COLLABORATIVE MECHANISTIC REASONING:

A PROPOSED MECHANISM FOR LEARNING

IN INTERACTIVE INSTRUCTION

by

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DEDICATION

I dedicate this thesis to my husband Farbod and our daughter Kimia.

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ABSTRACT

A large body of research supports the positive impact of interactive instruction on student learning. The mechanism for this increased student learning, however, is less well understood. We propose collaborative mechanistic reasoning as a possible mechanism for this enhanced learning (McDermott, Shaffer, & University of Washington Physics Education Group, 2002; V. Otero, Pollock, & Finkelstein, 2010). In this research, we analyze video episodes of small group work during weekly LA preparation sessions, using a discourse analysis framework developed by Russ et al. (2008) to identify elements of mechanistic reasoning. This framework allows us to identify episodes of high-level mechanistic reasoning in LA discussion. In our analysis, we are focused on the highest level of mechanistic reasoning, *chaining*. We look closely at when and how LAs engage in collaborative chaining throughout their group work.

1. INTRODUCTION

Research shows that interactive learning environments increase student performance in science independent of factors like class size, course type, prior knowledge levels, and type of institution (Freeman et al., 2014; Von Korff et al., 2016). For meaningful learning to happen, students actively engage their minds while learning and constructing knowledge (Bretz, 2001). In other words, learning should be learner-centered rather than being exposition-centered.

In a metanalyses, Freeman et al. (2014) compared traditional lecturing with active learning environments. Their results show a higher learning gain in active learning environments for science, meaning when students work together, they learn more science and they remember it for longer. Von Korff et al. (2016) show that in physics instruction specifically, learning gains have been significantly higher when students are engaged interactively (Von Korff et al., 2016). These results confirm the inadequacy of the "teaching by telling" strategy in the classroom (McDermott, 2014) that includes traditional lecture-based instruction.

The inadequacy of instructional strategies commonly used in science classrooms made a reform in science education necessary. In the 1990s, this reform was developed based on the concept of inquiry. The National Science Education Standards (1996) and Science for All Americans (1989) emphasize that students will learn more science and will develop a deeper understanding of it if they learn it like a scientist would. In 2013, the Next Generation Science Standards (2013) also emphasized the importance of scientific inquiry. Similar to scientists, students are in the process of understanding the phenomenon at hand and they don't know the correct answer. They evaluate and reconstruct it into a better explanation like scientists would do (Kapon, 2017).

McDermott (2014) describes memorization as the opposite of inquiry. While conducting an inquiry-based classroom, teachers do not tell an inert body of scientific information. Rather they present a scientifically oriented question which could lend itself to empirical investigation (National Research Council, 2000b).

The reformists' goal was to promote inquiry in science classrooms (Russ, Scherr, Hammer, & Mikeska, 2008). Once inquiry was defined, then it was time to research features and aspects of it (National Research Council, 2000b). Science education researchers worked on how to set up inquiry classrooms to promote scientific inquiry abilities, help students construct scientific knowledge through inquiry, think like a scientist, and engage in an authentic practice of science (Conlin, Gupta, Scherr, & Hammer, 2007; Russ & Odden, 2017; Russ, Scherr, Hammer, & Mikeska, 2008).

Then there was need for new instructional strategies to employ inquiry. In inquiry-based science teaching, a teacher's pursuit is to give students opportunities to learn via authentic scientific practices (Conlin et al., 2007). Physics Education Research (PER) evaluates students' experiences in their practice of science (Russ, Coffey, Hammer, & Hutchison, 2009). The emphasis in the literature is on the need to include inquiry in science instruction. In other words, the science education reform view of inquiry is both the normal activity of a scientist and what students should be doing in a science classroom (Russ & Hutchison, 2006).

Logically researchers and educators want to have means of assessing any instructional strategy they employ in a classroom. This is the case for researchers and educators employing inquiry methods in their classroom. They want a methodical way of recognizing productive scientific inquiry and assessing whether students are making progress understanding natural phenomena (Russ, Scherr, Hammer, & Mikeska, 2008).

If student inquiry is an important goal, then a systematic means is necessary for researchers and educators to assess the quality of all aspects of inquiry. Inquiry learning includes experimentation, argumentation, and mechanistic reasoning. According to Russ et. al 2008, the last of these has received less research attention in comparison with the other two aspects of inquiry.

Mechanistic reasoning is a valuable aspect of inquiry (Russ & Hutchison, 2006; Russ, Scherr, Hammer, & Mikeska, 2008) and can be defined as reasoning about causal mechanisms that underlie natural phenomena. In a science discussion, mechanistic thinking is very valuable (Russ et al., 2009); Bao et al. (2009) argue that it is more important than the correct answer, since mechanistic reasoning can lead to correct answers but the opposite is not true. It is important for researchers and teachers to be able to recognize the beginning of mechanistic reasoning and components of it in students' discussion (Russ, Scherr, Hammer, & Mikeska, 2008). If teachers struggle to recognize productive student reasoning, it is unlikely that they will support it epistemologically. Epistemological framing sets expectations for what kind of activity will take place in the learning environment, and how students should engage in constructing knowledge (Scherr & Hammer, 2009). Once teachers recognizes productive student reasoning, they can give proper feedback on the plausibility and sensibility of students' mechanistic explanations. Proper feedback would be treating the student idea as a scientist would treat a colleague's idea. Teachers can epistemologically communicate to students that mechanistic reasoning is an aspect of practicing science like a scientist (Russ et al., 2009).

This brings out the necessity of formal criteria for identifying and analyzing mechanistic reasoning in students' verbal responses and their reasoning discourse about causal mechanisms (Conlin et al., 2007). Russ et al. (2008) developed a mechanistic reasoning framework to recognize and analyze students' conversations to see if they are reasoning mechanistically (Scherr & Hammer, 2009). This framework is a coding scheme that allows teachers and researchers to assess the substance and sophistication of student's mechanistic reasoning (Conlin et al., 2007).

If reasoning mechanistically and collaboratively helps student learning, then it is important to study collaborative mechanistic reasoning in physics classrooms so that educators can better support it. The research presented here is a case study that aims to look into the group dynamic of student reasoning. We did this by conducting in-depth analysis of video data from a single session of a group working on an introductory mechanics activity. Our first task was identifying student mechanistic statements during a discussion, using the framework developed by Russ et al. (2008) We then analyzed the highest-level mechanistic statements to see how many were pieced together by multiple group members, and characterize these collaborative mechanistic reasoning statements.

Our research questions are as follows:

1. What does it look like to apply Russ' mechanistic reasoning framework to the context of LA weekly preparation sessions?
2. What does chaining look like in this context?
3. Do LAs engage in collaborative chaining?

- If so, what does this look like?
- How often does collaborative chaining take place?
- How does collaborative chaining emerge from the group discussion?

2. LITERATURE REVIEW

This research studies a group of Learning Assistants (LAs) working on a mechanics tutorial, which is designed as a guided inquiry activity. Research literature on the definition of inquiry, features and aspects of it, tutorials, student reasoning, and effects of group dynamics need to be addressed and instructional strategies in science need to be identified.

Science education research literature supports the positive effects of inquiry methods on student learning in science (National Research Council, 2000b). In this section our focus is not on providing evidence for the benefits of inquiry as an instructional strategy; instead, we focus on definitions of inquiry, types of inquiry, and features and aspects of inquiry in a science classroom.

2.1. Inquiry in Science

Within science education research literature, there are many definitions of learning by inquiry and how to implement such instructional strategies (Russ, Scherr, Hammer, & Mikeska, 2008). These definitions are mostly similar but have been interpreted differently, and not all agree on the elements that constitute inquiry (National Research Council, 2012).

The National Science Foundation provided a monograph on inquiry for professionals in science, mathematics, and technology education. In this monograph, inquiry is defined as “an approach to learning that involves a process of exploring the natural or material world, and that leads to asking questions, making discoveries, and rigorously testing those discoveries in the search for new understanding” (National Science Foundation, 1999). In their view, the process of students learning science should be similar to that of a professional scientist in search of scientific understanding as much as possible.

The Exploratorium Institute of Inquiry offers a similar and simple definition of inquiry as learning by exploring natural phenomena, asking questions about them, discovering, and testing discoveries in order to build up new knowledge ("What Is Inquiry? | Exploratorium," n.d.).

Scientific inquiry is defined as a combination of science processes with scientific reasoning and critical thinking to develop scientific knowledge. Scientific processes are skills like observation, inferring, classifying, predicting, measuring, questioning, interpreting and analyzing data (Lederman, 1998). The National Research Council (NRC), in their National Science Education Standards (National Research Council, 2000c) defines scientific inquiry in two ways: How scientists engage in inquiry and how students should engage in such practice.

Research literature also focuses on clarifying essential features of classroom inquiry and what it should aim towards. In an inquiry classroom, students are engaged by scientific questions. While conducting an experiment, priority is given to evidence collected from the experiment. This evidence can help students develop models to use in formulating explanations. Students also propose an answer to the initial question and evaluate their formulated explanation with other proposed explanations (National Research Council, 2000b; Russ et al., 2009).

Apart from definitions and classroom features of inquiry, there is another characterization of inquiry that is discussed in the literature. Inquiry during a science class can be *open* or *guided* (National Research Council, 2000b) depending on how much guidance the teacher is providing. The scientifically oriented question can be provided by the teacher or not. The methods to conduct an experiment can also be provided or not! The results can be known beforehand or not. NRC's view on guided vs. open inquiry classrooms is more like a spectrum between these two types. Some authors have argued that some amount of guidance is appropriate and necessary in school (Kirshner, Paul; Sweller, John & Clark, 2006; McDermott, 2014). In particular, they argue that open-ended inquiry with minimal teacher guidance has been shown to hinder student performance in standard-driven education systems (Kirshner, Paul; Sweller, John & Clark, 2006). In the National Science Education Standards (National Research Council, 2000b, p. 29), variations on the five essential features of classroom inquiry are described, listed from open-ended to guided:

1. Learner engages in scientifically oriented questions
    - Learner poses a question
    - Learner selects among questions, poses new questions
    - Learner sharpens or clarifies question provided by teacher, materials, or other source
    - Learner engages in question provided by teacher, materials, or other source
2. Learner gives priority to evidence in responding to questions
    - Learner determines what constitutes evidence and collects it
    - Learner directed to collect certain data
    - Learner given data and asked to analyze
    - Learner given data and told how to analyze

3. Learner formulates explanations from evidence

- Learner formulates explanation after summarizing evidence
- Learner guided in process of formulating explanations from evidence
- Learner given possible ways to use evidence to formulate explanation
- Learner provided with evidence and how to use evidence to formulate explanation

4. Learner connects explanations to scientific knowledge

- Learner independently examines other resources and forms the links to explanations
- Learner directed toward areas and sources of scientific knowledge
- Learner given possible connections

5. Learner communicates and justifies explanations

- Learner forms reasonable and logical argument to communicate explanations
- Learner coached in development of communication
- Learner provided broad guidelines to use [to] sharpen communication
- Learner given steps and procedures for communication

2.2. Reasoning and Scientific Explanations

The NRC defines scientific inquiry as ways that scientists study the natural world and the explanation they provide by reasoning about evidence they have collected. In building a scientific understanding by scientifically explaining the target phenomenon, one cannot avoid reasoning; it is the involvement of reasoning that constructs a scientific explanation and results in a scientific understanding (C. T. Chen & She, 2015; Russ, Scherr, Hammer, & Mikeska, 2008). Many researchers characterize scientific reasoning as a knowledge-independent or content-independent skill (Bao et al., 2009; Kind & Osborne, 2017) Their claim is that general reasoning abilities are transferable into a new context (Bao et al., 2009; Kind & Osborne, 2017). Inhelder & Piaget (1958, p. 332) define scientific reasoning ability as a facility which has been “liberated from particular contents.” This extends into the importance of general reasoning skills. Kind and Osborne (2017) argue that general reasoning abilities can be counted as scientific reasoning skills; general reasoning becomes scientific reasoning during a science discussion.

The NRC (2000a), among many others, defines scientific reasoning skills as the ability to pose a scientific question, to propose a way to investigate the question, to collect and analyze data and to be able to interpret the results (C. T. Chen & She, 2015; National Research Council, 2000a) Reasoning is involved in every step of inquiry and is central to it (Koslowski, 1996). Therefore, science inquiry has the potential to promote these desired reasoning skills in students (Bao et al., 2009). In addition, scientific reasoning involves cognitive activities like critical thinking (Bao et al., 2009; Russ & Odden, 2017).

On the other hand, memorization does not play a role in inquiry learning (McDermott, 2014). However, factual recall is still frequently valued over developing scientific reasoning abilities in our current STEM education system (Bao et al., 2009). Bao et al. (2009) found little impact of content-rich STEM education on scientific reasoning skills. On the other hand, Chen & She’s (2015) results show that scientific reasoning ability can actually make acquiring content knowledge easier. This supports the importance of students' development of scientific reasoning skills.

These reasoning skills can help students solve complex physics problems independent of how many facts they can remember (Russ & Odden, 2017). This connects to the fact that learning includes the application of acquired knowledge to a new situation in order to synthesize brand new information or to elaborate on the existing information about a given phenomenon (National Research Council, 2000b). It is the reasoning skills that are transferable. How do these skills develop?

Bao et al. (2009) believe scientific reasoning skills can be developed through training. Teachers have the opportunity to train their students become more skillful in reasoning. Bao et. al. (2009) points out that educators need to employ more inquiry-based strategies that target reasoning skills as well as content knowledge in students, and researchers need to study the impact of these strategies on student reasoning skills (Bao et al., 2009).

In 2013, the Next Generation Science Standards (NGSS Lead States, 2013) maintained a central focus on scientific inquiry. In the NGSS framework, the expression “scientific skills” is replaced with “scientific practices”, in an attempt to explain what kind of practices are required for science inquiry. They explain that these behaviors are the kind of behaviors shown by real scientists as they coordinate knowledge and skills (NGSS Lead States, 2013).

Both content knowledge and reasoning skills are important goals of inquiry-based instruction and they are two separate things (Bao et al., 2009). Educators who want their students to learn both must teach and formatively assess both and the main goal of assessment should be to support student learning (Black & Wiliam, 1998). This means that there must be a means of assessing scientific reasoning skills in students as well as content knowledge assessments. These assessments can be developed through research.

Again, the NRC defines scientific inquiry as efforts towards developing knowledge and understanding of scientific ideas (National Research Council, 2000b). So, it is the students' ideas that needs to be assessed by researchers or teachers. When evaluating students' ideas, correctness should not be the sole driver (Russ, Scherr, Hammer, & Mikeska, 2008). Rather, their reasoning should be the focus. Reasoning is central to the whole inquiry process so our questions should evolve around how to recognize the beginning of productive student reasoning and how to pursue the development of such reasoning by studying their attempts at providing a scientific explanation.

Science tries to explain physical phenomena scientifically and scientific explanation provides us with information about the causes and conditions of the re-occurring phenomenon. According to Conlin et. al. (2007) scientific explanation is "an argument that lays out the causal mechanisms by which the phenomenon occurs, given the laws and initial conditions" (p. 1).

When looking formally into inquiry instruction, Russ et al. (2008) identified three aspects of inquiry: experimentation, argumentation and mechanistic reasoning. Experimentation involves collecting data by performing experiments. During an inquiry lesson, a scientifically oriented question can lead to experimentation. As students are performing experiments together, argumentation naturally comes up as well. Argumentation involves drawing logically appropriate inferences from data. It includes generating claims, supporting claims with evidence, and responding to counterclaims.

Lastly, mechanistic reasoning involves reasoning about the underlying mechanism that brings about a phenomenon. This aspect of inquiry, which has received less research attention, is the main focus of our study.

Russ & Odden (2017) reframed mechanistic reasoning as a kind of model-based reasoning. In their view models can be mental or physical representations of how a system operates. They also argue that in physics, models are mostly mechanistic, meaning they describe a causal mechanism. They claim that model-based reasoning is intertwined with the experimentation aspect of inquiry in the broader process of sensemaking.

2.3. Sensemaking frame and teacher responses

Sensemaking, as described by researchers Russ & Odden (2017), is an activity through which inconsistencies in one's knowledge framework are resolved by argumentation and explanation building. In their intertwining view, data collection does not necessarily come first; rather, experimentation and model-based reasoning reinforce each other in learning. Developing an initial model could come first and help students know where to look or what to look for in their experimentation. Their stance that these aspects of inquiry do not occur linearly aligns with the stance of other researchers, such as those at the Exploratorium Institute for Inquiry ("What Is Inquiry? | Exploratorium," n.d.).

