A COORDINATION CLASS ANALYSIS OF COLLEGE STUDENTS' JUDGMENTS ABOUT ANIMATED MOTION

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The coordination class construct was invented by diSessa and Sherin to clarify what it means to learn and use scientific concepts. A coordination class is defined to consist of readout strategies, which guide observation, and the causal net, which contains knowledge necessary for making inferences from observations. A coordination class, as originally specified, reliably extracts a certain class of information from a variety of situations. The coordination class construct is relatively new. To examine its utility, transcripts of interviews with college students were analyzed in terms of the coordination class construct.

In the interviews, students judged the realism of several computer animations depicting balls rolling on a pair of tracks. When shown animations with only one ball, students made judgments consistent with focusing on the ball's speed changes. Adding a second ball to each animation strongly affected judgments made by students taking introductory physics courses, but had a smaller effect on judgments made by students taking a psychology course. Reasoning was described in this analysis as the coordination

of readouts about animations with causal net elements related to realistic motion. Decision-making was characterized both for individual students and for groups by the causal net elements expressed, by the types of readouts reported, and by the coordination processes involved.

The coordination class construct was found useful for describing the elements and processes of student decision-making, but little evidence was found to suggest that the students studied possessed reliable coordination classes. Students' causal nets were found to include several appropriate expectations about realistic motion. Several students reached judgments that appeared contrary to their expectations and reported mutually incompatible expectations. Descriptions of students' decision-making processes often included faulty readouts, or feedback loops in which causal net elements or readouts were adjusted. Comparisons of the interviewed groups' coordination were found to echo differences and similarities in animation judgments made by larger groups of students who were not interviewed.

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CHAPTER 1—INTRODUCTION

1.1 MOTIVATION

This dissertation examines the utility of the coordination class construct, in the context of investigating students' judgments about the realism of several different animated depictions of balls rolling along two pairs of tracks. To motivate such an examination, four questions are briefly addressed in the following paragraphs.

Question 1: What is the coordination class construct?

The coordination class construct was introduced in an article titled "What changes in conceptual change?" (diSessa & Sherin, 1998) with the claim that, in order to understand conceptual change, it is valuable to address shortcomings in our understanding of what it means to "have" a concept. A key implication of the coordination class construct is that it is profitable to consider reasoning as the application of knowledge elements much smaller than those that would be typically identified as concepts.

The coordination class construct is a model intended to describe how people recognize, or metaphorically "see", information in the world. A coordination class is a hypothetical knowledge structure that allows a person possessing it to reliably make observations and infer from them information of a certain type, in many different contexts. In the terminology of coordination classes, when a person makes observations and uses prior knowledge to make inferences from those observations, the person has performed an act of *coordination*. Possessing a coordination class for *force* (or *location*), for example, would allow a person to reliably coordinate information about forces (or locations) across a variety of situations.

Question 2: Why choose students' judgments of motion as a context for examining the utility of the coordination class construct?

Previous work, described in section 1.3.1, indicated that the two-tracks apparatuses (shown in Figure 1.1) could provide a rich arena for the study of student reasoning. They also provide a rich arena for studying students' coordination. The task of judging the realism of a set of animated depictions of motion on the two-tracks apparatuses requires extended acts of coordination; to accomplish the task, one must make several observations about each animation, decide (implicitly or explicitly) which observations lead to information useful for judging realism, and make the necessary inferences from those observations.

In the course of investigating students' judgments of the realism of animated depictions of motion on the apparatuses, it became apparent that, under slightly different circumstances, many students pay attention to different features of identical motions and come to very different conclusions about which animations depict realistic motion. This is naturally interpreted with the coordination class construct as the result of reliability problems in students' coordination; in short, students "see" the motions in incompatible ways under slightly different circumstances.

The situation of interest is complex enough to yield interesting patterns of coordination, but is simple and well-controlled enough to allow comparative analyses of students' coordination. Because the animations were created by the investigator, the external stimuli for students' observations are well-understood. This simplifies the matter of understanding students' observations. Although students' coordination is complex, the task of sorting out how students coordinate information in this situation is more manageable than it might be in many situations.

