Recognizing Mechanistic Reasoning in Student Scientific Inquiry: A Framework for Discourse Analysis Developed From Philosophy of Science

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ABSTRACT: Science education reform has long focused on assessing student inquiry, and there has been progress in developing tools specifically with respect to experimentation and argumentation. We suggest the need for attention to another aspect of inquiry, namely *mechanistic reasoning*. Scientific inquiry focuses largely on understanding causal

mechanisms that underlie natural phenomena. We have adapted an account of mechanism from philosophy of science studies in professional science [Machamer, P., Darden, D., & Craver, C. F., (2000). Thinking about mechanisms. Philosophy of Science, 67, 1–25] to develop a framework for discourse analysis that aids in identifying and analyzing students' mechanistic reasoning. We analyze a discussion among first-grade students about falling objects (1) to illustrate the generativity of the framework, (2) to demonstrate that mechanistic reasoning is abundantly present even in these young students, and (3) to show that mechanistic reasoning is episodic in their discourse.   © 2008 Wiley Periodicals, Inc. *Sci Ed* 1–28, 2008

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 (National Research Council, 1996), which calls for "changing emphases to promote inquiry" (p. 113). Much of the challenge in achieving this ambition has been in defining what constitutes "inquiry" and how to assess it in students. The ambiguity of the objective makes it difficult for researchers, curriculum developers, and teachers to pursue it systematically.

There has been progress with respect to particular aspects of scientific inquiry. The logic of controlled experimentation, for example, is relatively simple to define as an instructional target, and this has facilitated a fair amount of research on how students develop the control of variables strategy (Chen & Klahr, 1999). There has similarly been attention to students' abilities for drawing logically appropriate inferences from data (e.g., D. Kuhn, 1993). The more general notion of scientific argumentation has been more difficult to define, but several recent efforts have posited coding schemes for assessing the sophistication of students' arguments, identifying the extent to which students generate claims, support claims with evidence, and respond to counterarguments (Erduran, Simon, & Osborne, 2004; Felton & Kuhn, 2001).

Of course, there is more to scientific inquiry than controlling variables and argumentation. In fact, it is possible to study abilities for controlling variables in contexts that are not scientific, and the frameworks for analyzing the structure of argumentation apply to politics or law as much as they do to science. More specifically, there has been little attention to the substance of those experiments and arguments as part of understanding and assessing inquiry, honoring a division in science education research between "two main types of knowledge, namely, domain-specific knowledge and domain-general strategies" (Zimmerman, 2000, p. 102). Thus, science education research has devoted extensive attention to student misconceptions or naïve theories, with the instructional target of expert conceptions, and the study of inquiry has mostly concerned "domain-general strategies." In this article, we attend to the substance of student thinking as part of inquiry-oriented assessment. In particular, we call attention to the role of *causal mechanism* in scientific inquiry.

Within the history and philosophy of science, the "scientific revolution" has been characterized as a shift from "occult" to mechanistic accounts of the natural world (Westfall, 1986). Within science education, research and curriculum development has focused on promoting mechanistic reasoning over teleological and anthropomorphic reasoning for understanding biological phenomena (Louca, Elby, Hammer, & Kagey, 2004; Southerland, Abrams, Cummins, & Anzelmo, 2001; Tamir & Zohar, 1991). That is, both historically and for students, progress in scientific inquiry is characterized in part by a shift toward reasoning about causal mechanisms. In this respect, a mechanistic idea is more "scientific" than an occult or teleological idea, whether or not it is correct.

There is further support for focusing on mechanism as part of inquiry-oriented assessment in evidence of its role in children's abilities for experimentation and argumentation. Schauble (1996) showed that children's (mechanistic) understanding of domains has a meaningful and valuable impact on how they implement the control of variables strategy. Koslowski (1996) went further to argue that reasoning about causal mechanisms is central to scientific inquiry and should not be understood as subordinate to the procedures of controlling variables.

A 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 what constitutes controlled experimentation or scientific argumentation. While there are many examples of students' mechanistic reasoning in the literature (e.g., Brewer, Chinn, & Samarapungavan, 1998; diSessa, 1993; Hammer, 2004; Metz, 1991; Schauble, 1996; White, 1993), no one has provided an explicit definition.

Consider the following instance in which a student describes 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)

Chin and Brown (2000) characterize Rick's explanation as an attempt "to come up with a model or minitheory that would explain the mechanism of how things worked in the physical world" (p. 122). We agree, but our agreement relies on a shared intuitive sense of this notion of causal mechanism. Those who do not share that intuition may find it difficult to identify this type of reasoning as mechanistic. Even if this example were clear to all science educators, other examples would be ambiguous and controversial. Consider how Kelly, a college student, 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.

Is Kelly's explanation mechanistic, partially mechanistic, or nonmechanistic? By what criteria could we decide? It may be especially difficult to identify the beginnings of mechanistic thinking when our understanding of what we are looking for is at the level of "we know it when we see it." There is a need to supplement examples from previous research by articulating an explicit definition of mechanistic reasoning so that its progress can be pursued and evaluated systematically.