Scientific reasoning includes evidence-based reasoning (reasoning about the data collected from the experiment) and model-based reasoning (modeling) (Russ & Odden, 2017). Models are "testable, modifiable representations of scientific ideas" (Windschitl, Thompson, & Braaten, 2008, p. 956). These representations can be physical or mental.

They represent “key features, relationships, and processes” that run the system (Russ & Odden, 2017, p. 2). A mental model can also be characterized as a “set of ideas that describes a natural process” (Passmore & Stewart, 2002, p. 188).

Teachers communicate their expectations to students through feedback on student work. Feedback may emphasize correctness or scientific ideas. Teachers are to support students’ reasoning in the classroom, recognizing and valuing students’ mechanistic ideas even when it is not fully correct (Russ, Scherr, Hammer, & Mikeska, 2008). This will help students see the activity at hand as a meaning making activity as opposed to a task to be completed (Scherr & Hammer, 2009).

Inquiry is idea-oriented (McDermott, 2014) so assessing inquiry involves assessing the quality of student ideas. The means to assess the quality of ideas are again the aspects of inquiry (Russ et al., 2009). Sometimes assessments tend to value correct content over correct aspects of inquiry. However, a good inquiry resulting in a wrong conclusion is still good inquiry and must be validated. A teacher’s response to inquiry can influence how students see and frame such an activity. The history of science is full of wrong conclusions contributing to the right ones. So, no student’s inquiry should be disregarded only because of its wrong conclusions (Russ et al., 2009).

The student’s framing of the activity at hand during a physics class can affect what they notice, what knowledge they access, and how they act (Scherr & Hammer, 2009). Do they frame the activity as making sense of Physics or as completing the worksheet (Conlin et al., 2007)? Do they see physics learning as an active process of meaning-making or a passive process of receiving information (Russ & Odden, 2017)?

For teachers, assessing students' mechanistic reasoning skills is appropriate, and showing interest in such reasoning is important as well. Students need to see that the teacher values mechanistic reasoning because this is what actual scientists do. Also, the efforts to make sense of the phenomena and producing mechanistic ideas are more important than just getting the right answer (Russ et al., 2009).

Student sensemaking has been the focus of much science-education research (Kapon, 2017; Potter et al., 2012; Russ & Odden, 2017; Scherr & Hammer, 2009). In a physics class, to frame the activity at hand (e.g., the physics problem presented) as an opportunity to sensemake is far more optimal than framing it as completing the worksheet (Conlin et al., 2007), “or an occasion of rote use of formulas” (Scherr & Hammer, 2009, p. 149), or even getting the right answer and meeting curriculum standards, because students are there to satisfy their own curiosity, not to satisfy the curriculum’s curiosity (Russ & Odden, 2017).

Russ & Odden sum up the description of sensemaking from literature as “a central practice in physics learning that involves adding elements and reconciling inconsistencies in one’s knowledge framework through argumentation and explanation building.” (2017, p. 12). In their work, evidence-based reasoning and model-based reasoning are two intertwined subcomponents of a larger activity called sensemaking. Trying to make sense of phenomena is actually doing science! This is what a scientist does! A scientist successively constructs, judges, and refines plausible theories. Science practice is valuable, independent of the correctness. Historically wrong ideas have contributed so much for making sense of the natural world. One easy example is Newton’s light theory, which was later proved wrong but still laid the foundation for future scientists (Russ et al., 2009).

The teacher plays a big role in setting up an environment in their inquiry class that promotes sensemaking. Teachers encourage students to spend a lot of time evaluating scientific ideas in relation to their experience with the real physical world and until those scientific phenomena make sense (Russ et al., 2009). Teachers who value student reasoning skills over correctness must be able to assess the quality of their reasoning by eliciting their thinking. Qualitative questions play an important role in giving teachers access to student thinking. To assess student reasoning, the teacher needs to attend to the substance of their thinking, and that does not involve only conceptual knowledge but also involves promoting understanding and expert theories (Russ et al., 2009; Russ, Scherr, Hammer, & Mikeska, 2008).

2.4. Mechanistic reasoning and Epistemological Framing

When attending to students reasoning in a physics classroom, mechanistic reasoning is of importance. Mechanistic explanations are useful tools for sensemaking of physical phenomenon. So, teachers should evaluate if students are giving mechanistic ideas, give feedback in a way that helps students recognize the novelty of mechanistic explanations, and elaborate how the students' idea makes sense (Russ et al., 2009).

Some researchers have studied student expectations in science classrooms. Are students being simply a receiver of knowledge provided by experts? Or, do they see themselves as having a role in the construction of knowledge? Do they think the end goal is completing the assignment or do they value ideas and focus on them (Scherr & Hammer, 2009)? The epistemological message that the teacher sends to the student tends to communicate the teacher's priorities and beliefs about science, which influences students' expectations.

Epistemological framing is a set of expectations associated with the activity at hand (Conlin et al., 2007). It is a sense of what is happening here. In our case it is what is going on in a classroom with respect to physics and how students frame it. Framing is the interpretation of an event, utterance or situation based on what happened before. It involves knowing what to expect in the future, seeing what needs our attention and determining what action to take (Scherr & Hammer, 2009). "Framing is a construct developed in anthropology and linguistics to describe how an individual or group forms a sense of what it is that is going on here… Framing presents a communicative task in which participants collaboratively establish the nature of their shared activity." (Scherr, 2009, p. 3).

The content also connects with the epistemological frame. While studying a phenomenon in a class, the teacher can ask for similar everyday phenomena or offer one herself. So reasoning in Physics is not epistemologically discontinuous with everyday reasonings (Russ et al., 2009; Russ & Odden, 2017). This can help shift student's epistemology. This shift in epistemology with respect to physics can make physics less detached and more connected to student's life (Russ et al., 2009). This could be specifically more fruitful during group work since it has been shown that 86 percent of the time, group members share the same epistemology (Conlin et al., 2007).

In order to shift any framing or to communicate the right framing to our students, first there is need to recognize relevant student framings in a classroom. There are linguistic and behavioral clues that can help us understand student's framing of the activity at hand (Conlin et al., 2007). These linguistic and behavioral clues are a reflection of student's framing.

Scherr & Hammer (2009) were able to identify four groups of "behavior modes" i.e., frames, in students working in groups on activities from *Tutorials in Introductory Physics* (McDermott et al., 2002), a research-based curriculum supplement designed for small-group discussions. These four frames are *discussion*, *worksheet*, *joking*, and *TA* (receptive to working with a Teaching Assistant). While working on tutorials, students show sharp transitions between frames. The discussion frame is a "behavioral cluster of sitting up, speaking clearly, and gesturing frequently" (Scherr & Hammer, 2009, p. 148). The discussion frame is very much animated and is the frame that our study is focused upon.

Conlin et al. (2007) shows that there is a strong relationship between the discussion frame and "scientific quality of students explanation" (Conlin et al., 2007, p. 1) meaning there is a correlation between how students behave vs how they reason. They explain that the proportional increase in students mechanistic reasoning statements is also due to the increase in the number of statements when students frame the activity at hand as discussing each other's ideas (Conlin et al., 2007).

Scherr & Hammer (2009) also find a relationship between the discussion behavioral clusters and reasoning about causal mechanisms in phenomena. They argue that this correlation could be because students in discussion frame use animated gestures and these can help them simulate and depict (depiction) entities, activities and their organization in a mechanism.

The importance of students being in the discussion frame brings about the benefit of employing tutorials. Tutorials help physics students discuss their epistemological framing in the learning process (Elby, 2003; Scherr & Hammer, 2009). This discussion helps them set the right mindset in what it means to learn physics (Elby, 2003). The active mental engagement helps them reconcile their intuitive thinking with science formalism. This makes physics meaningful for them and sets the stage for using physics formulas and solving quantitative problems meaningfully (McDermott, 2014; Russ & Odden, 2017; Scherr & Hammer, 2009).

2.5. Mechanistic reasoning and inquiry

We can look at scientists' reasoning to understand student reasoning too (Russ, Scherr, Hammer, & Mikeska, 2008). Scientists try to understand a new phenomenon by reasoning mechanistically and by providing mechanistic explanations.

Observing and recognizing mechanistic reasoning in students is more valuable than obtaining a correct answer right away. This distinction can influence how teachers respond to student discussion and in turn how students engage in inquiry (Russ et al., 2009) .

Scientific inquiry is about constructing causal mechanistic accounts for the phenomenon, rather than just coming up with the correct answer. Mechanistic ideas are very much appropriate in an inquiry class (Russ et al., 2009) and mechanistic reasoning is a valuable aspect of inquiry (Russ & Hutchison, 2006; Russ, Scherr, Hammer, & Mikeska, 2008). Students in a science inquiry class should mechanistically reason and this could be very productive for their construction of scientific knowledge (Russ & Hutchison, 2006).

This means researchers and educators need to be able to recognize and assess this kind of reasoning in students' discourse (Conlin et al., 2007; Russ & Hutchison, 2006; Russ, Scherr, Hammer, & Mikeska, 2008). In assessing the quality of student inquiry, mechanistic reasoning is as relevant as the other two aspects of inquiry. So, it should be attended to alongside with argumentation and experimentation (Russ & Hutchison, 2006; Russ, Scherr, Hammer, & Mikeska, 2008).

2.5.1 What is mechanistic reasoning?

Scientific reasoning involves constructing coherent explanations of the physical phenomena being studied (Conlin et al., 2007). This kind of reasoning in physics could be explaining the natural phenomena by describing the mechanism underlying it (Russ, Scherr, Hammer, & Mikeska, 2008). This mechanism helps in understanding the causal relationship that brings about the phenomena.

Mechanistic reasoning is a subcategory of model-based reasoning. It is not completely equivalent to model-based reasoning simply because not all models explain the causal relationships underlying the phenomenon. However, models in physics are mostly mechanistic (Russ & Odden, 2017). While there is not a unique agreed-upon specific definition of mechanistic reasoning, but Russ et al. (2008) collects characterizations of mechanistic reasoning from literature and characterizes it as non-teleological, causal, built from experience and description of "underlying or relevant structure" (Russ, Scherr, Hammer, & Mikeska, 2008, p. 504). Finally they explain it as "describing how the particular components of a system give rise to its behavior" (Russ, Scherr, Hammer, & Mikeska, 2008, p. 504).

The concept of mechanistic reasoning is difficult to define, and this line of reasoning as an aspect of inquiry is difficult to pin down (Russ, Scherr, Hammer, & Mikeska, 2008) but the ability to mechanistically reason is present in children even at young age (Russ et al., 2009; Russ, Scherr, Hammer, & Mikeska, 2008). Mechanistic reasoning is broader than just causal reasoning (Russ et al., 2009). It not only covers what causes bring about the effect in mechanism, it also explains how these causes bring about the effect (Russ, Scherr, Hammer, & Mikeska, 2008). In short, mechanistic reasoning is reasoning about mechanisms (Russ & Odden, 2017).

Children's mechanistic reasoning can be utilized with the teacher's help (Russ et al., 2009). So, the subject matter provided by the science teacher should be rich with mechanistic possibilities to give students practice in mechanistic reasoning. As is the case with reasoning skills in general, this particular reasoning skill can be developed with practice and it is also transferable (Adey & Shayer, 1994; Z. Chen & Klahr, 1999).

Building up explanations that are mechanistic is essential in doing science (Conlin et al., 2007). Being mechanistic means, describing a causal mechanism. Mechanisms are important in constructing scientific explanations (Russ, Scherr, Hammer, & Mikeska, 2008). Doing science means searching for a mechanism and explaining it (Russ et al., 2009). "in many fields of science what is taken to be a satisfactory explanation requires providing a description of a mechanism" (Machamer, Darden, & Craver, 2000, p. 1). Even incorrect mechanistic reasoning is more scientific than any religious belief or teleological idea (Russ, Scherr, Hammer, & Mikeska, 2008)

2.5.2 The constructions of a mechanism

Mechanisms are set within each other. Higher level mechanisms carry within themselves lower-level ones and so on (Machamer et al., 2000). What is important is that they are tools in physics education not goals. The goal is not the mechanism itself rather, it is to identify it (Russ, Scherr, Hammer, & Mikeska, 2008).

Mechanisms are composed of entities and activities (Russ et al., 2009): entities engage in activities and these activities change the properties and/or organization of the entities. Through these changes the mechanism alters the system from its setup conditions to its termination conditions (Machamer et al., 2000; Russ, Scherr, Hammer, & Mikeska, 2008) and the phenomenon of interest is produced (Russ et al., 2009). So, a mechanism goes through stages of regular change and scientists aim to explain how one stage is produced by the previous stage (Russ et al., 2009). Therefore, a mechanistic explanation describes the mechanism and all its stages (Russ et al., 2009).

In recognizing mechanistic reasoning, we can look for what entities exist in that mechanism, what properties they have, in what condition is the mechanism at first, in what activities these entities are able to engage, how these activities change the properties or the organization of the entities, and finally how this mechanism comes to its termination stage through these phases (Russ et al., 2009). These phases are connected in a way that “each phase follows from the one before and leads to the one after it” (Russ et al., 2009, p. 880)

2.5.3 Chaining

Chaining is a general reasoning strategy that links how each phase of the mechanism is connected to the phases around it. It is the most complete evidence that students are reasoning mechanistically (Conlin et al., 2007). Students rarely engage in chaining statements unless they have already engaged in less sophisticated elements of mechanistic reasoning (Russ, Scherr, Hammer, & Mikeska, 2008), because the relevant components of the mechanism and their properties must be identified before students can construct a plausible explanation about the mechanism of the phenomenon (Russ & Hutchison, 2006). So, the most sophisticated and difficult reasoning strategy seems to be chaining (Russ, Scherr, Hammer, & Mikeska, 2008). Scherr & Hammer (2009) call chaining a “verbally expressed logical inference” (Scherr & Hammer, 2009, p. 170). Scientists in their pursuit of scientific explanation search for a chain that can connect one stage of the mechanism to the stages around it (Russ et al., 2009).

Information about the entities and activities that are components of a mechanism can help in understanding the stages the mechanism goes through. General properties of entities involved in the mechanism can produce information on possible activities that produced them and in what activities they can engage. On the other hand, information on activities can provide clues to what entities engaged in those activities or what entities were produced as the result of those activities (Darden & Craver, 2002; Russ, Scherr, Hammer, & Mikeska, 2008). To chain is to use information about entities and activities in a specific stage of the mechanism to derive information about them in other stages (Russ et al., 2009).

Chaining “involves linking several of the elements together, either to make a prediction or to reason about how things must have happened in the past” (Conlin et al., 2007, p. 1). Using the information about entities, their properties, their organization and the characteristics of activities to learn how each stage of a mechanism produces the next stage is called chaining forward (Russ et al., 2009). Using this information to reason about how the previous stage brought about the current stage is called chaining backward (Russ & Hutchison, 2006).

2.6. Tutorials in Introductory Physics

Science education research literature supports both inquiry and collaborative work for science classrooms (National Research Council, 2000b; Von Korff et al., 2016). There are many instructional strategies that employ such combination. The example that we will focus on is "Tutorials in Introductory Physics" (McDermott et al., 2002), which is a research-based, research-validated curriculum supplement designed for calculus-based introductory physics courses. Tutorials are carefully sequenced worksheets that employ both guided inquiry and interactive engagement techniques (McDermott, 2014; Von Korff et al., 2016). The physics problems in them are mostly qualitative and meant to be discussed in small groups of three or four students (McDermott, 2014; Scherr & Hammer, 2009).

McDermott (2014) argues that in physics, developing reasoning abilities might be the most important activity in the intellectual development of a student, and that curriculum development should focus on reasoning skills rather than misconceptions: "It is the reasoning that distinguishes related concepts in physics from one another, identifies their relationship, and enables their correct application." (McDermott, 2014, p. 739)

Small group discussions are a part of the *Tutorials in Introductory Physics* (2002) curriculum. They are meant to be facilitated by Teaching Assistants (TAs). TAs are not there to lecture; instead, they pose additional questions to conduct a dialogue with students. They usually provide limited guidance to students during tutorials, just enough for them to carry on (McDermott, 2005, 2014; Scherr & Hammer, 2009).

The overall instructional philosophy of the tutorials is to "elicit, confront, and resolve" students' naïve theories about physics (McDermott, 2014). McDermott et al.