Question 3: What form does the coordination class analysis of student reasoning take?

Transcripts of interviews, in which students describe their reasoning as they make judgments about the realism of sets of motions, are analyzed with the coordination class construct. The analysis largely takes the form of identifying common elements involved in students' coordination and identifying common processes by which students coordinate information about the realism of the motions. The products of the analysis are applied to an examination of how students made decisions about the realism of the motions, and to a comparison of the coordination patterns of students from two different groups.

Question 4: What can be gained from using the coordination class construct to analyze students' judgments about motion?

The coordination class construct promises a more articulated understanding of how knowledge and observation interact, and of what it means to learn and use scientific concepts. A more articulated understanding of these issues could have several implications for teaching practice; for instance, if the elements hypothesized for coordination classes prove useful for understanding student reasoning, it may indicate that instruction based on helping students to modify those elements, or the processes by which they interact during reasoning, could be a more effective means to promote conceptual change than instruction based on other models of scientific concepts.

The coordination class construct is relatively new, and has not been well-investigated. The most important aspect of the work in this dissertation may simply be that it represents a concrete application of the construct to student data. Such an application promises to improve our understanding of the construct and its implications. If the analysis presented in this dissertation sheds light on student reasoning, it will represent progress toward resolving several issues about the application of the construct to data and will provide an indication that it is worthy of continued use.

This analysis also provides a step toward improving the theory base of PER. Closely tying results about student judgments of motion on these tracks to a cognitive model increases the probability that findings from this investigation can be informative for other situations.

1.2 OVERVIEW

As part of an investigation of student reasoning about balls rolling on tracks, students were asked to judge the realism of animated depictions of motions. A change in the presentation of the motions had a strong effect on the judgments made by introductory physics students. When shown motions with only one ball, most students made judgments consistent with focusing on speed changes of the ball. When shown two balls rolling on adjacent tracks, many students made judgments different from their one-ball judgments. In particular, many students judged one of the two-ball animations to be realistic, minutes after recognizing that the same motion contained unrealistic speed changes in the corresponding one-ball animation. Students in a psychology class did not exhibit this apparent inconsistency to the same degree as introductory physics students.

Interviews with students from an introductory physics class and a psychology class provided evidence for students' use of complex reasoning processes in judging the realism of the depicted motions. Students reasoned causally about how the shape of a track would affect the motion of a ball. Students determined which features of the animations were important for their judgments, and made observations to extract information from the animations. Students made inferences from their observations to judge the realism of each motion. For many students, the information attended to and the types of inferences made depended strongly on whether one or two balls were shown.

The processes of student decision-making in this situation will be analyzed in terms of the *coordination class* construct. As a preliminary step toward clarifying what it means to learn and use scientific concepts, DiSessa and Sherin described coordination classes (1998) as knowledge structures capable of flexibly recognizing and reading out certain classes of information (location or force, for example) in a range of situations. A coordination class contains two structural parts, a collection of *readout strategies* and a *causal net*. In the study introduced above, readout strategies are, roughly, the strategies students used to make observations about animations, and the causal net is the collection of reasoning strategies used by students to make inferences about the realism of motion depicted in individual animations. Coordination classes are hypothesized to be reliable, so that the many observations possible within one situation can lead to a single stable conclusion (*integration*) and so that the same type of information can be reliably inferred from observations made in many different situations (*invariance*). The apparent inconsistencies in student judgments about balls rolling on tracks must be accounted for in light of these two types of reliability.

Although the coordination class construct points to a more articulated description of certain types of cognition, it is relatively new and its implications are not yet well-understood. To add to understanding of the utility of the coordination class construct, this dissertation examines the adequacy of the construct for describing student decisions about balls rolling on tracks. Several questions are addressed, including questions about how viewing student data through the lens of coordination classes can structure an analysis of student reasoning, and questions about the similarities of coordination episodes for different students in the same situation, or for the same student in slightly different situations. The dissertation concludes with a report of the utility of the coordination class construct as a tool for analyzing the data available from this study. Possible changes to improve the utility of the construct, and suggestions for future study of student reasoning with coordination classes, are proposed.