To better understand students' mechanistic reasoning, we draw from the philosophy of science, where the concept of mechanism has been successfully employed to understand both the development of advanced scientific research theories and the contributions of individual scientists' ideas (Bechtel & Abrahamsen, 2005; Glennan, 1996, 2000; Machamer, Darden, & Craver (MDC), 2000; Tabery, 2004; Thagard, 1998; Westfall, 1986). We begin by reviewing literature on causal mechanistic reasoning in both students and scientists, with special attention to analyses in which the latter can inform our understanding of the former.

We then turn to our principal objective: we offer a new framework for discourse analysis, developed from philosophical accounts of the work of scientists, designed to identify mechanistic reasoning in students' thinking. We illustrate this framework with an example of first-grade students discussing falling objects. The framework reveals that mechanistic

reasoning is abundantly present even in these young students, and that it appears episodically throughout their conversation. Application of this analysis tool 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. These results from the first-grade discussion indicate the generativity of using this framework for discourse analysis and suggest its utility for future work on student scientific thinking.

CHARACTERIZING MECHANISTIC REASONING

Attempts to characterize mechanistic reasoning fall into two main categories: those that identify the mechanistic reasoning in children's explanations, and those that identify the mechanistic features of scientists' reasoning. In what follows, we describe the former line of work from education and psychology research, including its utility as a starting point and its limitations as a systematic analysis tool for identifying mechanism in student discourse. We then describe the latter work from the philosophy of science and describe how it can be productively employed to address the limitations of current educational research.

Characterizations of Students' Thinking From Education and Psychology Research

Even for very young children, seeking and constructing explanations for natural phenomena is a ubiquitous part of everyday life. Extensive research has examined the psychology and cognition associated with a developing understanding of explanation (e.g., Callanan & Oakes, 1992; Keil & Wilson, 2000; Lombrozo & Carey, 2006). This work identifies types of explanations that are psychologically or philosophically appropriate for different situations as well as the causal reasoning involved in constructing each type of explanation. For example, Keil and Wilson (2000) describe "three prima facie distinct kinds of explanation—principle based, narrative based, and goal based" (p. 6). From their review of the literature, Wellman and Gelman (1992) conclude that

> Children exhibit three different forms of causal reasoning, involving in the case of naïve physics a kernel sense of mechanical forces; in the case of naive psychology a kernel sense of belief-desire causation; and in the case of naïve biology a kernel sense of biological functions. (p. 367)

Whether the different forms of explanation line up cleanly along scientific domain lines is debatable (see Keil & Wilson, 2000), but other research with children and students affirms that even very young children can and do reason in different ways to support their understanding of natural phenomena (e.g., Duschl, Schweingruber, & Shouse, 2007; Hickling & Wellman, 2001; Springer & Keil, 1991). Here, we explore one particular type of explanation and reasoning appropriate for scientific understanding: that involving causal mechanism.

There is a large body of research devoted to understanding the role of mechanisms in scientific explanations. Some work within developmental psychology suggests that knowledge of mechanisms is an essential component of domain-specific theories (e.g., Carey, 1995; Keil, Levin, Richman, & Gutheil, 1999; Springer & Keil, 1991). Other research presents evidence that knowledge of mechanisms is in fact what helps us identify and understand the causal structure of the world (e.g., Ahn & Kalish, 2000; Ahn, Kalish, Medin, & Gelman, 1995; Shultz, 1982).

As mechanism is important to scientific explanation in general, reasoning about mechanisms is an important aspect of student inquiry. Students should attempt to explain how things happen, and teachers should recognize and promote their efforts (Brewer et al., 1998;

Chinn & Malhotra, 2002; Hammer, 2004; Metz, 1991; Schauble, 1996; White, 1993). This literature provides several characterizations of what counts as "mechanistic" and thus valuable for scientific explanation and inquiry.

Mechanistic Reasoning Is Nonteleological.   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, Southerland, and Cummins (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 has made progress in defining mechanistic explanations by contrasting them with teleological ones.

Mechanistic Reasoning Is Causal.   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 of 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. Koslowski (1996) similarly 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). Carey (1995) claims 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 domains such as biology. Abrams et al. (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 phenomena generally describes them as identifying the process between causes and effects.

Mechanistic Reasoning Is Built From Experience.   Other researchers discuss students' knowledge of mechanisms as abstractions from specific experiences in the physical world. The work of Keil et al. (1999) on biological thought suggests that students accumulate experiences within a domain to develop specific mechanisms that are "in essence highly concrete mental models of how things work in a particular area" (p. 316). diSessa (1993) goes further to provide a cognitive account in which individual cognitive elements called "phenomenological primitives" ("p-prims") are abstracted from common everyday experiences and used

to reason about novel situations. For example, diSessa identifies what he calls Ohm's p-prim ("An agent or causal impetus acts through a resistance or interference to produce a result") that is relevant to a number of physical mechanisms—from pushing a book across surfaces with different friction to inserting new resistors in a circuit (diSessa, 1993, p. 217). 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).

