Lagrangian you need to know the kinetic energy also. So, I mean that's, I'm sure I remember thinking at the time, "boy it can't be that easy, can it?" But, I mean, it is. If it's an inextensible, inextensible chain, every bit of that chain is moving at the same velocity.

Interviewer: Okay.

Ben: So, you know, kinetic energy is one half m v squared (writes t = 1/2mv2 on board) there by definition. You know, every bit of that chain is moving at the same velocity, so this (v) is just gonna be constant of the length of the chain.

Interviewer: Okay.

Ben: Not constant in time because its speeding up (motions hands down across the diagram).

Interviewer: Right.

Ben: And uh, you know, you can look at how fast x of t is changing (write x(t) on the board at start of chain), you know and that's going to be how fast this, this first little bit of chain is moving, which I just said is the same as how fast every bit of the chain is moving. So v here (in T equation) is just gonna be, you know, the first derivative of x - (writes ½ mx2).

Interviewer: Okay.

Ben: - squared, in time. So then yeah, the Lagranian is T minus U (writes L = T – U).

Interviewer: So why is it that for the potential energy you have to sum up over every little point but for the kinetic energy you can just say the whole thing is like one point?

Ben: Oh, so technically I did sum up over al, everything.

Interviewer: Okay.

Ben: And I did that when I argued that, you know, you can say the kinetic energy of the ith little bit of -

Interviewer: Okay.

Ben: - chain is one half the mass of that little tiny bit times however fast it happens to be movin' squared (writes Ti = 1/2mixi2).

Interviewer: Got it.

Ben: And I just got into that implicitly 'cause I said, every bit's movin', every little piece of mass is movin' at the same speed –

Interviewer: Okay.

Ben: So I, I did, I summed up for the kinetic energy too but I just did it implicitly.

Interviewer: Okay.

Ben: Using the mass of the whole chain.

Interviewer: Okay. Okay. Cool. Um, and the potential energy didn’t work that way because, why did potential energy not work that, why couldn’t you do it that easily for potential energy?

Ben: Oh, why couldn’t I, okay, why couldn’t I just do the sum implicitly?

Interviewer: Yeah.

Ben: Because, um, here, each little bit, you know, this bit and that bit (boxing out pieces of chain on the diagram) and that bit and that bit –

Interviewer: Uh-huh.

Ben: - they all contributed equally to the kinetic energy.

Interviewer: Okay.

Ben: You know, that’s [mass] the same and that’s [velocity] the same for each bit.

Interviewer: Mm-hmm. Okay.

Ben: So you can just do an algebraic sum really.

Interviewer: Mm-hmm.

Ben: But, uh, for the potential energy, you know the amount this bit [in middle of hanging part] contributes –

Interviewer: Mm-hmm.

Ben: - is, uh, different than the amount this bit [bottom of hanging part] contributes to the potential energy.

Interviewer: Because?

Ben: Because they’re at different heights.

Interviewer: Okay.

Ben: Now, I mean, there’s a way, because, I mean, I don’t think I thought this at the time, or if I did I couldn’t see an easy way to make it work. But, I mean, I could see now there’s uh, kind-of an easy way because the potential energy is linear in height -

Interviewer: Mm-hmm.

Ben: - things are gonna average out. I mean, that bit and that bit [top and bottom] added together will give the same contribution as that bit and that bit [next to top and next to bottom].

Interviewer: Got it.

Ben: So there's a way to do a center of mass argument there too, but –

Interviewer: Yeah, that's fine. Okay. Okay, great. Cool, so then, uh, let's see. The equation of motion. Well, you could just, I mean, how did you do the equation of motion?

Ben: Okay.

Interviewer: How did you find the equation of motion?

Ben: Can I erase this?

Interviewer: Yes you can.

Ben: Okay. [Erases board but leaves diagram] Okay, so the equation of motion. I mean, on this paper, I started with the physical fact that once you have a Lagrangian, which I figured out in part a. Then this relation [Lagrange's Equation which he writes up] here is just a physical fact of nature. I mean –

Interviewer: Okay.

Ben: In, in my mind, this [Lagrange's equation] is on par with this [F = ma].

Interviewer: Okay.

Ben: I mean that's, and really this [Lagrange's] is just a, you know, fancy repackaging of this [F=ma].

Interviewer: Okay.

Ben: You know, its basically in terms of energy instead of forces but um -

Interviewer: Okay.