1.3 THE STUDY

1.3.1 The two-tracks demonstration and previous findings

The study described here is based on a pair of physics classroom demonstrations. In each *two-tracks* demonstration, two metal balls roll along metal tracks A and B (see Figure 1.1). The major difference between the flat-valley apparatus and the V-valley apparatus is the shape of the valley on track B. When the two balls are released from rest at the left end of the tracks on either apparatus, the ball on track B (the valley track) wins the race to the right end of the tracks.

Flat-valley apparatus

V-valley apparatus

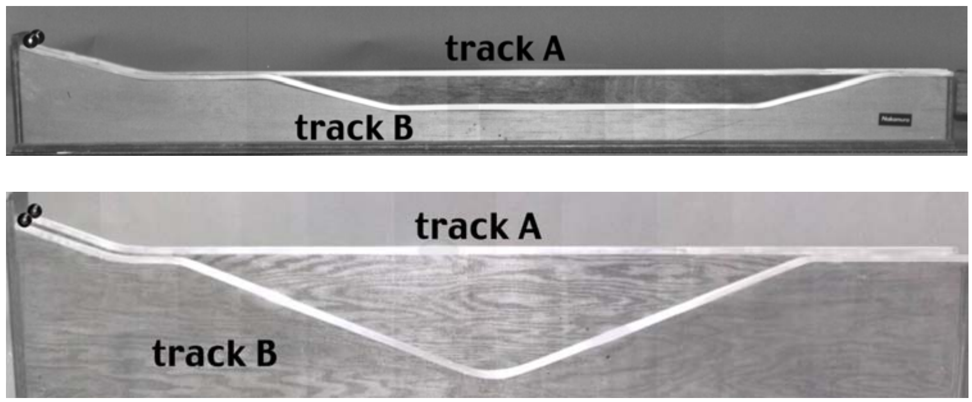


Figure 1.1 Equipment for two-tracks demonstrations, shown with a ball at the beginning of each track. The tracks are approximately 1.5-meter long.

In a previous investigation performed at the University of Massachusetts-Amherst, students in introductory physics classes were asked to predict the winner of the race for the flat-valley apparatus (Leonard & Gerace, 1996). After an introduction to the actual apparatus, but before viewing a performance of the demonstration, the majority of students in the study predicted that the balls would reach the end at the same time. Many students offered reasoning related to energy conservation to support this prediction. Even after viewing the flat-valley demonstration and discussing explanations for why the ball on track B reached the end of the track first, nearly half of the students in the investigation predicted that the race on the V-valley apparatus would result in a tie. Introductory physics students are not unique in this respect; in informal explorations of their beliefs about these demonstrations, a large fraction of educators (including physicists) have predicted that the balls should tie.

1.3.2 Preliminary investigation: Depictions of motion

Leonard and Gerace investigated student reasoning about the race outcome. The majority of students predicted outcomes that do not occur when rolling friction is kept to a minimum, as it is for the two-tracks demonstrations. These outcomes necessarily correspond to unrealistic rolling for the two-tracks situations. The investigation results raised the question of whether students could distinguish depictions of realistic motion from depictions of unrealistic motion in the two-tracks situation.

To investigate this question, five motions were developed for each set of tracks, with four corresponding to unrealistic motion and one corresponding to realistic motion. Each motion was represented in two different ways: with an animated depiction to be shown on a computer screen and with a strobe diagram, printed on paper. Only the motion of ball B varies; the motion of ball A is the same in all choices. Of the five choices for each apparatus, two result in ball A winning the race, two result in a tie, and one (the realistic motion) results in ball B winning the race. The choices for which the balls tie on the V-valley apparatus, in particular, include unrealistic speed changes. (The choices and their representations are described in detail in chapter three.)

In a preliminary investigation, a set of students in an introductory physics class who had not seen the two-tracks demonstrations was identified. The students were shown the actual flat-valley and V-valley tracks, and were then asked to identify the motion from each set of animations and each set of strobe diagrams most like the motion that would occur for real balls rolling on the tracks of the corresponding demonstration apparatus.