Mechanistic Reasoning Describes Underlying or Relevant Structure. Some researchers describe mechanism in terms of how underlying structure and activities can account for observable changes in the system. 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, 2000, 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). In these characterizations, mechanisms account for observations by showing that underlying objects cause local changes in the system by acting on one another.

Some research describes the importance of structure to mechanistic reasoning without requiring that the described structure be microscopic or nonobservable. For example, Carey (1995) claims that causal mechanisms rely on "interactions among the entities in the domain" (p. 273) without reference to whether those entities are "reductionist" in the sense of being at a level below observation. Schauble (1996) defines mechanisms as "explanatory models, . . . either structures or processes, that account for the observed phenomena" (p. 103). Springer and Keil (1991) similarly describe the mechanisms that "mediate" (p. 768) physical and biological events as consisting of "causal agents" and "causal processes" (p. 769), both of which must be specified in giving explanations. This line of research suggests that mechanistic reasoning involves describing how the particular components of a system give rise to its behavior.

Limitations of Characterizations of Students' Thinking

While there has been a substantial amount of attention to the origins, nature, and importance of mechanistic reasoning in education and psychology research, the literature has not provided a sufficiently precise definition of mechanistic reasoning to support systematic analysis of student discourse, and the notion remains conflated with causality.

Lack of Precision. 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. Recall 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.

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 illustrating "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 pressures judgments of mechanism to be all or nothing: either an explanation matches the exemplar or it does not.

   Some of the work described above goes farther than others in unpacking the notion of mechanism. Research describing mechanisms as involving causal agents, structure, or processes (e.g., Schauble, 1996; Springer & Keil, 1991) suggests identifiable components of mechanistic explanations. For example, Springer and Keil's (1991) work demonstrates that even very young children can distinguish between appropriate and inappropriate causal agents. However, these articles still do not use the constructs of agents, structure, and processes to analyze student discourse. In some cases, the research methodology does not allow such analysis because researchers asked students to choose among given mechanisms rather than construct their own explanations. Thus, although some work better defines the notion of mechanism in the abstract, it still only offers examples of "best case" explanations and does not provide practical tools for evaluating student discourse.

Reliance on Causality.   Mechanistic reasoning is often loosely defined as "causal," and we might expect that cognitive psychology literature on causal learning would provide insight into mechanistic reasoning. Gopnik and her colleagues (e.g., Gopnik & Sobel, 2000; Gopnik, Sobel, Schulz, & Glymour, 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 years 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, 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.

However, what these authors call causal learning is not the same as what is described above as mechanistic.[1] Although in the studies by Gopnik and Sobel (2000) and Gopnik et al. (2001), children recognized that blickets *cause* the detector to go off, it is unlikely that they had any conception of *how* blickets do so. These two levels of explanation parallel T. S. 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. S. Kuhn, 1977, p. 28)

These "broad causes" are more like what we have identified as mechanistic reasoning. Mechanistic reasoning involves more than noting which causes are associated with which effects; it concerns the process underlying the association. Characterizations of mechanistic reasoning that rely mainly on causality risk underestimating its breadth by equating it with "narrow" causes.

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 17 different types of causality in children's explanations. Although he finds 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 students' explanations for biological phenomena, Abrams et al. (2001) classified students as able to give causal explanations that were still "scientifically inappropriate" in that they failed to describe mechanisms for physical changes. 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)

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[1] These authors do not claim that their work describes mechanistic reasoning, and we do not suggest that their work *should* address mechanistic reasoning. We merely note that their work aims to characterize a different aspect of children's thinking than that which we are calling "mechanistic." Thus, that research is perhaps not the appropriate starting point for thinking about characterizing students' mechanistic reasoning.

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.

Other work from developmental psychology makes an even stronger claim: not only is mechanistic reasoning more than causality, knowledge of domain-specific mechanisms is cognitively distinct from domain-general causal understanding. Most of the work in this area has been with regard to students' intuitive theories of biology (e.g., Carey, 1995; Keil et al., 1999; Springer & Keil, 1991; Wellman & Gelman, 1992). In their work describing the development of biological thought, Keil et al. (1999) present three studies with children and naïve adults that suggest

> one can have some understanding of likely causal patterns without having any particular mechanisms in mind. (p. 316)

They posit a cognitive model where abstract notions of causal relations among entities in a domain are distinct from domain-specific mechanisms. Thus, these two types of knowledge can be developed and tapped independently. In her discussion of the development of causal understanding, Carey (1995) critiques literature that uses data that students have knowledge of "input-output relations [cause-effect pairs]" (p. 284) to claim that students have theories of biology that include "theory-specific causal mechanisms" (p. 273). She speculates children may have cognitive structures that contain knowledge of the entities and the relations among those entities in a domain, but that this

> 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)

If domain-specific mechanistic reasoning is cognitively distinct from domain-general causal reasoning, it may be inappropriate to base our definitions of the former on the latter.