(2002) created the tutorials because they noticed that students struggled to reason in the absence of a memorized formula, and they wanted students to be more intellectually engaged. The tutorial developers first identified students' common misconceptions for specific topics that are relevant in introductory physics. Their intention was for students to express these misconceptions during tutorial discussions. They target common misconceptions by providing a situation in which the students are likely to make a mistake based on their misconceptions. This flaw in students' thinking is confronted when they are led to arrive at a contradiction in their reasoning. When students realize that this contradiction exists, they are guided to resolve their misconceptions. Then there are more opportunities in the homework assignments for them to apply, reflect, and generalize their understanding of physics.

During the tutorials, students reason through developing core conceptual knowledge all the way to transferable knowledge that they can apply to real-world situations (Bao et al., 2009; McDermott, 2014). Thoughtful discussion during tutorials helps students practice their reasoning skills (Conlin et al., 2007; Russ & Odden, 2017). Also expressing and defending their interpretations with others can be seen as an ongoing peer review, which in turn can improve students' analyses and help the quality of their interpretations (Creswell & Poth, 2017). During the tutorials students not only have to explain their reasoning but also engage in various lines of reasoning and making predictions to construct the conceptual knowledge necessary (Scherr & Hammer, 2009).

Tutorials in Introductory Physics (2002) has been in use for more than 20 years now. Reform-minded physics professors welcomed them into their large classrooms with the goal of addressing core conceptual issues (Scherr & Hammer, 2009). Tutorials are usually used after the lecture section and in recitation sections of large classes, and are facilitated by Teaching Assistants or Learning Assistants (LAs) (V. K. Otero, 2015; Scherr & Hammer, 2009; Von Korff et al., 2016). The very nature of tutorial work--the size of the group, and the fact that students are seated at the tables most of the time--makes it easy to study for research. The rich instructional setting provides opportunity to study all sorts of interactions and improvement in groups and to watch how they learn together (Scherr & Hammer, 2009). There has been extensive research on student collaborative work during tutorials (Conlin et al., 2007; Conlin & Scherr, 2018; Scherr & Hammer, 2009). The tutorials are research validated and they have been proven to have a large positive effect on student learning (McDermott, 2014).

3. METHODS

The data analyzed in this study were collected in the Learning Assistant Program of the Department of Physics at Texas State University. Texas State University is a large regional public university in Central Texas, and is classified as a Hispanic Serving Institution (HSI) (US Department of the Interior, n.d.). The university's student population was 39% Hispanic and 57% overall non-White in Fall 2020. In Fall 2020 the undergraduate students in the Department of Physics were 39% Hispanic and 53% non-White. The percentage of women enrolled in the major has varied over the past several years between 21% and 28%, at or above the national average.

Since 2012 the Department of Physics has had a Learning Assistant (LA) Program supporting the introductory courses for physical science and engineering majors. The LA Model is a model for undergraduate peer instruction developed at University of Colorado Boulder and broadly adopted across the U.S. (V. K. Otero, 2015). In this model, undergraduate LAs facilitate group discussions in courses that have been transformed to be interactive and student-centered. With the guidance of weekly preparation sessions and a pedagogy course, LAs support students to engage in productive collaborative learning (V. K. Otero, 2015). At Texas State the LA Program is currently situated entirely in the physics department, and the required pedagogy course is an upper-division physics elective, *Physics Pedagogy and Cognition*. Over the past several years, the program has included approximately 35 LAs each semester. The majority of graduating Texas State physics majors have had at least one semester of experience in the LA Program (e.g., 70% of the graduating majors in the 2018-2019 academic year).

The Physics LA program at Texas State has a special emphasis on building and supporting community among LAs and faculty. As part of this emphasis, the weekly LA preparation sessions are communal: all LAs and LA-supported faculty meet together each week for two hours. For the first half hour to 45 minutes of each weekly preparation session, the entire group engages in discussions relevant to everyone; the remaining time is spent grouped by course, with all LAs and faculty in the same course preparing together. During course-specific preparation, LAs work together in groups of three or four, with at least one experienced LA at each table. They work through material for the following week for about 60 minutes, most often from *Tutorials in Introductory Physics* (McDermott et al., 2002), then the entire course-specific group comes back together for a debrief and exchange of ideas during the last 10 to 20 minutes of the preparation session. As part of a larger study, our research group creates video records of the weekly Learning Assistant (LA) preparation sessions every Friday.

3.1. Data selection

For this specific study, we began by watching one full semester of recorded LA preparation sessions. We focused on the small group portions of each session. There were fourteen sessions, with approximately one hour of group work in each session, and video data of two groups from each session, for a total of 28 hours of small group video data. We selected one of these sessions for in-depth analysis.

We purposefully chose this specific session for detailed analysis because in the first watching, the LAs' body language got our attention. According to Dr. Scherr's epistemological framework (2009), most of our LAs showed body signs of being in the sensemaking epistemological frame. This specific group of LAs consisted of four masculine-presenting LAs named Travis, Mark, Nate and Alex (all pseudonyms). Nate was an experienced LA, and the other three were in their first semester as LAs. The tutorial they were working on was "Friction and Tension." Out of total 59 minutes of this session, 53 minutes had group work at the table and the rest was the whole group debrief, which we excluded from our analysis because we were interested in small-group collaboration and reasoning.

Once the session was chosen, rev.com was used to transcribe the group work section of the video data. A group of our researchers went through the transcripts and did corrections, edited words/statements and added some non-verbal actions such as body gestures and pointing. Once transcripts were corrected, they were uploaded into two accounts of MAXQDA in two separate devices by two of the researchers. No more transcript edits were allowed after this step.

3.2. The coding schemes

Once transcripts were uploaded into MAXQDA, the mechanistic reasoning coding scheme was added identically in both MAXQDA accounts. Here are the code categories from Russ et al.'s (2008) framework, with brief descriptions:

1. **Describing the Target Phenomenon (DTP):** Students clearly describe or demonstrate the phenomenon they are trying to explain. Scientists might start with knowledge of a phenomenon and try to search for the underlying mechanism that causes it, or they might predict a phenomenon based on the knowledge they have of the components necessary for the phenomenon to occur.

2. **Identifying Setup Conditions (ISC):** Students identify the conditions under which the mechanism starts, including where the entities are spatially and temporally located at the beginning that is enough for the change to start.
3. **Identifying Entities (IE):** Students identify objects (entities) that are a component in the constitution of the phenomenon. Scientists identify entities that can bring about or affect the production of the phenomenon.
4. **Identifying Activities (IA):** Students identify actions and interactions of the entities that are also a component in the mechanism. Identifying relevant activities that entities engage in is another step in understanding the mechanism and how it changes.
5. **Identifying Properties of Entities (IPE):** Students identify specific properties of the entities that are relevant to the phenomenon and the underlying mechanism. Scientists also identify and isolate the properties of entities that are relevant to the production of the phenomenon.
6. **Identifying the Organization of Entities (IOE):** Students describe the spatial location and the structure of entities that affect the mechanism.
7. **Chaining (C):** Students use reasoning that links how each phase of the mechanism is connected to the phases around it. In the case that the phase is connected to the phase after it, the chaining is considered **forward chaining**. When the phase is connected to the phase before it, the chaining is considered **backward chaining.**

8. **Animated Models (AM):** Students use external models such as diagrams and body gestures to bring out the reasoning they are running in their heads and communicate it to others.
9. **Analogies (A):** Students use comparisons to other phenomena in order to understand a new phenomenon or mechanism.

3.3. Friction and tension tutorial

The *Friction and Tension* tutorial that was the subject of this video was studied and worked by all members of the research team. See Appendix B for a copy of this tutorial. This tutorial consists of four sections:

1. **Surface area:** Students compare the magnitude of the friction forces on a book by an incline in two cases where the book is at rest but the orientation of it on the incline changes. Then they are guided to draw a free body diagram for both orientations of the book. The point of this section is for them to recognize that the contact surface area between book and incline does not play a role in the magnitude of the frictional force on the book by the incline.
2. **Coefficient of static friction:** Students compare the magnitude of static frictional forces on the book with and without sandpaper attached to the incline. Then an analogy situation is presented with a cart (frictionless) on an incline held in place with a tread. Then the thread is replaced with a strong fishing line and students are asked to compare magnitude of the tension forces in the thread and fishing line experiments. The point of this section is for students to reconsider the experiment with the incline and

sandpaper, using the analogy of the finishing line to recognize that attaching sandpaper will increase the magnitude of maximum possible static frictional force but the magnitude of the actual fractional force to hold the book on the incline will remain unchanged.

3. **Increasing the angle of incline:** Students compare the magnitude of static frictional force on the book by the incline when the angle of incline is increased. In this section students again consider the analogy of a cart with fishing line, this time also on a steeper incline. The point here is for them to recognize that by raising the incline, the maximum force of static friction will decrease but the magnitude of the actual static friction force increases to keep the book at rest.

4. **Determining the existence and direction of friction forces:** Students draw arrows to represent the direction of the static or kinetic frictional forces in five cases. In all five cases, there is a small block on a bigger block, and a hand pulls on a thread attached to one of the blocks. The point of this section is for students to recognize that friction is not always in the opposite direction of motion.

3.4. Tutorial and coding

Our team consisted of three members: two graduate research assistants (coders) and one faculty (supervisor). In a meeting session with all three team members present, the team collaboratively made decisions about how to apply the coding scheme to the scenarios in the Friction and Tension tutorial. We discussed what exactly each code means for this specific tutorial. Since the target phenomenon throughout the tutorial is a body at rest, we concluded that the mechanism underlying the target phenomenon is the balance of forces acting on it. The results of our discussion are summarized in Table 3.1:

Table 3.1. Coding Scheme Interpretations

Codes	Component of mechanistic reasoning	Interpretations for friction and tension tutorial
Describing the Target Phenomenon (DTP)	Target Phenomenon	The book is at rest on an incline. Two blocks at rest on a table
Identifying Setup Conditions (ISC)	Set-up Conditions	Incline angle, materials (incline/sandpaper/book), how the book is set on the incline (spine vs. flat/surface area)
Identifying Entities (IE)	Entities	Incline, book, earth (objects)
Identifying Activities (IA)	Activities of Entities	Forces (Entities exert forces on each other) - e.g., how hard earth is pulling on book, book sliding?
Identifying Properties of Entities (IPE)	Properties of Entities	Mass of book; surface smoothness (μ); ...
Identifying Organization of Entities (IOE)	Organization of entities	Angle of incline to horizontal, position/orientation of book on incline
Analogies (A)	Analogies	The comparison of the fishing line tension force with static frictional force
Animated Models (AM)	Animated Models	coordinate system, free body diagram, force vectors... anything drawn on the whiteboard, formulas and mathematical models, body gestures, images on the tutorial, using objects around them
Chaining (C)	Chaining	Connection between two reasoning statements when the second statement explicitly builds on the first statement.

A preliminary round of analysis was done by the author only. During this experimental coding, we realized that the LAs mostly treat forces as entities. For example, while the group is constructing their first free body diagram, Nate asks, “Doesn't normal have to be the same magnitude as gravitational?” Travis responds, “It doesn't. ... ’Cause they are not a third law pair.” Both of these statements treat forces as object-like things. Based on this, we initially coded discussions of forces as "identification of entities." This meant that magnitude of forces would be coded as "properties of entities," and the direction of forces coded as "organization of entities."

However, throughout the tutorial there are also instances of the LAs treating forces as interactions between objects – for example, in statements such as "Force of gravity on, by -- on the book by the Earth" and "...the frictional force between sandpaper and book if it's moving." In these examples, the entities are the book, the Earth, and the sandpaper, and as interactions between these objects, forces should be coded as "activities of entities." The LAs move fluidly between these two ways of describing the phenomena in the tutorial; this fluidity created a coding challenge, particularly in instances where the language was ambiguous due to missing words or incomplete sentences.

After a team discussion of this coding issue, we decided to consistently code forces as activities. In addition to resolving the challenge of how to code ambiguous statements about forces, this decision allowed for the objects involved in the target phenomenon to be coded differently from the forces between them: the objects are coded as entities, and the forces the objects exert on each other are coded as activities of entities. In order to track the occurrence in the data of the LAs using the language of entities to describe forces, we created a note "Treating Forces as Entities," or "TFE.". Each time LAs treated forces as entities, the forces were coded as "Identifying Activities" and the code notes were edited to include "TFE." When the LAs used an action verb to describe a force, the TFE note was not added. For example, anytime the “on by” language was used to describe a force, the statement was coded as Identifying activities (IA) without noting TFE.

To avoid adding new entities from other phenomena into our coding, we decided that each time an animated model is introduced, we would not code the entities and activities inside that Animated Model (AM) and we would only code within analogies if those analogies are regarding previous questions on the tutorial with the same entities being analyzed.

We decided that formulas and mathematical expressions and tools such as trigonometric functions are to be treated like mathematical models and any time LAs refer or recite a formula or mathematical expression, it will get an AM code.

The coding framework heavily emphasizes verbal statements, with the exception of animated models. This means several different kinds of non-verbal actions are coded as Animated Models, and the level of sophistication of these elements of reasoning were not represented in the code. We coded an animated model to the most immediate statement of the same LA.

Since not all Chaining statements took place within a single utterance, we decided to apply the code for Chaining at the end of the reasoning chain, so the statement that completed the Chaining was coded with C.

3.5. Inter-coder agreement

At first, we watched the videos together and coded it in real time, refining our understanding of the coding scheme as we worked. Then the two graduate research assistants coded sections of the video separately. We used the MAXQDA inter-coder agreement feature to find disagreements. We discussed all disagreements and reached an agreement on all codes, so at the end of this process the inter-coder agreement was very high.

After finishing coding and inter-rater discussion for all three videos, the first researcher reviewed the first video, because in our discussions of inter-coder differences we developed our ideas and learned to see things more carefully. This revision did not result in much code changing; rather it resulted in more statements getting coded, meaning there were valuable statements that did not catch our attention at the beginning when we did not have a lot of experience. By the end of first video, codes were up to current standard and there was no need to re-code the second or third video.

The first video (24 minutes) was coded collaboratively with both researchers and the faculty research supervisor as a team. Therefore, the inter-rater agreements before and after discussion were very close. Our agreement was 99 percent before discussion and 100 percent after discussion.

The second video was coded in segments. The first 10 minutes were coded individually by each graduate research assistant, and then discussed before continuing to code. Inter-rater agreement was at 77 percent before discussion and 100 percent after discussion. We then coded a few minutes collaboratively, and then the last ten minutes were coded individually by each research assistant. Initial inter-rater agreement for the last ten minutes of the second video was 42 percent. The low initial agreement was primarily rooted in the sudden shift in the LAs' discussion to mathematical analysis of a hypothetical scenario, which required new refinement of application of the coding scheme. Each disagreement was discussed between at least two team members to be resolved. Inter-rater agreement after the discussion was 100 percent.

The third video was coded individually by the two graduate research assistants. Inter-rater agreement was at 43% percent before discussion. Most disagreements fell into two categories: IE and IA codes based on inference from the LAs' use of language about forces, and AM codes based on the LAs' gestures. After discussion, the team agreed that students' use of "on, by" language (e.g., force on the book by the sandpaper) warranted both IE and IA codes. The team re-watched and discussed the gestures to arrive at agreement on what instances warranted AM codes. Inter-rater agreement was 100 percent after discussion.

4. ANALYSIS

Throughout our analysis of this LA preparation session, we have assigned a total of 875 codes to 1045 statements. We begin analysis of the resulting codes by investigating the density of codes. Graphing the codes by statement numbers (utterance) is an easy way to visualize the distribution and density of codes. In making the scatter plot we graphed all the codes on one plot, organized by the sophistication hierarchy and in terms of the statement number (utterance).

In making our graph we demonstrate the hierarchy of the codes by giving higher-level codes a higher vertical value. This is similar to how Russ et al. (2008, p. 521) present their data, with the exception that they did not include the non-hierarchical codes in their graph. Analogies (A) and Animated Models (AM) are not in the code hierarchy as they can be very simple or very sophisticated. In order to include them in our graph, we put both codes on line zero. The dots on line zero represent AM codes and the squares represent A codes.

4.1. Most frequent codes: Activities and Animated Models

As we see in Figure 4.1 Line 4 with 763 codes is the densest code in our session. Line 4 represents Identifying Activities (IA). This high density makes sense because the whole tutorial revolves around discussing forces exerted on and by objects, which we code as Activities of entities.

The second densest line is Line 0 with 591 codes. Out of these 591 codes, Animated Models account for 566 codes and Analogies account for 25 codes. AM codes are therefore the second most dense code. We coded statements with the AM code any time LAs were drawing, pointing at, or talking about a diagram or mathematical expression. We also coded statements as AM when LAs simulated motion relative to the diagram and used hand gestures to clarify the orientation of entities or direction of forces. Very often, LAs drew free body diagrams, discussed them, and referred to them to reason about the phenomenon at hand. Furthermore, LAs referred to and used mathematical models such as the static friction inequality to sensemake about the relationship between entities and the activities in which they engaged.