It was expected that students might notice unrealistic speed changes in the depictions of unrealistic motions, and might therefore choose tying motions with lower frequency in the preliminary investigation than that with which they had predicted a tying result in the Leonard and Gerace study. In contrast to these expectations, the fraction of students who identified a tying motion as most realistic in the preliminary investigation, from either the strobe diagrams or the animations, was similar to the fraction predicting a tie in the Leonard and Gerace study. Although students commented on some features of the ball motions in addition to the race outcome, many students offered reasoning related to energy conservation to support their choice of a tying motion, as they had done to support their tying prediction in the Leonard and Gerace study.

1.3.3 Primary investigation: How do students identify realistic motion?

The results of the preliminary investigation suggested that the identification of unrealistic speed changes may not have been the main consideration for students as they attempted to identify the most realistic motion for the two-tracks situation. Comparisons between the motions of balls A and B, along with the application of formal physics knowledge, each seemed to play a role in students' decisions. To further investigate questions about how students judge motions, computer animations were developed with no images of ball A, showing virtually the same motions for ball B as those used in the preliminary investigation. These will be referred to as *one-ball* animations, and the original animations will be called *two-ball* animations. Students in several large introductory physics lectures, as well as in a large educational psychology lecture, were asked to identify the one-ball and two-ball animation for each apparatus depicting the most realistic motion. Strobe diagrams were not used in the primary investigation.

For the one-ball animations, the majority of students in each course made choices consistent with having focused on the speed changes of the ball, and only a small fraction of students in any course chose the unrealistic one-ball V-valley motions that would result in a tie with two balls. For the two-ball animations, a smaller fraction of students in the educational psychology course than in the physics courses chose tying motions; in particular, the fraction of students who chose tying motions for the V-valley apparatus ranged from 20% of students in the educational psychology course to more than 60% of students in two of the introductory physics courses. These results suggest that most students can recognize some unrealistic speed changes in animations when only one ball is present, and that the observing ball A's motion may have had a larger influence on the judgments of students in the introductory physics courses than on the judgments of students in the psychology course.

The response patterns described above raise several questions about what students expect for realistic motion in the two-tracks situations and about what they observe when viewing the animations. To address these questions, individual semi-structured interviews were conducted with students from an introductory physics course and students from an educational psychology course. In these interviews, students described their reasoning while completing the one-ball and two-ball tasks for each apparatus.

1.3.4 An interpretive framework: The coordination class construct

The coordination class construct will be used here to interpret the interview transcripts and to create a model for interpreting the response patterns of students in the large lecture task administrations. The specifications for coordination classes capture some of the prominent features of students' interviews. These include:

- Developing expectations about realistic motion for the two sets of tracks with a mixture of (potentially contradictory) ideas.
- Focusing on a limited number of observations about information-dense animations.
- Judging two-ball animations differently from one-ball animations.

DiSessa and Sherin (1998) describe a *coordination class* as "a systematic collection of strategies for reading a certain type of information out from the world" (diSessa & Sherin, 1998 p. 1155). The task of a coordination class is to coordinate information that can essentially be directly observed, so as to reliably infer information that cannot be directly observed. For example, a sudden change in the speed of a moving object may be readily observed, but a change in kinetic energy cannot be directly observed. A change in the kinetic energy of the object might be inferred from the observed speed change, other knowledge about the moving object (for instance, its mass distribution and rate of rotation), and appropriate physics knowledge.

In information-dense environments, a coordination class must direct attention to the particular observations that will be useful for inferring the desired information. A coordination class consists of two major parts: the strategies used to accomplish the observations (*readout strategies*), and the resources used to make inferences with the results of those observations (*the causal net*). DiSessa and Sherin describe two types of reliability required of a coordination class: it must coordinate several different observations from one situation to arrive at a coherent set of inferences (*integration*) and it must coordinate the different types of observations available across different types of situations to reliably infer the same type of information (*invariance*). Continuing the kinetic energy example, a coordination class useful for determining kinetic energy would include knowledge about the information necessary for determining kinetic energy, readout strategies for making observations to obtain that information in a variety of different situations, and the causal net resources necessary for reliably determining kinetic energy from different types of observations in different circumstances (*invariance*). A person with such a coordination class would *integrate* the available observations to reach a stable conclusion about kinetic energy in a given situation (rather than, for example, obtaining one result when considering the rate of rotation and a contradictory result when considering the speed of the center of mass).