There is a critical need to supplement the characterizations and examples of mechanistic reasoning from previous research by articulating an explicit definition so that the progress of mechanistic reasoning can be pursued and evaluated systematically during inquiry. Chinn and Malhotra (2002) acknowledge this deficiency 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. We turn to research from the philosophy of science for help in achieving that objective.

Characterizations of Scientists' Thinking From History and Philosophy of 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). Mechanical philosophy conceived of the world as a machine of inert, passive bodies that moved only through physical causation by direct contact. Mechanical philosophy culminated in Newtonian mechanics when later scientists extended it to include "action at a distance" (Westfall, 1986).

The notion of "mechanism" as a basis for scientific explanation has been refined since the time of Newton. Historical and philosophical studies of scientific progress have modified and extended the description of mechanisms to be continuous both with the ideas of the mechanical philosophers and with contemporary practice (Bechtel & Abrahamsen, 2005; Glennan, 2000; Salmon, 1978; Tabery, 2004; Thagard, 1998). Glennan (2000) describes a mechanism as "a complex system that produces. . . 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 through generalizations (nonuniversal "laws") such that changes in one part bring about changes in another part. Similarly, Thagard (1998) 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). MDC (2000) conceptualize 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). These definitions have progressed beyond the early mechanical philosophers' restrictions of physical contact forces mediating changes in passive bodies.

Although mechanical explanations once held a singly privileged place in scientific explanation, present day philosophers of science debate whether all scientific explanations should or can be mechanistic. For example, the mathematical formalism of quantum mechanics provides elegant explanations for phenomena in spite of not being mechanistic. Nonmechanistic conceptions of scientific explanation described in the philosophy of science literature include the deductive-nomological models that explain phenomena by subsuming them under more general covering laws of nature (Craver, 2002b; Hempel, 1962), probabilistic models that rest on inductions made from calculations of statistical chance (Hempel, 1962), mathematical models driven by boundary conditions (T. S. Kuhn, 1977), and unification and reduction models (see Rosenberg, 2000, chapters 2 and 3 for a review). Philosophy of science as a field has not reached a consensus on which of these characterizations reflect the true nature of explanation, or even whether a single characterization is appropriate for all disciplines.

By focusing only on the development of mechanistic explanations in this work, we do not mean to neglect this philosophical debate or the merits of any of the other types of explanations discussed above. We do not suggest that children should not learn to reason with physical laws or mathematical formalisms. Instead, we merely point to mechanistic explanation as *one* type of explanation that is appropriate and valued in professional science practice that should thus be recognized and promoted in children's reasoning about phenomena. We believe this type of explanation may be especially appropriate to encourage in students as it helps them tap into their existing intuitions about the physical world (diSessa, 1993).

Machamer, Darden, and Craver's Account of Bioscientists' Search for Mechanisms

In searching for a precise characterization of student mechanistic reasoning, we collaborated with Darden (e.g., MDC, 2000), a professor of philosophy of science at the University of Maryland. This preliminary collaboration drew on her expertise and prior work unpacking the pursuit of mechanistic explanations in professional bioscience to describe the reasoning of first-grade students in a science discussion (Russ, 2006). The analysis succeeded in articulating the substance and value of student comments more precisely than other available analyses, and also told a coherent story about the progression of the discussion. That preliminary effort laid the groundwork for a more systematic discourse analysis tool for recognizing mechanistic reasoning in students. We continue to find MDC (2000) to be the clearest synthesis of contemporary accounts of mechanism in professional science, and retain it as the basis for our analytic framework. 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. (MDC, 2000, 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.

MDC (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 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, 2000, 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 in this section to describe features of MDC's characterization of mechanisms.

The mechanisms that underlie phenomena are composed of *entities* and *activities*.[2] Activities are the components of mechanisms that produce change—they are 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 whereas the fluid has an electric potential 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,

[2] Unlike other philosophical accounts of mechanism that focus on interaction 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.

Na^+ ions cannot diffuse and depolarization cannot occur unless the four alpha helices are located next to one another so that 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. S355). 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 such physiology 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 involves taking 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 motif is common in DNA-binding proteins (Brennan & Matthews, 1989), making it more likely for scientists to use it 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" (Craver, 2002a, p. S93) and observe the effects on the phenomenon at a higher level. 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.

Adapting Machamer, Darden, and Craver's Philosophical Account to Analyze Student Thinking

We recognize aspects of student science discussions in MDC's formal characterizations and rich descriptions of professional science activity. Not only does their framework align well with our conception of how science is practiced by research physicists, it also shows significant overlap and correlation with the kinds of things we see students doing in the classroom. However, our goal is different from MDC's. 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, on the other hand, want to characterize student thinking and discourse about mechanisms—what students do and say when reasoning about new mechanisms for phenomena they observe.

To develop our framework, we started with MDC's proposal that mechanisms explain how phenomena are produced by tracing the productive changes continuously from setup 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 step in constructing an unknown mechanism. MDC's description of the parts of a mechanism helped us recognize those parts that students might identify in their discussions of new phenomena. Specifically, we use MDC's 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 *setup conditions*. We have also translated two of the reasoning strategies from MDC's framework into language that appropriately describes the work of students: *abstract schema instantiation* and *chaining*.[3] The simple version of abstract schema instantiation we see in students is *analogical 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. *Forward* and *backward chaining*, as we discuss below, are of primary importance to our coding scheme.