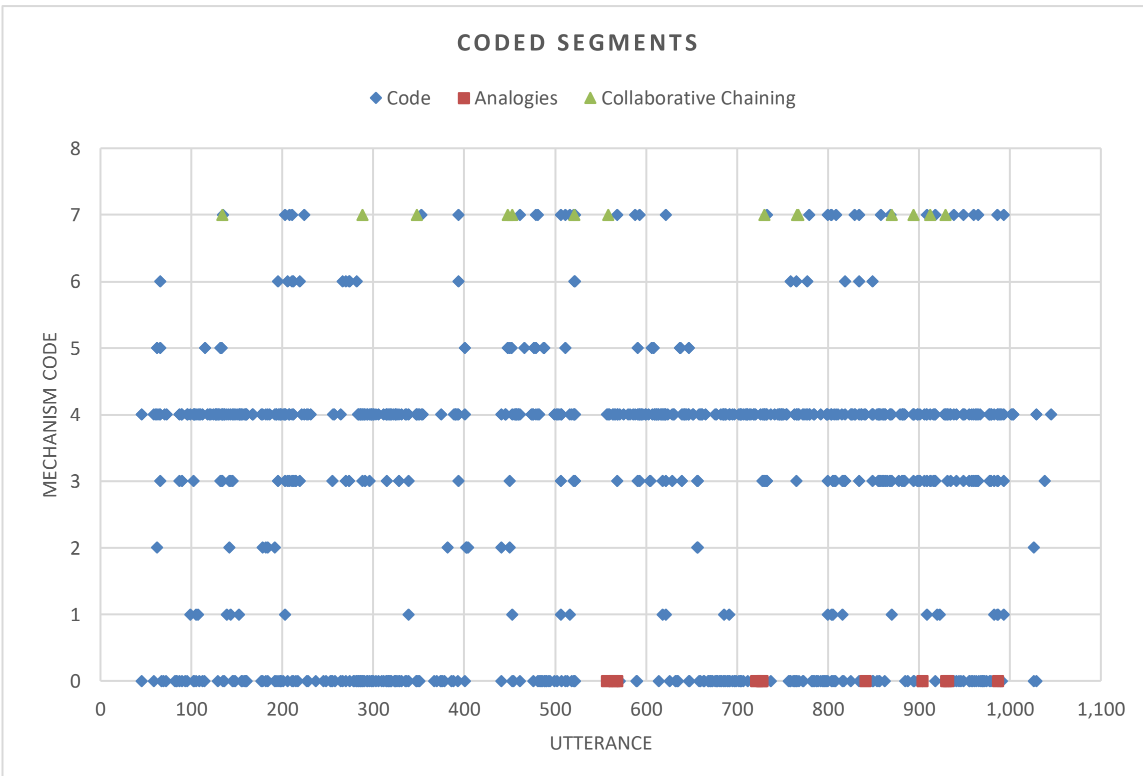


Figure 4.1. Mechanism Coding of LAs Conversation: The numbers on the vertical axis represent the codes as follows: 0- Animated Models (AM) and Analogies (A); 1- Describing Target Phenomenon (DTP); 2- Identifying Setup Condition (ISC); 3- Identifying Entities (IE); 4- Identifying Activities (IA); 5- Identifying Properties of Entities (IPE); 6- Identifying Organization of Entities (IOE); 7- Chaining (C)

Analogy on the other hand, with only 25 codes, was the least dense code in our analysis. Analogy-coded statements were rare in part because they did not start until the end of the second section of the tutorial, where LAs had two analogous scenarios to discuss. Analogies in general are used to understand a new phenomenon by comparing it to another well-understood scenario. In the first coded Analogy, Mark is trying to understand a tension experiment by comparing it to the friction experiment the group had already thoroughly discussed:

> *Experiment two is the same as experiment one except the thread is replaced by a much stronger fishing line. Is the magnitude of the tension force on the cart in experiment two… this is gonna be the same just as in the previous question, it's gonna be equal.*

Later Travis is trying to determine the direction of frictional forces on each block in the second scenario shown in Figure 4.2. He is reasoning that second scenario is analogous to the first one:

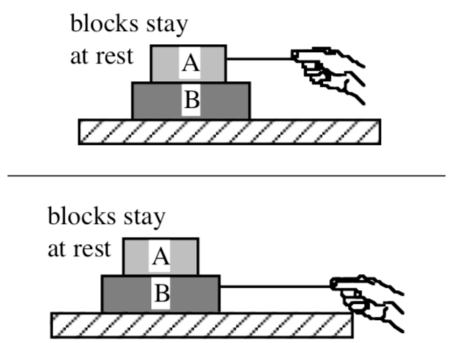


Figure 4.2. Analogous Target Phenomena

> *If we're saying that these [points] are zero then the same logic means …Yeah alright, so we're gonna say that these are zero, [points] then same, by the same logic that would have to be zero.*

Finally, it is important to point out that in analyzing the quality of LAs reasoning, we are not focused on cannon correctness. As you can see the first analogy example is based on a scientifically correct idea and the second example is not, but we recognized both analogies and coded the statements.

For a better resolution of Figure 4.1 we broke the graph down into 3 separate graphs which can be found in Appendix B.

4.2. Chaining

Line 7 represents Chaining code which is the highest code in the mechanistic reasoning coding scheme. We are interested in analyzing chaining statements as chaining is the most complete and sophisticated level of mechanistic reasoning. In analyzing the location of chaining codes with respect to the statement numbers, Russ et al.(2008) discusses possible triggers that could prompt students to move from discussing in the lower codes level to a higher quality mechanistic conversation. In their work they analyzed elementary student's discourse and there was a clear jump into higher codes which in many cases was triggered by the teacher asking a question or asking for elaboration. Teacher intervention can motivate students into sensemaking frame. Inversely in our data we do not see such sharp transitions to higher codes, mainly because our subjects are Learning Assistants who are trying to sensemake of the tutorial so they can teach it. Also, we chose this specific session because mostly their body language indicated they were in sensemaking epistemological frame.

Looking into the density of Chaining codes in Figure 4.1 the density is higher in the last one third of the session. It seems that they have figured out the mechanism by that time and are conducting a high-quality conversation which result in more chaining by connecting each phase of the mechanism to the phases around it.

Our goal here is to characterize LAs' mechanistic reasoning while they are collaboratively working through the tutorials. We are looking for collaborative Chaining. Chaining as the highest-ranking code in Russ's framework can be a proper indication of group's collaboration in reasoning. It is important to point out that we are not focused on the correctness of LAs ideas as long as they are mechanistic ideas. More specifically we are interested in their chaining and how collaborative those chaining statements are.

A chaining statement is a general reasoning strategy that links how each phase of the mechanism is connected to the phases around it. Chaining is considered *forward* if the phase of mechanism is connected to its next phase and is considered *backward* if the phase of mechanism is connected to the phase before it (Russ et al., 2009).

We recognize chaining as having at least 3 parts: statement one, chain, statement two. Statements one and two can take one or more codes, depending on the complexity of them. The chain is some sort of connection between these two statements. The chain does not have to necessarily be a causal word like "because". Sometimes even a pause/comma would provide connection. In this study we encountered chain words such as then, otherwise, that, to and so.

Due to the stationary nature of the tutorial content and the fact that all objects are at rest, most of the Chainings we encountered were forward Chaining. But there were few instances that LAs chained backward. These backward Chainings mostly start by stating the scientific idea first and stating the cause after. The following example shows a backward Chaining:

> *"It's the same thing like, the max might increase, but the magnitude that's happening for these two blocks, aren't changing. 'cause gravity is affecting it the same, and everything so" (Mark)*.

Mark is comparing tension force on two carts with very good wheels on an incline and both at rest. One is tied up with a threat and other is held in place by a strong fishing line. Mark first states that both tensions are equal then provides reason that all other variables like gravitational force are unchanged.

As we are getting into deeper analysis of the Chainings we encountered throughout our work, we should point out that in our work, individual chaining is recognized when all three parts of it is offered by the same person whereas Collaborative Chaining is recognized when at least one part is offered by another person. In the following sections, we describe and categorize chaining statements according to their features:

- Conditional statements chaining
- Short pause chaining
- Questioning chaining
- Back-to-back chaining
- Overlapping chaining
- Multi utterance chaining
- Collaborative chaining

4.3. Individual Chaining

In our analysis, there were 51 utterances that got coded as chaining. Out of these 51 Chaining codes, 36 were individual Chainings. Table 4.1 shows the distribution of these Chaining codes amongst different LA's statements. All names are pseudonyms.

Table 4.1. Individual Chaining

Learning Assistant (LA)	Number of individual Chaining
Travis	23
Nate	7
Mark	3
Alex	3

The following are a few samples of Individual Chainings that we encounter throughout our analysis. An utterance is a turn at talk. First, we present Individual Chainings that happen in one single utterance. Naturally all single utterance Chainings are individual Chainings. Next, we present Individual Chaining samples from our data that happen in multi utterances.

4.3.1 Conditional statement individual Chaining

So often we encountered Chaining in the form of a conditional statement. Where an if-then structure plays the chain role. Here we present an example of conditional statement chaining followed with an explanation of the context of reasoning and an elaboration on how we coded it.

> *An easy way to think about that is if you put the ramp at 90 degrees then there's no normal force (Travis).*

Travis is reasoning that as the angle of incline is increasing, the magnitude of the normal force on the book is decreasing so the normal force will be zero once the incline is vertical. As demonstrated in Figure 4.3, statement one is coded as Identifying entities (IE) because he is identifying the ramp as in entity in this mechanism. This statement is also coded with Identifying Organization of Entities (IOE) as Travis is talking about the spatial orientation of the ramp. Statement two is coded as Identifying Activities (IA) because he is identifying the normal force and is reasoning that $F_N = 0$.

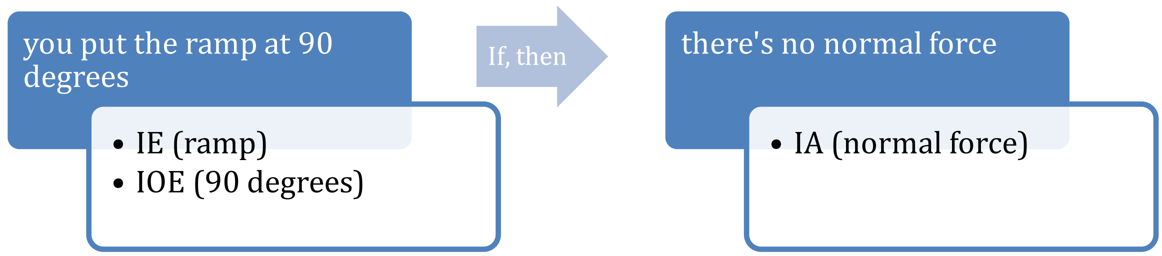


Figure 4.3. Conditional Statement (Individual Chaining Sample 1)

The conditional statement Chainings do not always include an “if” and an “then” as the chain. Here is an Individual chaining in the form of a conditional statement with “if” and a comma (a pause) as the chain.

> *Yeah, but if μ changes, it doesn’t necessarily change the force of static friction (Travis).*

Here Travis is reasoning about how solely adding the sandpaper to the incline will not result in a change in the magnitude of static frictional force on the book by the incline. In other words, a change just in μ_s without changing other entities in the mechanism will not result in a change in the static friction.

μ_s is a characteristic of the roughness of the incline, so we coded the first statement as Identifying Properties of Entities (IPE). The second statement was coded with Identifying Activities (IA) code as Travis is talking about a change in the interaction between the ramp and the book. These codes are illustrated in Figure 4.4.

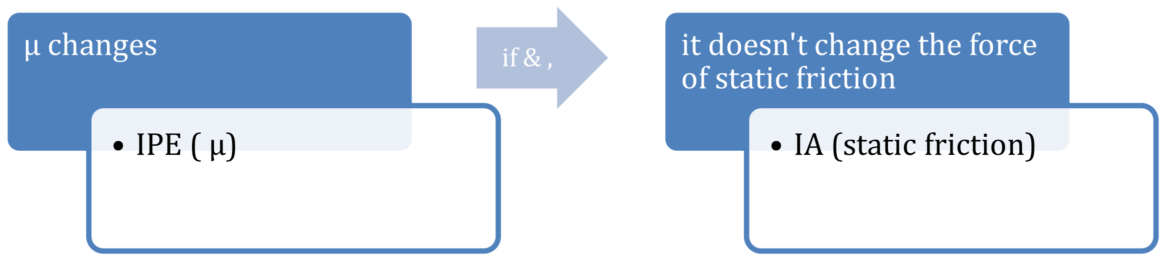


Figure 4.4. Conditional Statement (Individual Chaining Sample 2)

4.3.2 Short pause individual Chaining

A's at rest, net force is zero (Travis).

This is an example of an individual chaining in which there is no word for the chain or connection. Here the connection is just a pause. Travis is reasoning that block A is at rest therefore net force on it has to be zero Figure 4.5 and Figure 4.6 shows our coding of this chaining using Russ's framework. We coded Statement one with Identifying Entities code (IE) because block A is an entity in this mechanism and with Describing Target phenomenon code (DTP) which is the block being at rest. We coded statement two with Identifying Activities code (IA) because net force is a sum of the forces acting on block A and forces are activities/interactions.

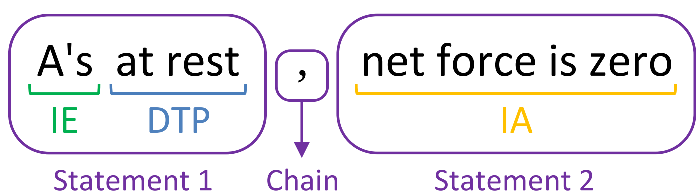


Figure 4.5. Short Pause Individual Chaining Coding

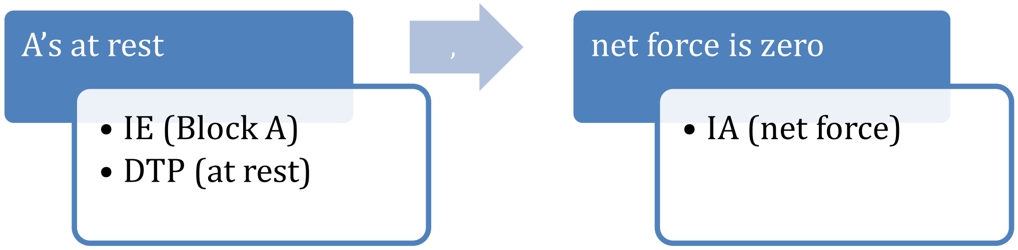


Figure 4.6. Short Pause Individual Chaining Diagram

4.3.3 Questioning in individual Chaining

Chaining could also be posed as a question. Phrasing their ideas as a question is a strategy that students use often in order to soften their stance which can open the floor for idea sharing and sensemaking. Also, by posing their ideas as a question, students distance themselves from their statements so if it is wrong, they do not lose face (Conlin & Scherr, 2018).

> *If it were equal… so I'm thinking, if it were equal to it, wouldn't that mean if there weren't friction that it would stay still? Isn't that what that would mean? (Alex)*

This example is an individual chaining posed as a question. Alex is reasoning that on the free body diagram if the magnitude of the gravitational force (F_g) were to be equal to the magnitude of normal force (F_N), that would mean the book would stay on the ramp even if the ramp were frictionless. Figure 4.7 shows our coding of Alex's statement. Notice that in his Chaining, the first statement is a compound of two conditions that are logically connected to each other with an "and".

It is worth pointing out that Alex's idea is wrong because forces are vectors, and their direction matters in their balancing. Chaining can be wrong but still mechanistic and valuable in education as Alex's reasoning here is mechanistic and valuable. The scalar view of forces misconception showed up a few times in the LAs' discussion. This could be a result of them treating forces as entities rather than treating them as interactions that entities have with each other, or as activities in which entities engage.

I think it can't be equal otherwise the net force is zero (Nate).

Here Nate engages in high-level mechanistic reasoning while treating Gravitational force on the book (F_g) and Normal force on the book by the incline (F_N) as scalars. He is reasoning that the magnitude of normal and gravitational force on the book cannot be equal because then the forces will balance out without friction being in the picture.