1.3.5 The utility of coordination classes

If the coordination class construct is to endure, it must prove useful for understanding human behavior. Analysis of the interview transcripts and interpretation of response patterns in coordination class terms will thus serve the dual purposes of illuminating student reasoning in the one-ball and two-ball tasks and testing the utility of coordination classes. Many of the issues associated with students' negotiation of the tasks in this study can be described in terms of the components and the reliability requirements of coordination classes.

- Each task involves the extraction and synthesis of perceptual information from the animations to construct a judgment about the realism of the motions portrayed; information construction is precisely the type of work *coordination classes* are supposed to accomplish.
- The animations present a great deal of information, so that students must selectively attend to the features of the animations that can be useful for making inferences about whether or not a depicted motion is realistic; this is tantamount to saying that students must select *readout strategies* that will gather information that their *causal nets* can interpret in terms of the motion's realism.
- The animations present information in the context of objects moving under the influence of gravity, the familiarity of which leads students to base their judgments on several different observations; this can be used to address the *integration* type of reliability hypothesized for coordination classes.
- Switching between flat-valley and V-valley apparatuses or one-ball and two-ball animations changes the context of the animated motions without greatly changing the motions themselves; this can be used to address the *invariance* type of reliability hypothesized for coordination classes.

1.4 GUIDE TO THE DISSERTATION

The literature review in the second chapter is primarily concerned with a discussion of coordination classes. Motivation for the use of the coordination class construct, its specifications and previous use in the literature, prior research related to balls rolling on tracks and specific findings of PER relevant to student reasoning in the one-ball and two-ball tasks are also discussed in the second chapter.

The development of the two-tracks animations and detailed descriptions of each motion are presented in chapter three. Realistic and unrealistic features of motions depicted in each animation are emphasized.

Response patterns for each task formed by the complete collection of students represented in the study are presented in chapter four, with a discussion of those patterns in terms of animation features. Response patterns for one-ball tasks are compared with those for two-ball tasks and response patterns for students from less technically oriented classes are compared with those from more technically oriented classes. This raises several issues to be addressed with coordination class analysis and sets the stage for later chapters. Also included in chapter four are descriptions of procedures for administering the tasks in large lectures and in interviews, and a description of student samples.

The main purpose of the fifth chapter is to establish connections between the vocabulary of coordination classes and segments of transcripts from student interviews. Students' expectations for realistic motion are identified as parts of their causal nets. A collection of codes for students' apparent expectations is developed, and the distribution of coding for those expectations within interview transcripts is discussed. Transcript segments describing specific readouts, and suggesting two different readout strategies, are presented.

A student's apparent expectations for realistic motion are sometimes incompatible with features of animations the student identifies as realistic. A student's judgments about an animation can be interpreted in terms of interactions among features of the animation, the student's readout strategies, and the student's causal net. Processes by which students appear to make judgments about animations are examined in chapter six, in terms of the expectations and readouts discussed in chapter five. Extended examples are used to discuss integration and invariance for some interviewed students.

The coordination class analysis is quantified in chapter seven with path diagrams that describe student decision-making in the V-valley tasks. These diagrams facilitate comparison between coordination class descriptions of student reasoning and some features of the response patterns of large groups of students, described in chapter four.

The usefulness of analyzing student decision-making with the coordination class construct is discussed in the final chapter. The importance of coordination processes, readout strategies, and coherence are particularly highlighted, in addition to students' explicitly stated beliefs about realistic motion on the tracks. Potential ambiguities in the coordination class construct and limitations of the procedures used in this study are pointed out, and possible improvements are proposed. Finally, implications of the coordination class construct and the results of this study are suggested for research and instruction, along with potential paths for future research.