Other aspects of MDC's framework are not helpful for our purpose of identifying how students reason about mechanisms.[4] The overall structure and nature of completed mechanisms, while important for MDC, is less relevant for our purposes than the individual

[3] MDC's modular subassembly strategy is not relevant for the data we have considered thus far, because the mechanisms involved are not intricate enough to warrant the use of groups of entities and activities. We imagine that subassemblies would be appropriate in more advanced settings.

[4] 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.

pieces and reasoning strategies used in constructing them. For this reason, we do not attend to levels of hierarchy. Nor do we look for students using the various empirical strategies for discovering mechanisms, because we are interested in informal science discussions, in which 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 inquiry that centers on controlled experimentation.

A DISCOURSE ANALYSIS TOOL FOR RECOGNIZING MECHANISTIC REASONING

The Coding Scheme

There are nine categories in our coding scheme, derived from MDC's framework: (1) describing the target phenomenon (DTP), identifying (2) setup conditions (SC), (3) entities (IE), (4) activities (IA), (5) properties of entities (IPE), (6) organization of entities (IOE), (7) chaining (C), analogies (A), and animated models (AM). We describe and give an example of each in turn.

1. *Describing the Target Phenomenon*. 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.
2. *Identifying Setup Condition*s. Setup conditions are descriptions of the spatial and temporal organization of entities that begin the regular changes of the mechanism that produce the phenomenon. We code as "identifying setup conditions" the moments when students identify particular enabling conditions of the environment that allow the mechanism to run. For example, the student discussing the buoyancy experiment might say, "I held both cans of coke under the water *before I released them*."
3. *Identifying Entities*. 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*."
4. *Identifying Activities*.[5] 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). 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,

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[5] The "identifying entities" code partially coincides with the reductionist descriptions of mechanisms form the science education literature (e.g., Chin & Brown, 2000; Chinn & Malhotra, 2002), though we do not require that the entities necessarily be microscopic or nonobservable. In addition, the "identifying entities" and "identifying activities" codes may capture the same aspects of explanation as Springer and Keil's (1991) causal agents and processes.

a student might say, "Each individual water molecule *pushes* up on the molecules on top of it."

5. *Identifying Properties of Entities*. Identifying and isolating 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."

6. *Identifying Organization of Entities*. 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 does not occur in the data presented below, but has been crucial in analysis of other student discussions (Russ & Hutchison, 2006).

7. *Chaining: Backward and Forward*. 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."

Analogies. Scientists also use analogies to similar mechanisms in other contexts or fields as a framework for understanding new situations (Darden & Craver, 2002; Dunbar, 1995), frequently beginning with a previously articulated mechanism and attempting to fit various aspects of the new phenomenon into the functional roles and constraints of the original. An "analogy" code is used when students compare the target phenomenon to another. For example, a student may say, "I am thinking about *water like a rope with tension* that can be pushed out of the way but still resists."

Animated Models. 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 "see" certain entities acting in the mechanism. For example, students might hold hands and then *link arms* to model the idea of water as like a rope with tension.

Hierarchy of Codes

We arranged the first seven codes in a numerical sequence based on their logical connections and on our perception of their scientific sophistication. 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. In addition, chaining seems to be the most difficult and sophisticated. The evidence from coding student conversations, as below, bears out our organization of the codes: Higher numbered codes (especially chaining) rarely appear without lower numbered 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" (Metz, 1991, 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. The mechanistic phase of Metz's oldest subjects is equivalent to our identification of activities and subsequent forward and backward chaining.

The last two mechanism codes, analogies and animated models, can be used in different ways. Students may use analogies as direct mappings to describe phenomena and identify components, and this use may be naïve or sophisticated; or they may use them as a 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, we code the occurrence of these aspects of reasoning but do not include them in the hierarchy.

Application of the Coding Scheme for Discourse Analysis

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 on homework or a test. We apply the codes to each individual student conversational turn, however, long it might be. One turn may have numerous codes (e.g., it may include identification of both entities and activities), or it may have no codes at all (if none of the categories apply).

The significance of a code is this: It marks evidence of mechanistic reasoning. Higher levels in the hierarchy represent more compelling evidence. Thus, if a student's explanation warrants a large number of codes, especially high-numbered codes, the evidence is more compelling that the student is reasoning mechanistically in that moment. In contrast, if a student explanation warrants only a single code—for example, the student may describe a target phenomenon or identify entities—the evidence of mechanistic reasoning is poor. An absence of codes (or the presence of a small number of low-level codes) does not necessarily indicate an absence of mechanistic reasoning—merely a lack of evidence. In other words, the coding scheme is a means of tabulating the specific aspects of discourse that are evidence of mechanistic reasoning. There is no a priori threshold for concluding that students are reasoning mechanistically.