Ben: - and, yeah that –

Interviewer: So then you just crank out the algebra of that.

Ben: Right.

Interviewer: Okay, great, great. And so then gives you, what did you have for your equation of motion in the end?

Ben: Okay, so, um, yeah. Yeah so, I mean, crank away partial derivatives are easy –

Interviewer: Right. Yeah, yeah, yeah I don’t need you to actually do that.

Ben: And, okay, so at the very end I came up with [writes eqn on board] that.

Interviewer: Okay, so then the next part asks you to solve for c of t.

Ben: Right. Okay, so –

Interviewer: So what did you do for that?

Ben: What I did, you know at the time I remember thinkin’, well you know, that’s, yeah, a little difficult. I don’t exactly know how to solve this equation, but I would know how to solve something like this [writes up homogeneous eqn].

Interviewer: What is that thing in front of the first y?

Ben: Oh, its just some constant.

Interviewer: Oh, okay, got it.

Ben: You know, um, this is just an exponential solution.

Interviewer: Okay.

Ben: Right here. And, you know, I wasn’t exactly sure, I couldn’t just write down the solution –

Interviewer: Mm-hmm.

Ben: - you know, it wasn’t a pre-packaged thing in my head. How to, you know, just write down a solution dealing with this inhomogeneous term right here. (pointing to g/2 term on board).

Interviewer: Okay,

Ben: So what I then tried to do was switch variables. (motioning back and forth with hands)

Interviewer: Okay.

Ben: Right, you know, redefine this equation here, or the function c –

Interviewer: Okay.

Ben: - in a clever way that would leave me to this equation.

Interviewer: Okay.

Ben: To an equation of this form [homogeneous].

Interviewer: Okay.

Ben: And then once I solved it for y, I could then go back by definition to how c relates to y and –

Interviewer: Right.

Ben: - go backwards that way.

Interviewer: Okay.

Ben: So, the first time I tried to do it I said let y of t equal g over 2 minus c, uh, g over l c of t (writes “Let $y(t) = g/2 – g/lc(t)$” on board) Which, you know, is is really kinda silly because, I, I just, this this [putting g/l in front of c] was just a rote mistake, you know.

Interviewer: Okay.

Ben: I just missed that positive [from eom] and made it minus [in redefining variable].

Interviewer: Oh I see.

Ben: So the correct way to do it, which that’s why I scribbled all this out (pointing to his paper).

Interviewer: Oh I see.

Ben: And then, you know –

Interviewer: So you made that a positive?

Ben: That, right, right.

Interviewer: Okay.

Ben: Unfortunately not before working it all out with the minus here.

Interviewer: Ahh. Got it.

Ben: I mean the reason you need a mi, plus here is because that [redefined y], then just makes the left hand side of this equation, you know, just y.

Interviewer: Uh-huh. Uh-huh.

Ben: And then, um, if you’re gonna talk about how does y change in time –

Interviewer: Mm-hmm.

Ben: This constant term doesn’t matter.

Interviewer: Right.

Ben: And its just gonna be, that. (writes g/l c double dot, erases it for y double dot.)

Interviewer: Okay.

Ben: So now you have, now, I’m just looking back here to be sure that’s what I did on here. [17 second pause] Oh right, I screwed that up. If this [redefinition of y] is true, then, I screwed it up up here [on board] on here [on his solution] its right.

Interviewer: Oh, okay.

Ben: If this is your definition

Interviewer: Mm-hmm.

Ben: Then, uh, the second derivative of y equals that [writes g/l c double dot].

Interviewer: Okay,

Ben: And then, I mean you’re, you’re rearranging this equation [inhomogeneous EOM] so you care about what this is (c double dot).

Interviewer: Mm-hmm.

Ben: So its l over g y double dot is c double dot.

Interviewer: Okay.

Ben: And then, then, this half of the equation is just y [LHS EOM] and this half over here [RHS EOM] is l over g y double dot. (Writes this on board and boxes it)

Interviewer: Okay.

Ben: So that, that’s the easy, simple exponential equation of motion that I know I can solve.

Interviewer: Okay.

Ben: So that’s what I did here, um. I know the solution is, you know, a sum of the positive exponential and the negative exponential.

Interviewer: Mm-hmm.

Ben: With some constants in front of ‘em. And, you can get those two constants by plugging in the two initial conditions that you know.

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