CHAPTER 2—REVIEW OF LITERATURE

2.1 A BRIEF HISTORY OF BALLS ROLLING ON TRACKS

The motion of balls rolling on tracks has provided a fruitful arena for the study of dynamics, and for the study of intuitive physics. Balls and tracks provide a familiar context--even young children are unlikely to be surprised when the speed of a ball increases on its way down a slope. The context is also similar in many ways to the idealized world so useful to physicists--with easily fashioned materials and easily observable distances, the dissipative effects of friction can essentially be ignored.

Galileo observed uniform acceleration for balls rolling down inclined tracks and used an idealization of a rolling ball to deduce that, in the absence of retarding influences, an object moving along a horizontal plane would do so at constant velocity (Arons, 1990, pp. 38-42). Piaget used balls rolling on inclined and horizontal tracks to investigate processes involved in separation of experimental variables and understanding conservation of motion as a subset of formal operations (Inhelder & Piaget, 1958). Trowbridge and McDermott used balls rolling on inclined and horizontal tracks to investigate student understanding of relative position, velocity and acceleration (Trowbridge & McDermott, 1980, 1981). The interactive computer application *Graphs and Tracks* helps students make connections between motions and their graphical representations, using the example of balls rolling on tracks with varied slopes (McDermott, 1990). Several descriptions of calculations or classroom uses for balls that race along pairs of tracks, similar to the two-tracks situation used in the study reported here, have been reported (Leonard & Gerace, 1996; Schmidt & Cieslik, 1989; Stork, 1983, 1986; Tillotson, 1990).

Leonard and Gerace (1996; 1999) describe an extended classroom demonstration involving both the flat-valley and the V-valley two-tracks races. In the scheme used by Leonard and Gerace, students are introduced to a set of tracks and then asked to predict which ball would win the race if they were released simultaneously from rest. Students are given three choices: (A) ball A, on the flat track, wins; (B) ball B, on the track with the valley, wins; and (C) the balls reach the end at the same time. This task is presented first for the flat-valley apparatus. Students discuss their reasoning about the flat-valley apparatus and make a prediction, which is recorded. The demonstration is then performed, and students see that ball B wins the race. Students re-discuss and revise their reasoning about the flat-valley race. When students are satisfied that they have invented a reasonable explanation for why ball B wins the race on the flat-valley apparatus, the task is repeated for the V-valley apparatus. Leonard and Gerace report results for administration of these tasks, prior to formal kinematics instruction, in a calculus-based course for math and science majors.

For the flat-valley apparatus, 17% of students predicted that ball A would win, 11% predicted that ball B would win, and 66% predicted a tie. The remaining students, 5%, did not make a choice. Two common reasons were given by students for predicting a tie: (a) the two balls have the same speeds at the beginning and the end because energy is conserved, so they reach the end at the same time, and (b) ball B goes faster in the valley and gets ahead but then slows down coming out of the valley, allowing ball A to catch up, so the balls finish approximately together. Even after students had seen the outcome of the flat-valley race and convinced themselves that they understood why ball B won, most were not convinced that ball B would win the race for the V-valley apparatus; 18% predicted that ball A would win, 25% predicted that ball B would win, 47% predicted a tie, and 10% did not make a choice.

The original impetus for the studies presented here was to investigate the reasoning that led so many students to persist in predicting that the balls should tie in the Leonard and Gerace study. As described in the introductory chapter, a pilot study was conducted in which students were presented with a set of animated motions for balls on the two-tracks apparatuses and asked to identify the most realistic motion. Because each tying motion includes unrealistic speed changes, it was predicted that a smaller fraction of introductory physics students would identify the tying animations as realistic than had predicted a tie in the Leonard and Gerace study. Results of the pilot study did not match this prediction. Follow-up studies, presented in this dissertation, were designed to explore how students make judgments about the animated motions.

2.2 SPECIFIC FINDINGS ABOUT PHYSICS NOVICES

In research on student reasoning about physical concepts, a large number of situations have been documented in which novice students reach different conclusions than expert physicists would. Pfundt and Duit (2000) have compiled an extensive bibliography of research in student reasoning in several areas of science, including physics. A bibliography compiled by McDermott and Redish (1999) describes several studies of novice understanding in physics. In the analysis of student responses for the tasks described in this dissertation, a few specific studies of novice understanding will be worthy of special mention. They are briefly described below.