TABLE 1
Interrater Reliability for Mechanism Coding

Coders	Interrater Reliability	
	Data Identification	Coding
First and second authors	0.88	0.86
First, second, and fourth authors	0.79	0.88

The codes are phenomenological in that they identify aspects of discourse. It is important to emphasize that we do not consider them cognitive elements, skills, or levels of ability. For example, we do not attribute students whose explanations are coded as "chaining" as "having the ability to chain." Moreover, we do not in any way consider the hierarchy a developmental sequence. For all of these reasons, we do not intend this scheme as a pedagogical rubric. It is only a research tool by which to systematically track evidence. As we demonstrate below, by helping track that evidence it helps focus analytic attention to features of the discourse and it supports interpretation of those features.

Interrater Reliability

Because we hope the coding scheme will facilitate both identification and analysis of mechanistic reasoning, we considered interrater reliability along two dimensions: data identification (recognition that a conversational turn has meaning in it to code) and coding (deciding which categories of the framework apply). Interrater reliability between the first and second authors was 88% for data identification and 86% for coding before discussion. Because these authors are both education researchers and work closely together, their agreement might reflect their tacit shared perspective. Such agreement may be viewed as either a strength or a weakness of the coding scheme: a strength in that the 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 interrater reliability among the first, second, and fourth authors independently of the agreement between the first and second authors; the fourth author was a classroom teacher at the time of the analysis. 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).[6] 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 prediscussion interrater reliability scores is given in Table 1. After discussion, there was 100% agreement among all coders for both categories.

The figures for interrater reliability do not include the first code (now "describing target phenomenon") because it was revised twice during the analysis of this transcript. Originally, the first code was "establishing phenomenon," and was meant to identify times when students, like MDC's scientists, attempted 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, while retaining the spirit of recognizing when students discuss phenomena they hope to explain, we renamed the code "describing phenomenon" and abandoned the effort

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[6] Agreement in coding among the first, second, and fourth authors is higher than among the first and second because it is for the reduced set of commonly identified data.

to identify students' intent. This change revealed another problem with the first code. Sometimes it was unclear which phenomenon the code referenced: the primary phenomenon of the discussion (say, "A can of diet coke floats and a can of regular coke sinks in water"), or peripheral phenomena (perhaps, "Rocks sink"). 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 a question posed by the teacher). Since these changes occurred during the coding of this transcript, independent interrater 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 interrater reliability when including this code (Russ & Hutchison, 2006).

CONTEXT FOR APPLYING THE DISCOURSE ANALYSIS TOOL

We illustrate the use of the coding scheme with a discussion among first-grade students about falling objects. We chose this discussion for analysis because it seems rich with mechanistic reasoning; applying the coding scheme allows us to check whether this method of discourse analysis gives results that match that intuitive assessment.

This discussion involves first-grade students at a public elementary school in Montgomery County, Maryland, taught by the fourth author (Mikeska, 2006). The students are engaged in science lessons one to three times a week for approximately 45 minutes each time. At the time of this classroom conversation, the instructor was participating in a project to develop materials to help prospective and current elementary teachers gain experience in interpreting and assessing the substance of student reasoning; her case study and a video of this discussion are part of those materials (Hammer & van Zee, 2006).

Educational policy in Montgomery County specifies that first graders should be able to describe the motion of objects. With this goal, as well as personal and mandated inquiry goals, Ms. Mikeska (as her students called her) asks the students to predict what will happen if she drops a book and a flat sheet of paper at the same time from the same height. During the first lesson in the topic, the students all agree that the book will hit the ground first and offer several explanations as to why. Ms. Mikeska defers further exploration until the next lesson.

At the next science lesson, Ms. Mikeska shows the students a tape of their previous 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 results are represented). The students show no concern over the disagreement, but the matter is resolved when Ms. Mikeska demonstrates the experiment several times, confirming their earlier prediction. Ms. Mikeska then asks them to predict what will happen when she drops a book and a *crumpled* sheet 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 discuss this pair of classes elsewhere (Hammer, Russ, Scherr, & Mikeska, 2008) with respect to students shifting into and out of modes of inquiry we consider scientific. There, our analysis is qualitative and informal. In this paper, we present a more rigorous analysis of mechanistic thinking using the coding scheme described above. Our data for this analysis are the transcript of the second day's discussion.[7]

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[7] Readers interested in studying the full transcript should contact Russ. The published case study includes the transcript as well as video of the class (Mikeska, 2006). To be consistent with the video, we use the children's real first names, with consent from their parents.

APPLICATION OF THE ANALYSIS TOOL TO STUDENT DISCOURSE

In what follows, we use examples from student discourse to illustrate the coding scheme and to show its utility for identifying aspects of mechanistic reasoning and gaining insight into student inquiry. In each section, we describe the student discourse, offer an informal analysis of its dynamics, and then use the coding scheme to systematically analyze the episode. We show how analysis with the coding scheme allows us to make sense of the discourse dynamics. 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 sheet of paper.

Little Evidence of Mechanistic Reasoning

Class Discussion.   Ms. Mikeska begins the large-class discussion by asking students to report their results. She expects all students to report that the book hit the ground first, and is surprised by what students report.