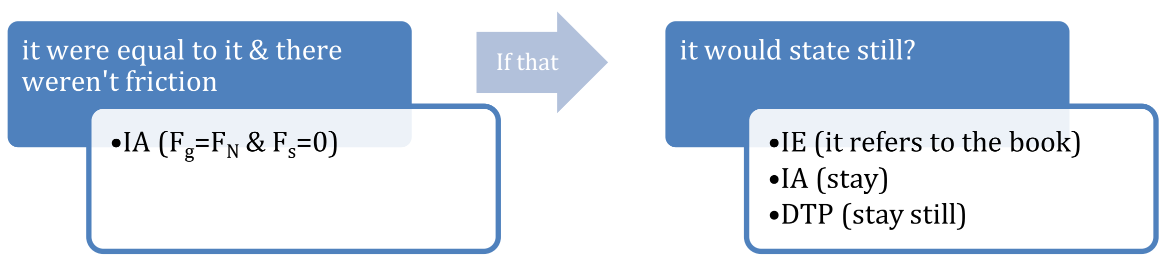


Figure 4.7. Questioning in Individual Chaining

4.3.4 Back-to-back individual Chaining

If it were kinetic, it would change, but since it's static, it doesn't (Travis).

Individual chaining happened also with non-hieratical AM statements. Here Travis is talking about the mathematical model in the form of static friction inequality and kinetic friction equation. He is reasoning that if we were talking about kinetic friction, the change in μ_k would result in a change in frictional force. Then he is reasoning that a change in μ_s does not necessarily cause a change in the static friction force. Here both Chainings are from an AM statement to an IA statement and they are connected with the word “but”. Chaining happens twice back-to-back in one utterance but due to MAXQDA limitation, we could not give two chaining codes to one utterance.

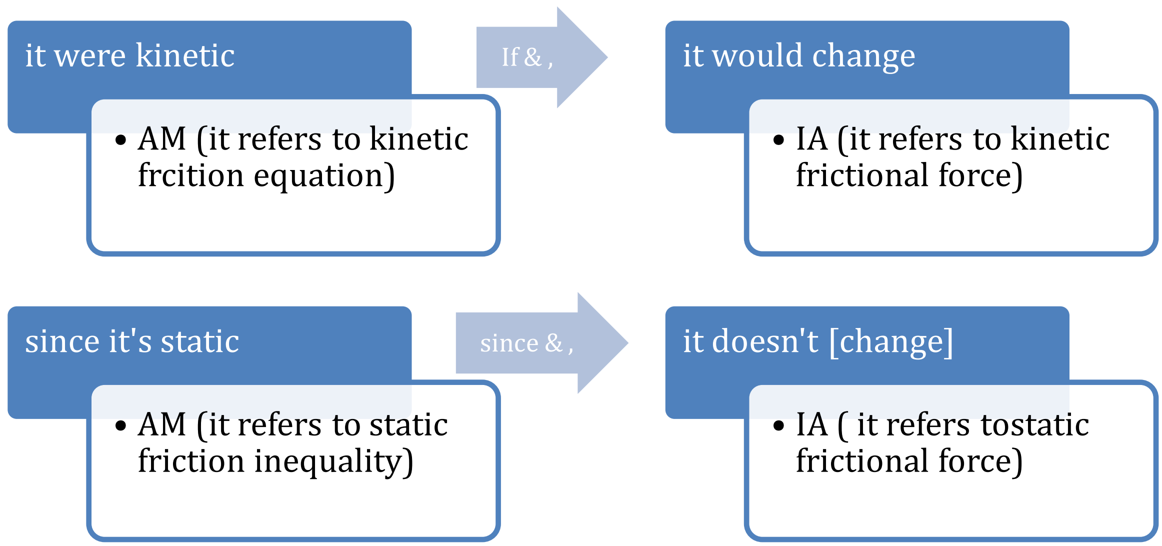


Figure 4.8. Back-to-Back Individual Chaining

4.3.5 Overlapping individual Chaining

More than one chaining can happen in an utterance, but the breakout might not be as clear the back-to-back Chaining as statement two in the first chaining can serve as statement one for the second chaining. For overlapping Chainings, we look for connections and not necessarily two distinct statements per chain. The following example has more than one chain in an utterance.

> *“I’m thinking of it as like the angle, [gestures on FBD] the incline increases, normal is decreasing. Where, and then… the friction, is, like… having to deal with more gravity ‘cause gravity is [gestures force directions with pencil over FBD] - it’s” (Nate).*

Here Nate is reasoning that by increasing the angle of incline the normal force will decrease because the vertical component of gravitational force will decrease, and friction needs to balance out a bigger parallel gravitational component.

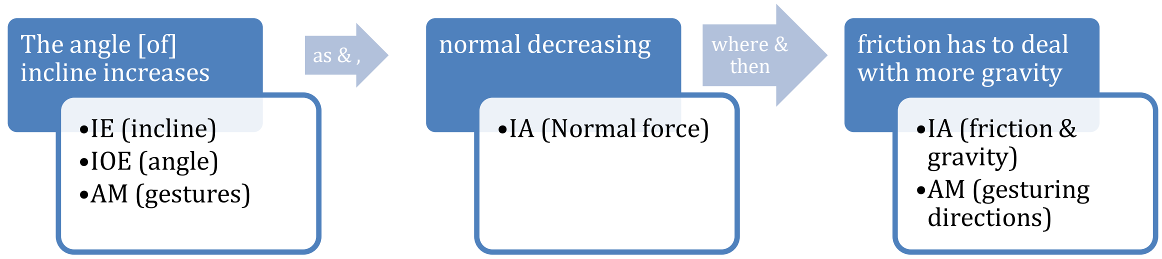


Figure 4.9. Overlapping Individual Chaining

4.3.6 Multi utterance individual Chaining

So many times, Chaining happened through more than one statement or utterance (turn at talk). In those cases, the code was given at the end of Chaining with a reference to the beginning statement of the chaining. Chaining was coded as many times as a chain happened, meaning as many times as statements got chained together. One limitation here is that MAXDA does not allow giving a code to a statement more than once. We could not code a single statement with two chaining codes even when it had two chains like the back-to-back Chaining or overlapping Chaining. However, this does not apply to multi-utterance Chainings as they do not occur in a single utterance, so we were able to code the chain as many times as it happened.

Table 4.2 shows an example of how a Chaining got broken into more than one utterance. Here Travis is chaining individually but it happens in two utterance with Alex's utterance in the middle.

Table 4.2. Individual Two Utterance Chaining

Student	***Statement***
Travis	Okay, so B by the table on the first case, **that would be zero**, right?
Alex	B by the table?
Travis	**Because** B's not moving, table's not moving, so there is gonna be **no friction** between them? [points at diagrams on paper]

Referring to Figure 4.2, Travis's reasoning is that since both table and block B are at rest, then the friction between them must be zero. The repetitive nature of this example is interesting as the third statement is very similar to the first statement. Figure 4.10 shows how the first chain is backward providing reasoning on why friction is zero, and the second chain is forward, reiterating that as a result of block and table being at rest, the friction between them is zero. Notice that the 3rd statement has almost the same codes as the first statements with the exception of an AM code where Travis points at the diagram while talking.

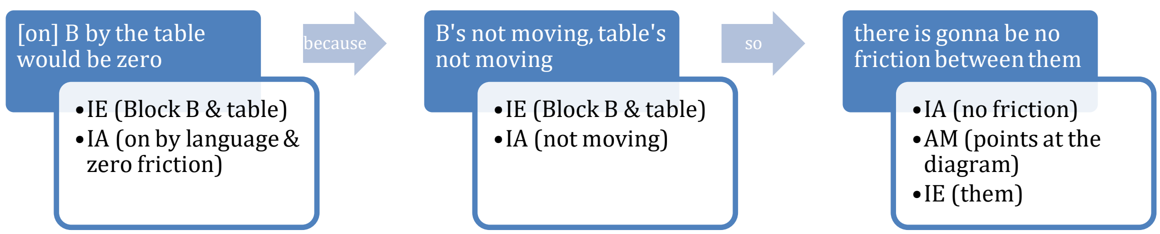


Figure 4.10. Multi Utterance Individual Chaining

4.4. Collaborative Chaining

Chaining has three components, two statements and a chain. Any time all three components of Chaining were not offered by the same LA, we coded it as a collaborative chaining. As a result, a collaborative chaining can have up to three LAs involved in it. For example, statements could be offered by different LAs while the chain is offered by a third LA. Naturally, all collaborative Chainings fall under multi-utterance Chainings category.

In the case of individual Chainings, it was easy to recognize and code the statement of the LA who was engaged in Chaining. But was more complicated when statements were chained collaboratively within the group. In our analysis, we decided to code the statement of the LA who completes the chaining since we were coding multi utterance Chainings at the end of them.

In our data, out of 51 Chaining codes, a total of 15 were collaborative Chainings. Table 4.3 shows the distribution of the number of times an LA was involved in a collaborative Chaining.

Table 4.3. Collaborative Chaining

Learning Assistant (LA)	Number of involvements
Travis	14
Nate	3
Mark	5
Alex	9

Here we are starting our analysis by presenting five examples out of the 15 collaborative Chainings we encountered in our study. We will present their dialogue in a table then; as we did for the individual Chainings; we will elaborate on the physics content that was being discussed at the time. Next, we will present a diagram with statement and their codes. Finally, we will explain the reasoning and the collaborative nature of the Chaining at hand.

Example 1: In Table 4.4 dialogue, the group is trying to compare the magnitude of the normal force on the book by the ramp with the magnitude of gravitational force on the book by earth. The book is at rest on the incline. Travis is trying to figure out which force vector should be longer on the free body diagram. He starts reasoning by offering a kind of a counter assumption discourse and Alex follows through.

Table 4.4. Conditional Statement Collaborative Chaining

Student	***Statement***
Travis	**If there’s no friction…**

Alex	There has to be friction.
Travis	Well yeah, assuming a frictionless ramp.
Alex	If it were frictionless **then it would be falling**…
Travis	Yeah, It would slide down and then…
Alex	and **then it would just be-just be this and that**…

As illustrated in Figure 4.11, we coded this conversation with Chaining twice. Both Chainings are in the form of a conditional statement. In the first Chaining Travis offers the first statement (hypothesis), and Alex offers the chain and the second statement (conclusion) therefore we coded the first Chaining as collaborative.

We coded the second Chaining as an individual chaining assuming that Alex is Chaining from his own statement "If it were frictionless then it would be falling"**.** But, interesting enough is that the second Chaining could also be collaborative. Right after Alex says, "it would be falling", Travis says "it would slide down", so we could have treated Travis's statement as the first statement then Alex chains it to the fact that then there is going to be only two forces acting on the book. This and that in Alex's statement refers to Gravitational and normal force on the book as he is pointing to these vectors drawn on the free body diagram.

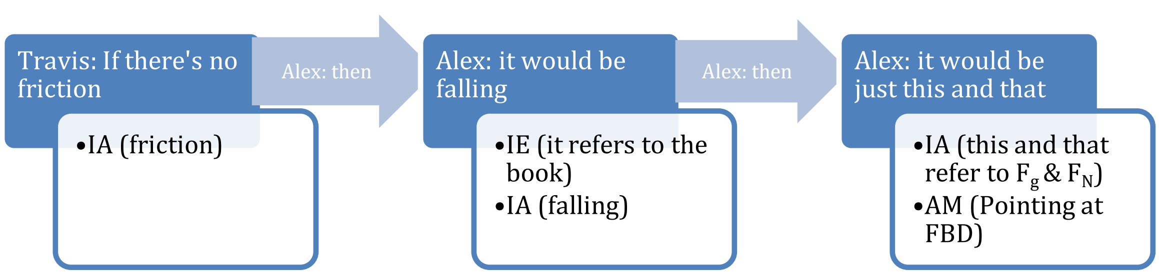


Figure 4.11. Conditional Statement Collaborative Chaining

Example 2: Here is an example of a backward collaborative Chaining. Again, due to the stationary nature of this tutorial, there was no temporal backward Chaining in it as in going back in the life timeline of a mechanism. In our study, we coded Chainings as backward when LAs offered conclusion first and then provided reasoning for it afterward.

Table 4.5. Backward Collaborative Chaining

Student	***Statement***
Travis	It would be on the y axis…
Alex	'**cause** it's perpendicular to the plane

In Table 4.5 dialogue, the group's discussion is about the direction of the normal force on the book by the incline. They have their coordinate system drawn such that the x-axis is parallel to the incline and the y-axis is perpendicular to it.

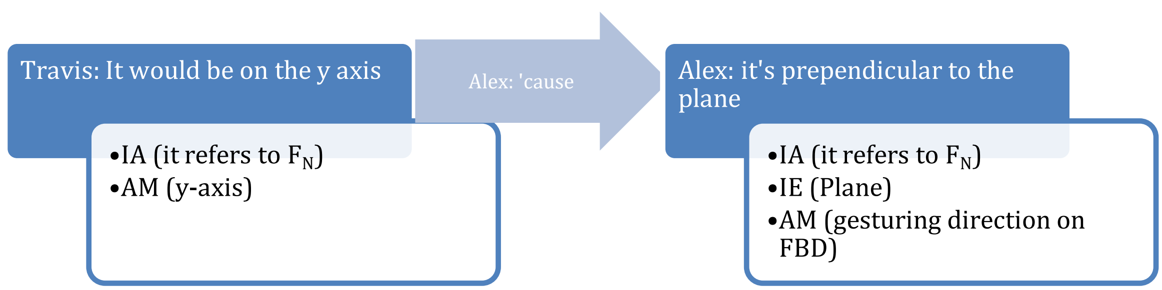


Figure 4.12. Backward Collaborative Chaining

In this collaborative Chaining, Alex is providing reasoning for Travis's statement. The first statement is offered by Travis, the chain and second statement are offered by Alex. This is a backward chaining since Alex is providing reasoning for why normal force vector is on the y axis.

Example 3: Not all Chainings are quick and verbally clear. Sometimes there are quite a few utterances between the first and the second statement of Chaining. In Table

4.6 dialogue, we see how Chaining statements can be far in utterances. Here LAs are trying to break the force of gravity on the book by the incline, into x and y components on their coordinate system.

This piece of reasoning starts with Alex realizing that the x component of gravity is along the ramp. Then Mark draws out the y-component of the gravity on the free body diagram on the y axis. Referring yet to the x-component of gravity, Alex says: “you could put it right here (points) as well, just to show that it’s not moving”. Finally, Travis completes the chaining by saying that force normal is equal to the y-component of gravity.

Table 4.6. Far Utterances Collaborative Chaining

Student	***Statement***
Alex	… and **the force of gravity** in the x direction would be along that ramp.
Mark	‘cause right here... (draws)
Alex	Wait what?
Nate	I think he’s saying, like, that’s the actual force of gravity and that’s the…
Mark	Yeah yeah
Travis	Yeah, it’s… [that’s?]
Alex	Oh, oh, okay I see what you’re talking...
Nate	… **y component**.
Alex	Gotcha.
Mark	And that… (draws) should be over here, right?
Travis	Yeah
Alex	Yeah, or you could put it right here (points) as well, just **to show that it’s not moving**. Just to make it more clear I guess.
Mark	Mmmm (affirmative)
Alex	Do you see what I mean?
Mark	Mmm-hmm.

Eleanor	(walks by) Did the coordinate system shift help? (kneels at table)
Alex	I think it did, actually.
Travis	Yes, it did
Alex	It makes more sense.
Alex	But, hmm. So what can we say about the **normal force**?
Travis	**So**, F-N is **equal to the component of gravity**.

This example is very interesting to us. Alex figures out the orientation of the x-component of gravity then he probably realizes that the static friction force balances off this component of gravity keeping the book at rest on the incline. When he says, "you could put it right here (points) as well, just to show that it's not moving", He is asking Mark to Translate the x-component of gravity to the origin. Figure 4.13 is a similar diagram to what LAs have drawn. It is provided to make the content of Alex's AM statement clearer.

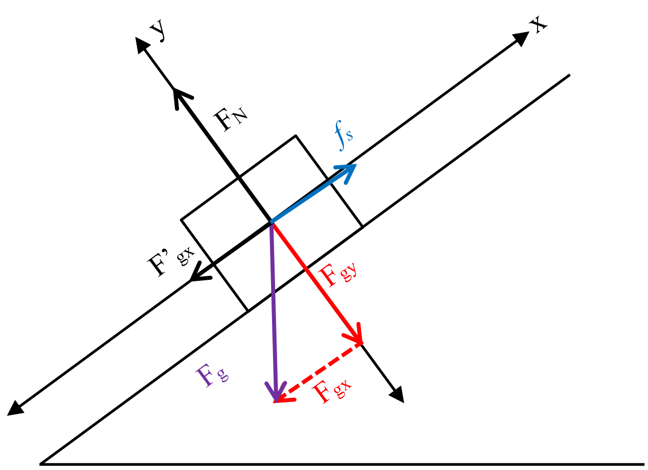


Figure 4.13. Free Body Diagram of Breaking the Gravity to Components

We strongly think that there is a nonverbal individual Chaining here however, in our analysis we were bound to LAs words and drawings. We avoided coding statements based on our inference or nonverbal clues even when we were really sure of our assumption. Basically, this is what we think is going on in his head, but we cannot code it as Chaining. He possibly is making a mechanistic connection in his head but not in his language. We coded his statement with IA, DTP, IE and AM but not Chaining. As a result, you only see one Chaining in Figure 4.14.