In a study reported by Trowbridge and McDermott (1980), college students observed balls rolling on pairs of tracks. One ball rolled with constant velocity along a horizontal track. The other ball rolled up an inclined track. The ball on the incline began behind the first ball but with a higher speed. It passed the first ball, and eventually slowed down so that the first ball caught up to and passed it again. Students were asked whether the balls ever had the same speed. Before instruction, several students claimed that the balls had had equal speeds at the two passing points. (This fraction was on the order of fifty percent for in-service teachers, and on the order of twenty five percent for students taking the general or calculus physics course.) Some students making this mistake specifically equated being ahead with rolling faster, being behind with rolling slower, and passing with having equal speed--in other words, these students failed to separate relative speed information from relative position information. After instruction, the fractions of students making this mistake decreased modestly for regular physics instruction and dramatically for instruction focused on helping students relate their experience to school physics concepts[1].

Several different researchers have found (see for example, Champagne, Klopfer, & Anderson, 1980; diSessa, 1993; Feher & Rice Meyer, 1992; Galili & Bar, 1992; I. A. Halloun & Hestenes, 1985) that, in some situations, novice physics students expect

1 See Rosenquist & McDermott (1987) for an instructional approach designed to help students resolve this confusion.

motion to die away in the absence of outside forces. Students have spent most of their lives observing motion in high friction situations, so it may not be surprising that students would maintain such an expectation.

In the Leonard and Gerace study described above, several students claimed that considerations of energy conservation led them to the prediction that the balls should tie. Students have been found to learn the "narrative" of transformations between kinetic and potential energy relatively easily (diSessa, 1996). Students may use the terminology of energy conservation inappropriately to claim that quantities are equal in situations where they recognize that some form of balancing may be salient. In terms of diSessa's theory of *p-prims* (discussed in section 2.3.3) this is related to student recognition of the "abstract balancing" *p-prim* in a situation (diSessa, 1993).

2.3 COORDINATION SYSTEMS

The central data for this dissertation are transcripts of interviews in which students completed the one-ball and two-ball tasks for each apparatus. In these interviews, each student made many observations of and judgments about animations; most students tried to describe the reasoning that led them from observations to judgments. The coordination class construct, discussed in this section, has been used for interpretation of the interview transcripts.

2.3.1 Motivation for coordination class construct

Numerous studies have convincingly shown that most students who take traditional introductory physics courses do not gain the solid understanding of physics concepts that their instructors might expect them to (Ambrose, Heron, Vokos, & McDermott, 1999; Beichner, 1994; Goldberg & McDermott, 1986; Hake, 1998; Hestenes, Wells, & Swackhamer, 1992). Students begin introductory physics courses with implicit and explicit ideas about the physical world, which shape what students learn in the course (Bransford, Brown, & Cocking, 1999; diSessa, 1982; Galili, Bendall, & Goldberg, 1993; Ibrahim Abou Halloun, 1985; Hammer, 2000; McCloskey, 1983; Mestre, 1994; Redish, 1994; Reiner, Slotta, Chi, & Resnick, 2000; Roth, McRobbie, Lucas, & Boutonné, 1997; Savelsbergh, de Jong, & Ferguson-Hessler, 2002; Smith, diSessa, & Roschelle, 1993/1994; Viennot, 1979). For many concepts, the sense that students make of course material bears little resemblance to the sense their instructors intend for them to make.

This has led to the realization that learning physics involves not merely the difficult task of helping students to develop physics concepts from scratch, but the even more difficult task of helping students to re-shape ideas that they have developed and used in many different situations over a long period of time. Rather than just conceptual development, physics education is now understood to involve conceptual change (diSessa & Minstrell, 1998; diSessa & Sherin, 1998; Dykstra, Boyle, & Monarch, 1992; Galili, 1996; Posner, Strike, Hewson, & Gertzog, 1982; Sinatra & Pintrich, 2002).