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.

Informal Observations.   Ms. Mikeska is frustrated when the students show no interest in reconciling their contradictory observations. Her instructional assessment is that the students are 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.

Mechanistic Analysis.   Ms. Mikeska asks 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 respond 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 restates 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 reasoning (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 contradictory phenomena suggests that they may not be behaving in a scientifically sophisticated way; scientists ideally agree on targets for explanation and then proceed to construct those explanations.

Moderate Evidence of Mechanistic Reasoning

Class Discussion. In response to the teacher'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 shrug their shoulders and claim ignorance. One student suggests 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.

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 be 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 see the teacher as looking for a more scientific-*sounding* answer, and responds with a science vocabulary word for that reason.

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 which 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.

Intermediate-numbered codes appear in this segment of the discussion, which provides more evidence of mechanistic thinking in this episode than in the earlier one. However, there is no evidence that the students identify any setup 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 scientific vocabulary she does not understand; if she were using entities that make physical sense to her, we might expect to see her also identify relevant properties of those entities. Here we see a possible value of this method of discourse analysis: the mechanism-coding scheme may help distinguish cases when students use terminology with meaning and when they do not. Note too that there is no evidence of backward or forward chaining (C); perhaps the students have not identified general properties by which the entities would participate in a causal chain of events.

Strong Evidence of Mechanistic Reasoning

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 begin 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.

Informal Observations.   The students are 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 disagree, 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.

Mechanistic Analysis.   Julio identifies 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 responds 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). She then picks up the paper, flattens it, and crumples it again (AM), demonstrating that nothing is lost or gained in the process. She "weighs" the paper in her hand to support her claim (AM). Autumn, who had earlier asked Brianna why she was manipulating the paper, supports Brianna's conclusion about heaviness (IPE) after seeing the visible model.

Brianna's comments convince 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. The coding scheme suggests 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, turns the class's attention to the only activity that could have caused any change in the paper's properties—the crumpling—and helps the other students recall that crumpling does not 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 (Goldin-Meadow, 2003). Our understanding of the value of Brianna's reasoning emerges from the coding scheme: Brianna supports her idea to the class by forward chaining from known activities and providing an animated model.

RECOGNIZING SHIFTS BETWEEN LEVELS OF REASONING

In general, the coding scheme aligns with our intuitive impressions from the conversation, but it also helps us recognize phenomena in the data that we might otherwise have missed. That, in the end, is our purpose with it: a systematic coding scheme allows us to establish target phenomena for our research, ultimately to support development of models of student knowledge and reasoning.
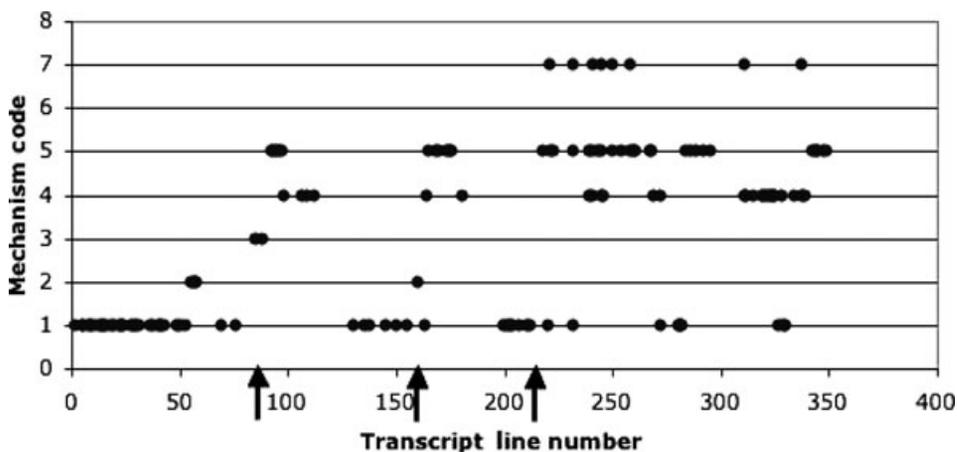
Figure 1. Mechanism coding of student conversation about falling objects. Arrows indicate apparent shifts in the quality of the conversation. The mechanism codes are as follows: (1) describing target phenomenon, (2) setup conditions, (3) identifying entities, (4) identifying activities, (5) identifying properties of entities, (6) identifying organization of entities, and (7) chaining (backward and forward).

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 et al., 2008). The graphical display in Figure 1 shows the occurrence of mechanism codes (on the vertical axis) over time (indicated on the horizontal axis by transcript line number). The graph shows that the patterns of codes shift several times over the course of the conversation. Three significant shifts are noted with vertical arrows.

The first shift, at line 82, shows student discourse transitioning from low-level codes to higher 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. 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, there is moderate evidence of mechanistic reasoning that persists for several minutes (see above analysis section), but without evidence at the highest level codes. There is then a transition back to low-level codes, 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, setup conditions, or organization of entities inaccessible.