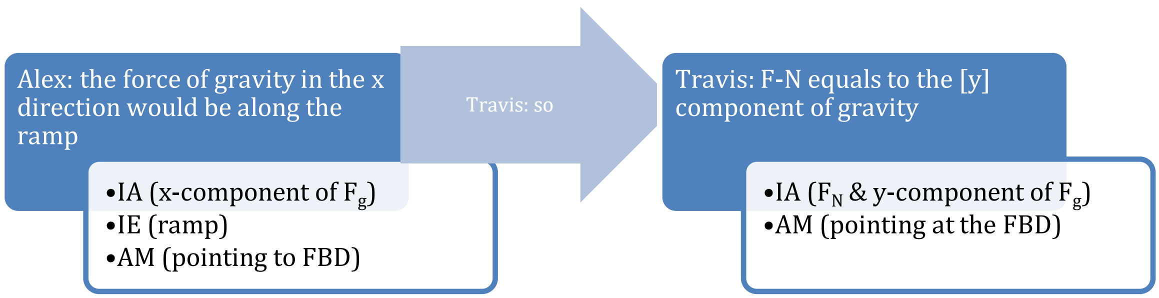


Figure 4.14. Far Utterances Collaborative Chaining

In the lieu of non-verbal reasoning, we also can wonder whether Alex's reasoning about the x component of gravity being equal to friction, causes Travis to immediately make connection and say the y component of gravity and normal force are equal.

Example 4: Table 4.7 shows an example of overlapping Chaining that is collaborative. The LAs are discussing what happens when the angle of incline is increased. More specifically, they are trying to figure out whether static friction force will increase or decrease as a result of increasing the angle.

Table 4.7. Overlapping Collaborative Chaining

Student	***Statement***
Mark	Well 'cause **at 90** it'd be **falling**.
Travis	Yeah, so there would be **no friction**.
Mark	Yeah. So it should be **getting less** than. Right.

Mark starts assuming a completely vertical ramp. Travis is trying to figure out changes in two variables: the normal force and static friction. Mark is on the 90-degree ramp idea and states that the book will fall. Travis chains off of Mark's statements that if it falls, then there is no friction. Mark chains off of Travis's statement that therefore the friction should be decreasing as the angle of incline increases.

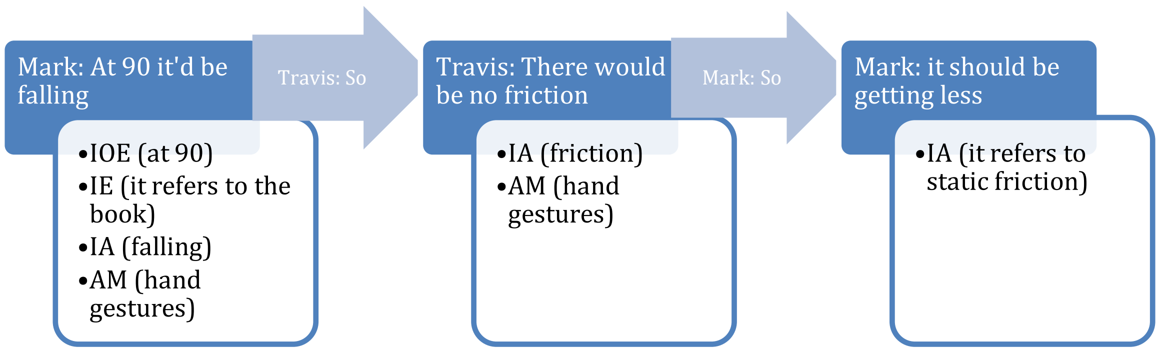


Figure 4.15. Overlapping Collaborative Chaining

This is an overlapping chain because the middle statement is the second statement for the first chain and is also the first statement of the second chain as shown in Figure 4.15. The AM codes are there because both LAs are making hand and arm gestures showing the increase in angle.

Example 5: The last collaborative Chaining we would like to present in this section is the one with three LAs involved in it. this is the only one of this kind in our analysis. In the dialogue of Table 4.8, LAs are trying to find out the change in the static friction on the book by the incline when sandpaper is attached to the incline where the book is resting on. LAs are reasoning that the magnitude of static friction will increase because μ_s is increased. Which scientifically is not correct, nevertheless it is a valuable mechanistic idea, so we coded it.

Table 4.8. Three LA Collaborative Chaining

Student	***Statement***
Travis	**It's greater, right?**
Alex	I thought it was greater than.
Travis	Yeah**, 'cause…**
Alex	**… μ_k… μ is… μ is increased?**
Mark	Oh. I don't… How do you get
Travis	**Because it was on a wooden ramp, and now it's on sandpaper.**
Alex	Yeah
Mark	Yeah but it's just like, I don't… this one I always hated 'cause I was like… are we, are, are we just assuming that the wood is smoother?
Nate	If that's… If that's the case, then (points) the **normal force** would have to **decrease** to keep it in **equilibrium** so it doesn't move.

You can see three Chainings in Figure 4.16, for this dialogue. However, there are four Chainings in this conversation. Nate's statement is the chain and the second statement of the collaborative chaining off of Alex and Travis. But Nate's statement is also an individual Chaining on its own. Nate's statement is a single utterance statement so due to MAXQDA limitations we could not code it Chaining twice. We chose to code it as collaborative Chaining.

Statement one first is offered by Travis then by Alex that static friction force increases. Then Alex and Travis both chain backward to provide reason for their statement. Friction has increased because μ_s is increased. Now Nate reasons that if μ_s is increased then normal force would have to decrease so friction stays the same. This means Nate is arguing that static friction force does not increase and stays the same. The tightness and the reflectiveness of this dialogue between the three LAs persuaded us that this is a three LA collaborative Chaining.

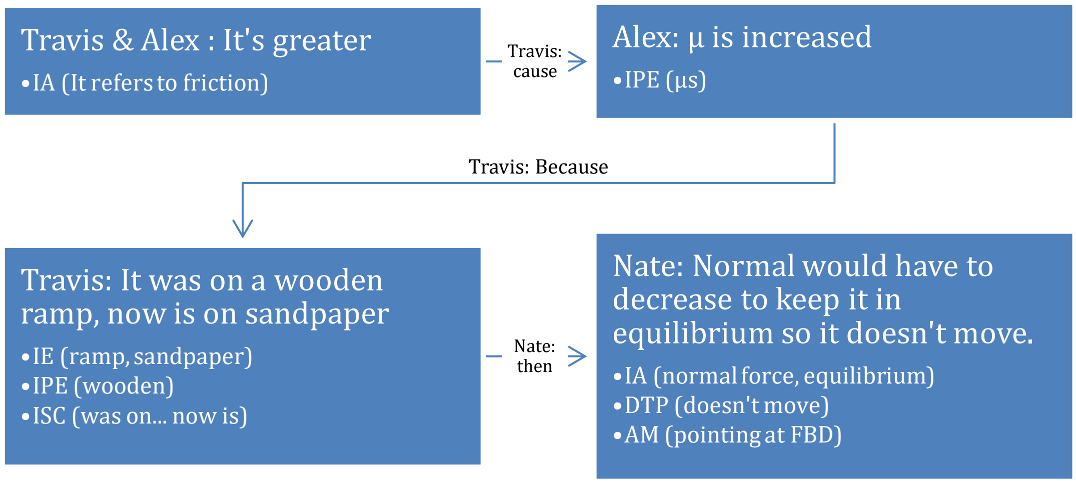


Figure 4.16. Three LA Collaborative Chaining

4.5. In-dept analysis of one collaborative Chaining episode

We will discuss in depth one episode of collaborative chaining to situate it within the larger discussion and relate this case to the literature on mechanistic reasoning. This episode occurs approximately halfway through the hour-long small-group discussion. In the six minutes before the collaborative chaining episode, the LAs discuss several conceptual issues related to the force of static friction exerted on the book by the sandpaper in experiment 3S as shown in Figure 4.17.

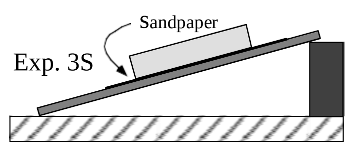


Figure 4.17. Experiment 3S

The main focus of the discussion is the mathematical expressions for static friction, $F^{fs}_{book,sandpaper} \leq \mu_s F^{N}_{book,sandpaper}$ and $F^{fsmax}_{book,sandpaper} = \mu_s F^{N}_{book,sandpaper}$, and how they relate both to the actual static friction force on the book by the sandpaper in experiment 3S, and to the boundary condition when the actual static friction force is equal to the maximum possible static friction force. The collaborative chaining episode at the end of this six-minute discussion is reasoning resolving their questions about the boundary condition, using the analogy of the wheeled cart attached to thread or fishing line in experiments 1M and 2M (see Figure 4.18).

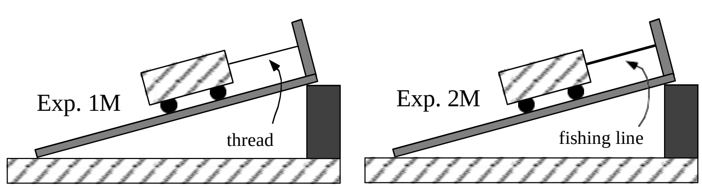


Figure 4.18. Experiments 1M and 2M

Figure 4.19 shows the codes during the six minutes leading up to this collaborative chaining episode, along with annotations showing the main discussion topics and an instructor intervention.

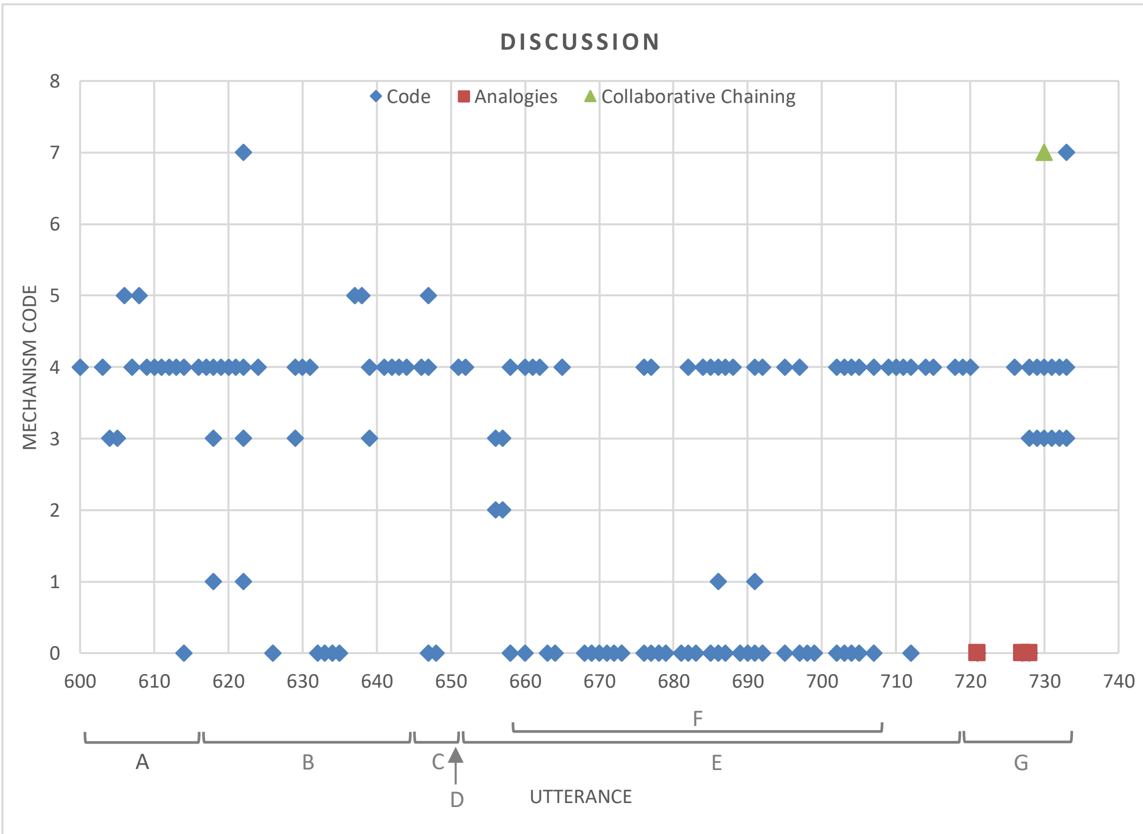


Figure 4.19. Collaborative Chaining Episode Example: a graph of the six minutes leading up to the collaborative chaining episode. (A) comparing friction force in experiment 3S to 6N; (B) discussion boundary condition of friction force equal to 6N; (C) returning to comparison of friction force and 6N; (D) instructor intervention; (E) using the diagram of experiment 3S to figure out the magnitude of the friction force; (F) (within E) using trigonometry and the free body diagram for experiment 3S to find an expression for the magnitude of the friction force; (G) returning to the boundary condition question, using the fishing line in experiment 2M as an analogy.

In section A (statements 600 to 616), the group is discussing the tutorial question: "Is the frictional force on the book in experiment 3S greater than, less than or equal to 6N?" This builds on the previous question, which introduced hypothetical values for the coefficient of static friction (0.75) and the normal force on the book by the incline (8N) and asked students to interpret the product of these two values (6N). The LAs debate whether the static friction force must be less than, or could be equal to, the maximum value:

> *Nate: Uh. I guess we don't know for sure. But it could be equal-*
>
> *Travis: No, we know it's less than-*

In section B (statements 616 to 644), they transition to discussing what would happen under the boundary condition of the static friction force being equal to the maximum possible value:

> *Mark: Yeah. Yeah, 'cause at that point wouldn't it- at the maximum, wouldn't it, you see a movement in it?*

In section C (statements 644 to 651) they briefly go back to discussing the question from part A, without arriving at a consensus response:

> *Travis: Looking at 3A, we can say it's definitely less than.*
>
> *Alex: Why?*
>
> *Travis: Is it though?*

Section C ends with an instructor intervention using the hypothetical numbers from the earlier question, noted by arrow D in the figure. The instructor uses a whiteboard marker as a prop, and asks the LAs to consider the case of the marker sitting on the table:

Instructor: The normal force from the table, um, [puts marker on table] ... being eight newtons, and let's go with [inaudible] for static friction. What would be the friction force in this case?

This intervention prompts the LAs to consider the geometry of the phenomenon, when their discussion for the previous several minutes was primarily about the mathematical expression for static friction. In section E (statements 651 to 718), the LAs are thinking about the magnitude of the static friction force using their free body diagram of experiment 3S (Figure 4.17), constructed earlier in the tutorial:

Travis: Yeah, if you wanna set it equal to something, it's gonna be that component of gravity

Alex: Alex: Yes. [taps white board - free body diagram]

Travis: Not this equation [points at whiteboard].

Section F is a subsection of section E where they get into a trigonometry conversation (statement 657 to 707) to find an expression for the component of the gravitational force parallel to the incline:

Mark: Yeah, so opposite over hypotenuse, so it'd be sine [points].

In section G (statements 718 to 733) they go back to the boundary condition, starting with a teacher-hat statement:

Alex: And like another thing. What- what if, what if they [students] said, what if they asked, Why aren't they equal?

This section ends with an individual chaining and a collaborative chaining with correct conclusion about boundary conditions, using an analogy. The final conversation is shown in Table 4.9, followed by the collaborative chaining and individual chaining diagramed in Figure 4.20 and Figure 4.21.

Table 4.9. Collaborative Chaining Using Analogy From an Earlier Scenario

Student	***Statement***
Alex	All right, so I got, I mean… it's also sorta like this one. 20 pounds test strength, that's the max. So if it is 20 pounds, if this was 20 pounds [points at tutorial document], would it still be staying there? Or would it then move?
Travis	I dunno. If it was 21 pounds…
Mark	It would break.
Alex	It would break… break
Travis	Yeah. The rope would snap.
Alex	So, like at 20 I feel like it would still stay there, right? Since it's the max.

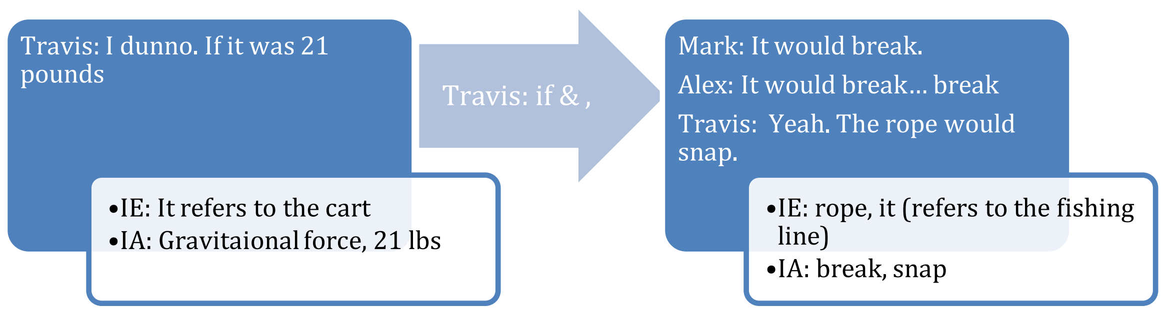


Figure 4.20. Collaborative Chaining Inside an Individual Chaining

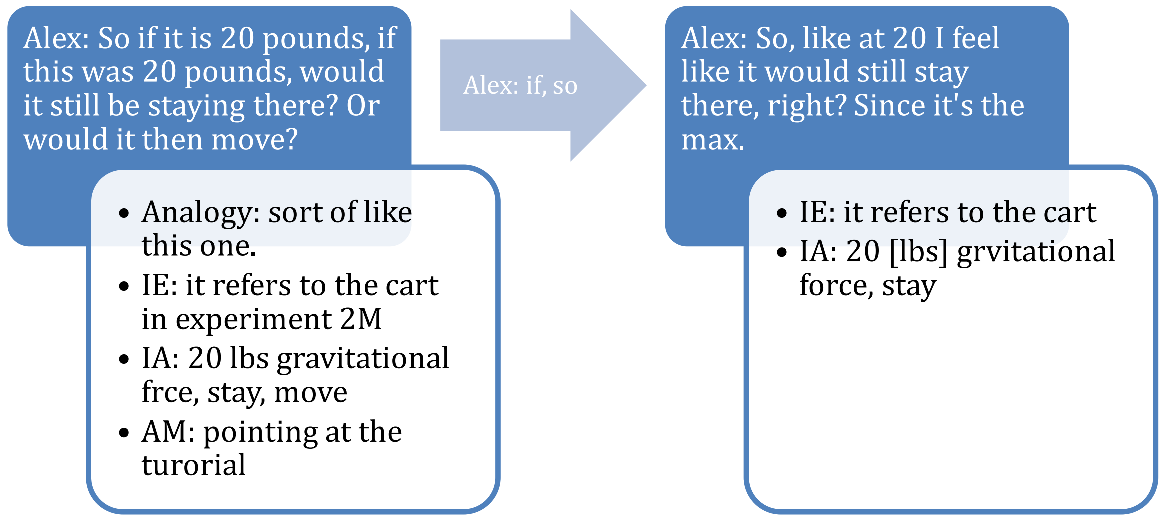


Figure 4.21. Individual Chaining Around the Collaborative Chaining

It is interesting that this breakthrough is happening after a teacher intervention. We think this intervention is prompting LAs collaboratively into a higher level and more sophisticated mechanistic reasoning with the means of an analogy. This is consistent with what Russ et.al (2008) show in their data. As the teacher questions or asks for an elaboration, this prompts students into higher level thinking.

Russ et. al. (2008) showed that codes increased up toward chaining, before the chaining happened. However, in our example, there are few high-level codes between statements 670 to 720, which is when chaining happens. It seems that this collaborative chaining happens in the absence of higher-level codes. We think it is the high-level analogy statements that are leading up to this collaborative chaining, which resolves the question the students are pursuing. These analogy codes are high level reasoning; however, Analogy codes are graphed on line zero alongside with the Animated Model codes, because both Analogies and Animated Models can vary in level of sophistication. Since Analogies are not in the hierarchy of the codes, we don't see the step-like behavior in the graph leading up to the chaining.

5. DISCUSSION

As stated in the introduction, the research questions for this study are as follows:

1. What does it look like to apply Russ' mechanistic reasoning framework to the context of LA weekly preparation sessions?
2. What does chaining look like in this context?
3. Do LAs engage in collaborative chaining?
    - If so, what does this look like?
    - How often does collaborative chaining take place?
    - How does collaborative chaining emerge from the group discussion?

5.1. Research Question 1: Applying Mechanistic Reasoning Framework

In this section we will respond to Research Question 1: What does it look like to apply Russ' mechanistic reasoning framework to the context of LA weekly preparation sessions?

Figure 4.1 shows the distribution of the codes for LAs working on the Friction and Tension tutorial. The graph shows the highest density in line 4, Identifying Activities (IA). During this session, LAs very often were engaged in reasoning about forces or whether the book will stay on the incline or slide down. This resulted in IA being the most frequent code.

The second highest density is on line 0 for Animated Models (AM). LAs often drew a diagram, used a mathematical model, or made gestures to get a better understanding of the underlying mechanism or to communicate their reasoning to the rest of the group. This caused AM to be the second most frequent codes for this session.

For discussion of a phenomenon like this, where the geometry of the situation is critical to the sensemaking, the coding graph will not accurately reflect the sophistication of the reasoning unless we create a way to identify the sophistication of the animated models and analogies. In Russ et.al.'s (2008) framework, AM & Analogy codes do not have encoded sophistication levels . However, encoding this level of sophistication is important for documenting students' reasoning about this scenario, and likely also important for others, especially in advanced (college-level) physics, as compared to elementary science courses.

Similarly, IA coding does not document the sophistication of the force discussions amongst LAs. Throughout our analysis, we encountered many statements, reasoning about forces. Some were very simple and some were very sophisticated. Some dealt with forces as entities and some dealt with forces as interactions. Some treated forces as scalars and some treated forces as vectors. All of these statements were coded as level 4, IA, but there was no coding within that to discuss aspects of forces, such as their vector nature or their relationship to other forces.

Treating forces as entities, which the LAs do in some instances in this session, would make space in the coding scheme to add this sophistication. If a force were coded as an entity, then the magnitude of the force could be treated as a property of the entity; direction as organization of entities; and relationships between forces (e.g., balancing) as activities of entities. This would move many of the codes currently on line 4 of the graph into lines 3, 5, and 6. As discussed in the Methods section above, however, the LAs move fluidly between describing forces as interactions and describing them as entities; this makes it challenging to consistently code forces according to the language used by the

LAs, particularly in instances where the language is ambiguous due to missing words or incomplete sentences.

5.2. Research Question 2: Characterizing Chaining

In this section we will respond to Research Question 2: What does chaining look like in this context?

Chaining shows up in various formats throughout our analysis. We categorized chaining statements according to their features in section 4.3:

- Conditional statements chaining
- Short pause chaining
- Questioning chaining
- Back-to-back chaining
- Overlapping chaining
- Multi utterance chaining
- Collaborative chaining

Referring to Figure 4.1, chaining is graphed on line 7. Both individual and collaborative chaining are interspersed across the whole hour of coded video. Also, chainings are clumped, whereas collaborative chainings are fairly evenly spaced out. Most clumps of individual chaining seem to start with a collaborative chaining.

5.3. Research Question 3: Identifying Collaborative Chaining

In this section we will respond to Research Question 3: Do LAs engage in collaborative chaining? If so, what does this look like? How often does collaborative chaining take place? How does collaborative chaining emerge from the group discussion?

Our analysis has identified multiple instances of collaborative chaining in the course of a single small-group working session during a Learning Assistant weekly preparation meeting.

To understand what collaborative chaining looks like, we have done an in-depth analysis of one episode of collaborative chaining in section 4.5. This episode of chaining takes place after a long discussion about boundary conditions and the breakthrough comes about after an instructor intervention. We believe the teacher intervention catalyzed the emergence of collaborative chaining from the group discussion.

After the teacher intervention, the LAs start using an analogy scenario. This analogy is key for them to understanding the boundary condition. It is high-level reasoning, though it does not show up as such on the Figure 4.1 as analogies are not given a sophistication level in Russ's framework (Russ, Scherr, Hammer, & Mikeska, 2008) high-level analogy is followed by one collaborative chaining and one individual chaining immediately after.

In our data, out of 51 Chaining codes, a total of 15 are collaborative. From the time the LAs start discussing the tutorial, the first coded statement is at 4:46 and the first chaining occurs at 8:56. This is a collaborative chaining, and is immediately followed by an individual chaining at 9:01.

The fact that the first chaining is a collaborative one is interesting: the first time they reach the most sophisticated level of reasoning, they do so collaboratively. After that, the collaborative chainings are approximately equally spaced out across the rest of the session (see Figure 4.1).

5.4. Limitations

Demonstrating that collaborative mechanistic reasoning is causally related to the well-established impact of interactive instruction on student learning is beyond the scope of this study; however, the fact that this phenomenon does occur is one step toward investigating it as a possible mechanism by which interactive engagement instruction produces more student learning.

Our coding was based primarily on the transcript of LAs' utterances, with some annotations we added about gestures. We chose to add gestures to the coding when they occurred during or immediately following an LA utterance; thus, we may have missed some meaningful gestures.

Because of limitations in the MAXQDA software, we could not give the same code twice to an individual statement in the transcript, even if it happened twice or more during that statement. Thus, some repetitions of existing codes may have been omitted.

In some examples of chaining, it was difficult to determine whether the chaining was collaborative or individual, because more than one LA repeated the same concept. For example, in the transcript shown in Table 5.1 the second utterance by Travis contains both the link ("and then") and the conclusion of a chaining about forces on two blocks from the last page of the tutorial. Identifying the first statement in the chaining is not straight-forward: both Travis (in the first line of the table) and Mark (in the third line of the table) express the first part of the reasoning. Therefore, we can't determine whether Travis is chaining from his own statement or from the more recent statement made by Mark. In this case, we categorized this as individual chaining (see Appendix C) in order to be conservative about our claims of collaborative chaining; however, we cannot rule out collaboration in the construction of this chaining. Therefore, our count of collaborative chaining events is a lower bound on the number of such collaborations.

IV. Determining the existence and direction of friction forces

Block A is on top of block B, which is on a table. In each of the five cases depicted below, a person is pulling a string that is attached to one of the blocks. In the first four cases, block A does not slip on block B. Draw an arrow to represent the direction of the friction force described in each column of the table, and indicate whether it is *static* or *kinetic* friction. If any friction force is zero, write “0”.

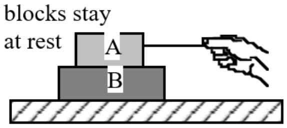
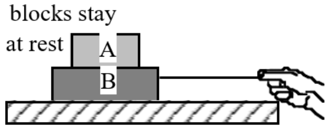
	Directions of friction forces:		
	on A by B	on B by A	on B by table
blocks stay at rest 			
blocks stay at rest 			

Figure 5.1. Friction Force Direction

Table 5.1. Ambiguous Chaining

Student	***Statement***
Travis	On A by B, is pulling it, B’s pulling it to the left.
Alex	Yeah, it’s going left on that one. So, that’s left on the other one. On B by table.
Mark	Wait, on A, by B should be to the left direction, right?
Travis	And then, on B by A that would have to be to the right?

5.5. Future work

While collaborative chaining is the only code that can be tagged as a collaboration between multiple LAs, the entire hour of small group discussion was highly collaborative. Our current analysis does not show how the LAs collaboratively constructed reasoning at other levels (e.g., collaboratively constructed animated models); nor can in identify individual chaining that may have been inspired by ideas expressed by others in the group. Additional analysis techniques will be needed to document this more extensive collaboration.

Table 5.2 combines the data from Table 4.1 and Table 4.3. As shown in the table, Alex has only three individual chainings but is involved in nine collaborative chainings. This large difference in Alex's number of individual chainings and collaborative chainings is very interesting and suggests that there could be a mechanism in the group dynamic that facilitates Alex's high-level reasoning. More broadly, this raises question of whether and how each member's mechanistic reasoning might affect the other member's reasoning. Such a dynamic would be valuable for researchers to understand. However, our data cannot differentiate between this possibility and others that would have the same result; for example, perhaps Alex has few individual chainings because the conversational space is dominated by Travis, perhaps because Travis is more comfortable thinking out loud than are the other members of the group. Analysis of additional video episodes is needed in order to further explore the question of how, and to what extent, collaborative inquiry supports individual students' reasoning in physics.

Table 5.2. Collaborative Chaining Contribution

Learning Assistant	Individual Chaining	Collaborative Chaining
Travis	23	14
Mark	7	3
Nate	3	5
Alex	3	9

As described in sections 3.4 and 5.1 above, the LAs' language about forces varied between treating them as activities of entities and treating them as entities themselves, and at times the language was ambiguous. We hypothesize that talking about forces as if they are objects makes it easier to describe the various features of forces and how they relate to other forces. For the analysis presented here, we chose to code all of these statements as level 4, Identifying Activities (IA); however, in the existing coding scheme there was no coding within that to discuss aspects of forces, such as their vector nature or their relationship to other forces. A secondary analysis of IA codes we labeled as "TFE" (Treating Forces as Entities) may help us understand the circumstances under which students chose this language rather than the language of forces as activities as entities. This analysis could lead to a more elaborated coding scheme that could include, for example, properties of activities and orientations of activities, in order to capture the complexity of reasoning involved in these scenarios.

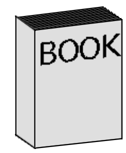
One unexpected phenomenon that emerged from our analysis was LAs' use of "teacher-hat" language during discussions. For example, during the episode analyzed in section 4.5, Alex brings the group's attention back to a particular conceptual issue by asking *"What if, what if they [students] said, what if they asked, Why aren't they equal?"* The issue under discussion is the magnitude of the static friction force and how it compares to the maximum static friction force given by the equation $F_{book,sandpaper}^{fsmax} = \mu_s F_{book,sandpaper}^{N}$. Before Alex's question, the group had agreed that that the magnitude of the static friction force was less than this maximum, but had not articulated reasoning for why that was the case. The other LAs were prepared to move on to the next question in the tutorial; Alex makes a bid to come back to this reasoning by posing his question in terms of what students might ask when the LAs assist them during classroom instruction. We refer to this as “teacher-hat” language because it explicitly raises the issue of anticipated student questioning when the LAs are in their instructional role. Our preliminary analysis of this phenomenon suggests that LAs use teacher-hat language to push the group to do higher level reasoning. In future work we will explore this phenomenon in more depth.

APPENDIX SECTION

APPENDIX A: FRICTION AND TENSION

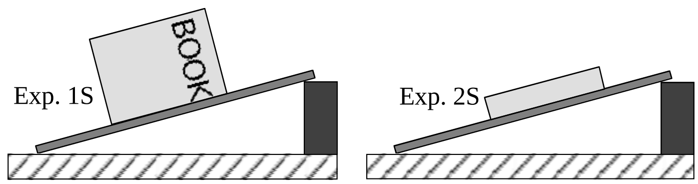
I. Surface Area

A. A student (named Sean) performs a few experiments with a book and a wooden incline. The book is shown in perspective at right.



In Experiments 1S and 2S, Sean places the book on the incline in two different orientations, as shown. In each case, the book remains at rest.

1. Discuss with your group: Is the magnitude of the friction force on the book in Experiment 2S *greater than, less than,* or *equal to* the magnitude of the friction force on the book in Experiment 1S? Explain.



2. If you have not already done so, draw a free-body diagram for the book in each experiment, 1S and 2S.

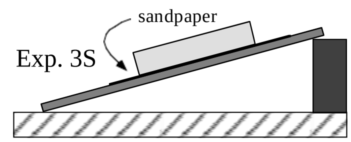
3. If you have not already done so, think about why someone might think the magnitude of the friction force in Experiment 2S is greater than that in Experiment 1S, regardless of whether you agree.

4. Write your final answer to question 1 here. How would you describe your thinking about the reasoning in question 3? Did you override it, or did you reconcile your own reasoning with it?

II. Coefficient of static friction

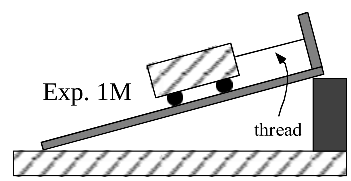
A. Sean now performs Experiment 3S. Experiment 3S is exactly the same as 2S, except that, in 3S, Sean has attached sandpaper to the part of the incline directly beneath the book.