The next transition appears when the teacher again asks them to explain their results at line 175, back to moderate levels of evidence. During this segment of the discussion, the students are joking about gravity being "tired"—engaging in a "fantasy mechanism" rather than a serious one. The coding scheme does not distinguish the two, which highlights, for us, the importance of closely inspecting the transcript. Analogies and animated models (which are common when these young students explain their understanding) are not displayed on the graph but coding reveals that while they are present in some moments, they are notably absent from this particular episode of fantasy reasoning. 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 the highest level codes. 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, 4, and 5 and level 7 suggests that codes 3, 4, and 5 provide necessary building blocks for chaining, after which students look for new aspects of the mechanism to pursue. For example, although some students originally attribute the paper falling first to its 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 evidence returns to midlevel codes, as the students look 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.

The coding scheme not only helps to identify possible points of transition in student reasoning but also informs speculation about why those shifts might occur. For example, the initial transition from the lowest to the middle-level reasoning is fleeting. The short duration of the segment with greater evidence of mechanistic reasoning may result from students' unfamiliarity with the entities they are discussing (which may prevent 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. Such possibilities are clues as to how the students may be viewing the purpose of the conversation, either as show-and-tell or a sense-making discussion.

CONCLUSION

Education reform is rightly focused on developing tools for assessing student inquiry in science, and there has been important progress in that regard with respect to student performances in experimentation and argumentation. However, evaluating student inquiry in these areas often equates to analyzing the *structure* of that inquiry, which may or may not shed light on the value of its *substance*. We suggest that it is the substance of inquiry that makes it *scientific*, and as such we need a way to examine that substance carefully.

Research attending to the substance of student thinking has largely been under the standard of conceptual knowledge, where the point is to promote change toward expert theories and understanding. Our purpose here is to analyze reasoning as mechanistic, independent of its correctness. Previous work has studied the nature and role of students' sense of mechanism (e.g., Abrams et al., 2001; diSessa, 1993; Hammer, 1995, 2004; Schauble, 1996; White, 1993) but has not unpacked the notion in a manner that supports systematic analysis of when and how students are invoking that sense or making progress developing it.

We turned to the philosophy of science for that unpacking, adapting an account by MDC (2000) to develop an analysis tool for recognizing and distinguishing causal mechanism in student discourse. We applied the framework to a discussion from a first-grade classroom, demonstrating how the coding can help distinguish and make sense of when students are making progress in understanding natural phenomena and when they are not. The data

we presented were mainly for illustration; 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.

We do not claim to have identified a *definitive* analysis tool for use in identifying mechanistic reasoning, nor do we imagine that this framework is the only possible one for this sort of discourse analysis. However, this framework may provide guidance to educators regarding a concept that has been difficult to define and reasoning that has been difficult to pin down. The framework helps make instructional intuitions about student mechanistic reasoning explicit and articulates specific aspects of productive scientific inquiry that teachers can see and respond to in student thinking. That is, it may be helpful in providing a language for developing and encouraging those intuitions in other educators. However, we caution that it should not be used as a pedagogical rubric. It is a tool for phenomenological analysis, and there is no reason to believe that guiding students toward the aspects it identifies would help them arrive at the whole.

Our primary objective with the framework is to support systematic analysis for research on learning. The application of the framework to the first-grade conversation provides examples of the kinds of findings we can anticipate. First, the framework developed from accounts of professional science identifies corresponding mechanistic reasoning in first graders, and so supports previous claims that even young children arrive in our science classes with productive intellectual resources for scientific thinking (e.g., Duschl et al., 2007; Hammer, 2004). Second, the analysis reveals that children may only apply those resources episodically: at some moments of the conversation, there is evidence of mechanistic reasoning, whereas at other moments students do not even identify entities or activities that could participate in a mechanism. The framework 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. This finding supports arguments elsewhere that student thinking is variable with context and difficult to characterize by unitary developmental levels (Siegler, 1996).

The framework we developed using insights from the philosophy of science suggests many possibilities for future research. First, the framework needs to be applied to more student discourse to assess whether the coding scheme truly captures something meaningful. Expanding the corpus of analyzed data will allow us to check both the feasibility and the fruitfulness of this analysis tool and method. Once we are able to reliably look for and find evidence of mechanistic reasoning, we can begin to identify continuities and progress in its development throughout grades K-16 (see Russ, 2006, for preliminary work in this direction). Another appropriate direction for future research is to relate the phenomenology of mechanistic reasoning to a cognitive analysis, with the aim of developing models of student knowledge and reasoning. Another possibility involves exploring the effects of various instructional strategies to promote mechanistic reasoning in students' science learning.

Finally, this work has significant implications for educational practice. In particular, it highlights that even very young students can engage in substantive mechanistic reasoning when given the opportunity. As such, it is appropriate for educators to provide students at all levels of science instruction with subject matter rich with mechanistic possibilities so that students can practice using this kind of reasoning to productively make sense of the physical world. The mechanistic coding scheme clarifies a major objective of inquiry, supporting its pursuit as an instructional target.

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