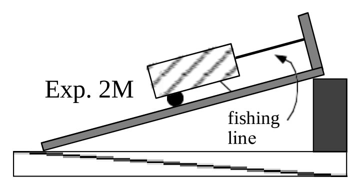
1. Discuss with your group: Is the magnitude of the friction force on the book in Experiment 3S *greater than, less than,* or *equal to* the magnitude of the friction force in Experiment 2S? Explain.



B. Another student, Mila, performs two experiments, 1M and 2M. (Mila and Sean are using different sets of equipment.) In Experiment 1M, Mila has put a cart with very good wheels on the incline. The cart does not roll down the incline, because she has tied a thread to the cart and to the top of the incline. Experiment 2M is the same as Experiment 1M, except that the thread is replaced by much stronger fishing line.

1. Is the magnitude of the tension force on the cart in Experiment 2M *greater than, less than,* or *equal to* the magnitude of the tension force on the cart in Experiment 1M? Explain.





C. The label on the package of fishing line says "20 lbs. test strength." What do you think this number means? Does the number 20 tell you how much the fishing line is pulling in Experiment 2M? Explain.

D. Reconsider Experiments 2S and 3S.

1. Is the magnitude of the friction force on the book in Experiment 3S *greater than, less than,* or *equal to* the magnitude of the friction force on the book in Experiment 2S? Explain. (Draw a free-body diagram if you think it will help you think.)

E. Suppose that the coefficient of static friction (μ_s) between the book and the sandpaper is 0.75. Suppose also that the normal force on the book by the incline in Experiment 3S is 8N.

1. Another student, Paula, multiplied 0.75 by 8 N to get 6 N. How would you interpret the number 6 in this instance? Explain.

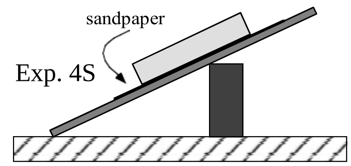
2. Is the friction force on the book in Experiment 3S *greater than, less than,* or *equal to* 6N?

F. Explain in your own words how Sean putting in the sandpaper was analogous to Mila replacing the thread with fishing line.

III. Increasing the angle of the incline

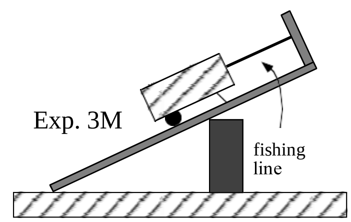
A. Sean now performs Experiment 4S. In Experiment 4S, he moves the block that supports the incline so that the incline makes a larger angle with the horizontal. The book remains at rest on the incline.

1. Discuss with your group: Is the magnitude of the friction force on the book in Experiment 4S *greater than, less than,* or *equal to* the magnitude of the friction force on the book in Experiment 3S? Explain.



B. Mila performs Experiment 3M. In Experiment 3M, Mila moves the block that supports the incline so that the incline makes a larger angle with the horizontal.

1. Is the magnitude of the tension force on the cart in Experiment 3M *greater than, less than,* or *equal to* the magnitude of the tension force on the cart in Experiment 2M? Explain.

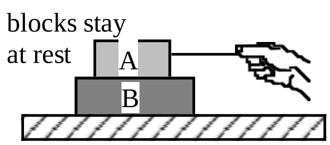
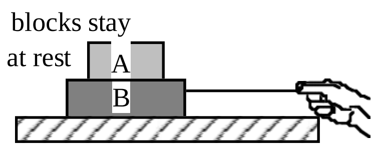
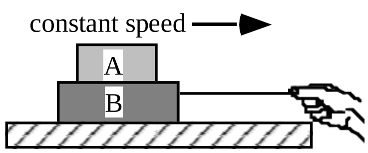
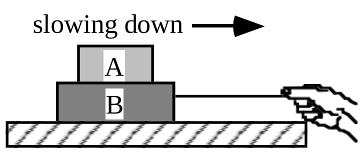
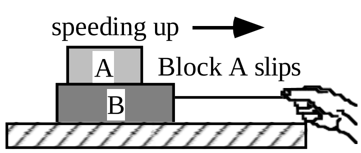


C. Reconsider Experiments 3S and 4S.

1. Is the magnitude of the friction force on the book in Experiment 4S *greater than, less than,* or *equal to* the magnitude of the friction force on the book in Experiment 3S? Explain.

IV. Determining the existence and direction of friction forces

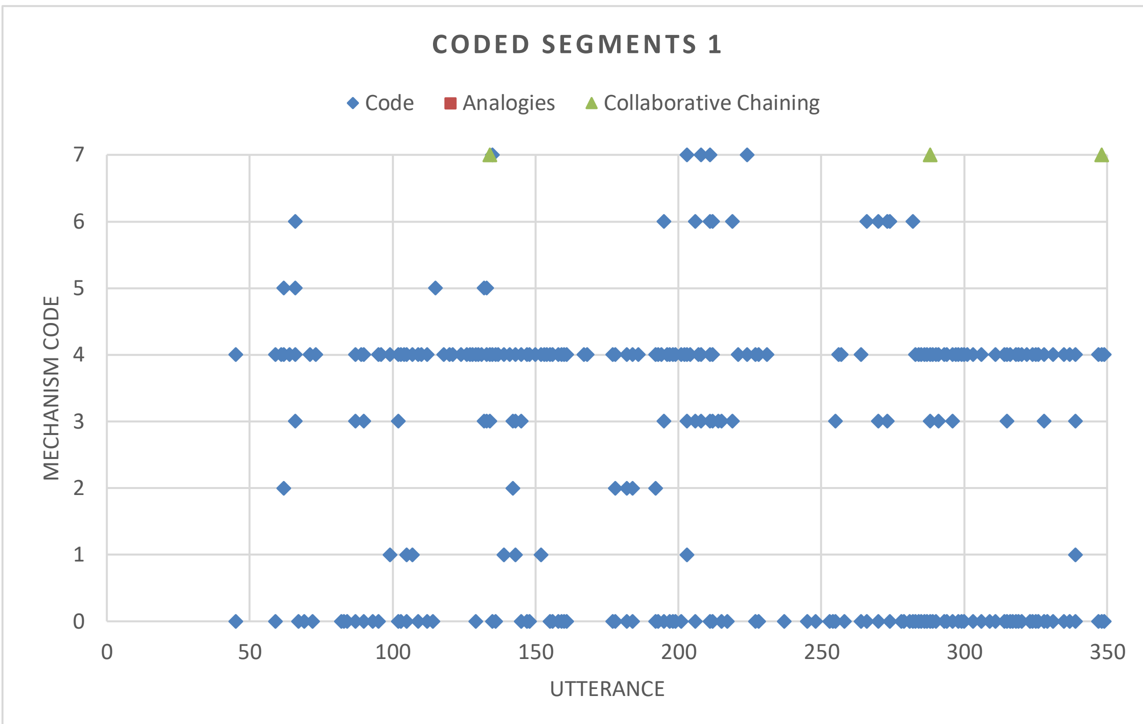
Block A is on top of block B, which is on a table. In each of the five cases depicted below, a person is pulling a string that is attached to one of the blocks. In the first four cases, block A does not slip on block B. Draw an arrow to represent the direction of the friction force described in each column of the table, and indicate whether it is *static* or *kinetic* friction. If any friction force is zero, write "0".

	Directions of friction forces:		
	on A by B	on B by A	on B by table
			
			
			
			
			

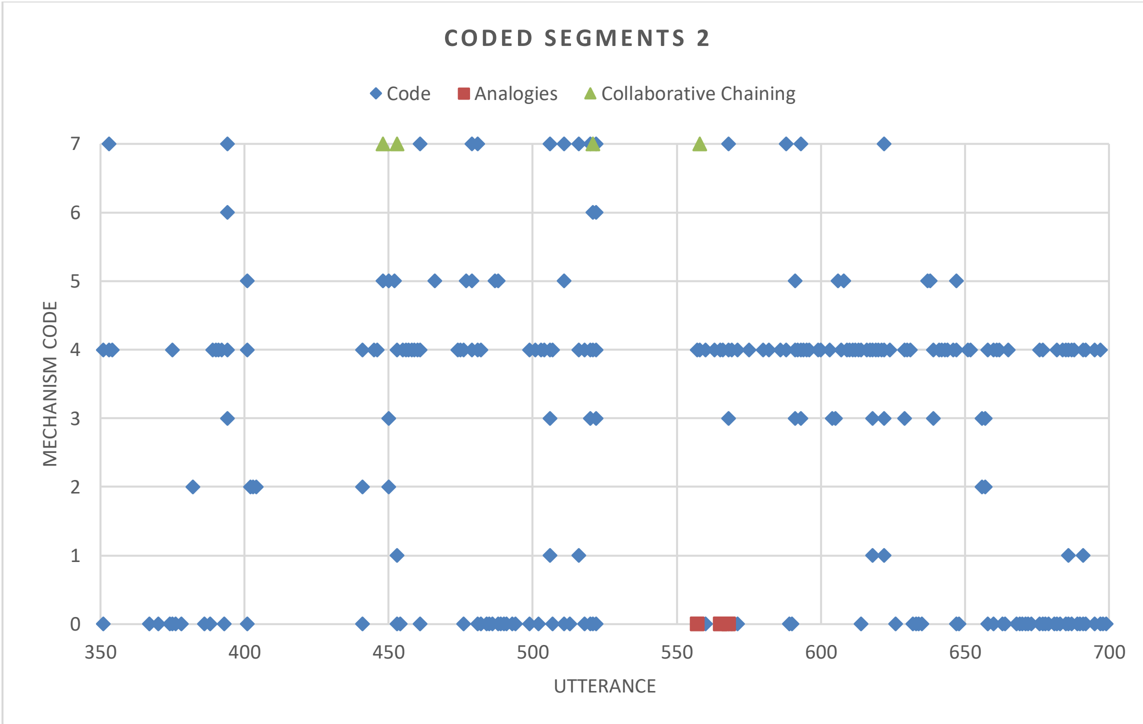
Sometimes people say that "the friction force always opposes the direction of motion." Depending on how the statement is interpreted, you can find counterexamples to it in these scenarios. What is the interpretation and what are the counterexamples?

APPENDIX B: MECHANISM CODING OF LAS CONVERSATION

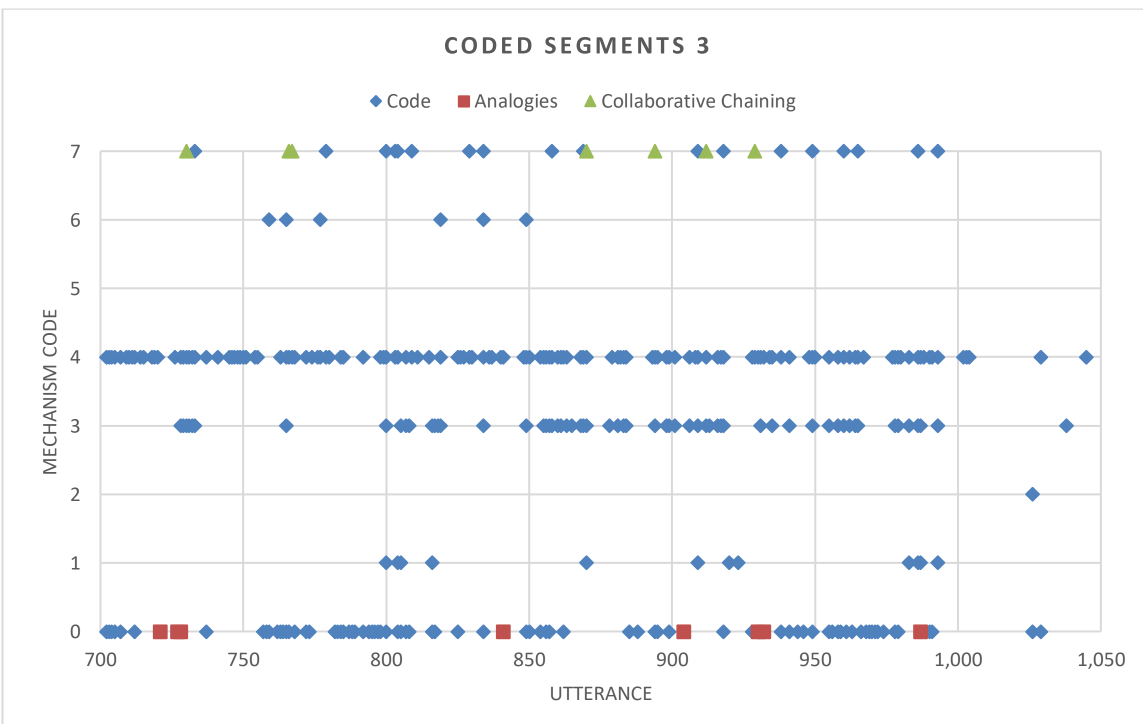
In the following graphs the numbers on the vertical axis represent the codes as follows: 0- Animated Models (AM) and Analogies (A); 1- Describing Target Phenomenon (DTP); 2- Identifying Setup Condition (ISC); 3- Identifying Entities (IE); 4- Identifying Activities (IA); 5- Identifying Properties of Entities (IPE); 6- Identifying Organization of Entities (IOE); 7– Chaining (C)



Code Segments 1



Code Segments 2



Code Segments 3

APPENDIX C: MORE CHAINING STATEMENT DIALOGUES

Collaborative Chaining (Example 1)

Student	***Statement***
Travis	On A by B, is pulling it, B's pulling it to the left.
Alex	Yeah, it's going left on that one. So, that's left on the other one. On B by table.
Mark	Wait, on A, by B should be to the left direction, right?
Travis	And then, on B by A that would have to be to the right?

Collaborative Chaining (Example 2)

Student	***Statement***
Travis	Yeah this one is zero, right? [points at tutorial]
Alex	This one [points to tutorial], 'cause like, nothing… nothing's happening.

Collaborative Chaining (Example 3)

Student	***Statement***
Mark	Yeah. You just see like, the change. So, "another student, Mila, performs two experiments, 1M and 2M." Ready? Imma just slaughter the names. "Mila and Ciane are using different sets of equipment. In experiment one, Mila has put a cart with very good wheels on the incline. The cart does not roll down the incline because she has tied a thread to the cart and to the top of the incline. Experiment two is the same as experiment one except the thread is replaced by a much stronger fishing line. Is the magnitude of the tension force on the cart in experiment two…" this is gonna be the same just as in the previous question, it's **gonna be equal**.
Alex	Yeah, **'cause** the max...might increase, but.

Collaborative Chaining (Example 4)

Student	***Statement***
Travis	Yeah. I have my third arrow pointing **left**. [holds up paper so Mark can see it]
Alex	Yeah.
Nate	Yeah.
Mark	Oh? Why is it…
Alex	**'Cause**…

Nate	It won't… it won't, the friction wouldn't be [inaudible]
Mark	Yeah **cause** we're trying to move it to the **right** and, yeah… [gestures directions/pulling with hands]

Collaborative Chaining (Example 5)

Student	***Statement***
Mark	But AB's not moving.
Travis	I know, but if you treat it as a system and you're applying a force to the right, then there will have to be friction to the left.
Nate	To cancel it out. To keep it at rest.

Collaborative Chaining (Example 6)

Student	***Statement***
Alex	I was, I was thinking zero…
Travis	If the blocks are at rest I'm gonna say zero between them, right?
Alex	That's what I'm thinking.
Travis	Yeah.
Nate	Yeah, because there's no forces in the horizontal- to cause them to- cause friction between each other.

IOE Collaborative Chaining (Example 7)

Student	***Statement***
Travis	Cause yeah if you think **static friction**, it's always gonna be just enough to, uh, keep it in **equilibrium**.
Mark	Dang it, okay that's why, that's why. Okay.
Travis	**'cause** if you were to change this magnitude [points]…
Alex	Then it would be.
Travis	**Then** it would **start moving**. [points]
Alex	Go **upward**. [points]
Travis	Start moving up the ramp [points], and then you'd have **kinetic friction**. Instead of- [taps board] static…

Collaborative Chaining (Example 8)

Student	***Statement***
Alex	All right, so I got, I mean… it's also sorta like this one. 20 pounds test strength, that's the max. So if it is 20 pounds, if this was 20 pounds [points at tutorial document], would it still be staying there? Or would it then move?
Travis	I dunno. If it was 21 pounds…
Mark	It would break.
Alex	It would break… break
Travis	Yeah. The rope would snap.
Alex	So, like at 20 I feel like it would still stay there, right? Since it's the max.

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