Conceptual change can be very difficult, and many researchers have spent significant time and energy developing and tuning instructional methods and materials to help students learn physics. Implementations of some of these methods and materials have been evaluated with a variety of techniques (Beatty & Gerace, 2002; Dancy, 2000;

Galili & Hazan, 2000; Grayson & McDermott, 1996; Hake, 1998; McDermott, 1990; Mestre, 2002; Redish, Saul, & Steinberg, 1998; Steinberg & Sabella, 1997; Touger, Dufresne, Gerace, Hardiman, & Mestre, 1995; Viennot & Rainson, 1999). Several implementations have proved successful at producing students who exhibit signs of much deeper learning than students from traditional courses (Elby, 2001; Goldberg & Bendall, 1995; I. A. Halloun & Hestenes, 1987; Hestenes, 1987; McDermott, Shaffer, & Sommers, 1994; Mestre, Dufresne, Gerace, & Hardiman, 1993; Van Heuvelen, 1991a, 1991b; Wosilait, Heron, Shaffer, & McDermott, 1998).

Nevertheless, it is difficult to claim directly that these methods and materials help students with conceptual change. Although conceptual change is widely discussed in the research literature, no consensus has been reached about what a "concept" is or what it means to "have a concept". If a stable and explicit model of "concept" can be developed, instruction for conceptual change can be developed and evaluated with that model, and claims about conceptual change can be made more coherently, efficiently, and convincingly.

2.3.2 Coordination class description

DiSessa and Sherin (1998) propose that some concepts can be modeled with a construct they call the *coordination class*. They argue that many scientific concepts shape the way we gain information about things in the world. These concepts perform several tasks to *coordinate* our perceptions of the world, in ways that might be immediate or might involve extended reasoning. Consider the following two statements about coordination classes:

> *Coordination classes ... are systematically connected ways of getting information from the world. (p. 1171)*
>
> *The difficult job of a coordination class is to penetrate the diversity and richness of varied situations to accomplish a reliable 'readout' of a particular class of information. (p. 1171)*

A coordination class is a hypothetical system whose purpose is to infer a particular type of information. Such a system could assess what features available in a particular situation could provide (directly observable) information that would be useful for making the necessary inferences. The system would include methods for observing those features appropriately. The system would also include the operations necessary for making inferences with the observed information. The system would be flexible enough to perform reliably in a variety of situations.

A coordination class has two major structural parts: *readout strategies* and the *causal net* (diSessa & Sherin, 1998). Readout strategies direct attention and gather information from the world in different situations. Wittmann (2002) describes readout strategies as filters that focus attention on meaningful elements in the world; as such, they break up the continuity of experience into chunks that can be digested and reasoned with. The causal net provides the reasoning pathways for inferences that link direct observations to the information needed. The availability of particular connections of observations to inferences, within the causal net, may result in the use of particular readout strategies. In general, coordination of information may be a complex process resulting from feedback among observations, elements of the causal net, and multiple readout strategies.

To be reliable, coordination classes must coordinate in two senses (diSessa & Sherin, 1998). The first sense, *integration*, has to do with the multiple possible observations available within one situation. There are often multiple sets of features in a single situation whose observation could lead to the desired type of information. A coordination class should be able to use those multiple feature sets to reliably arrive at a single set of inferences; if coordinating different feature sets in a single situation leads to different inferences, then there is a failure of integration. The second sense of coordination, *invariance*, has to do with coordination across multiple situations. A coordination class should reach inferences about the same type of information in a variety of situations, even if the particular set of features available for observation varies from situation to situation. If a change in context varies the type of information constructed by a coordination class, then there is a failure of invariance.

Equations, which can generate both quantitative and qualitative relationships, may be important parts of a causal net. DiSessa and Sherin (1998) caution, however, that non-quantitative assumptions about relationships are often more important to coordination than equations, and that simply identifying a causal net as a set of equations would be a mistake.

As described above, reliably getting information from the world involves several types of operations. Consistent with this range of operations, diSessa and Sherin (1998) describe coordination classes as knowledge systems--non-localized structures. A coordination class taps a large number of mental resources, potentially dispersed throughout a larger knowledge system. This means that a concept identified as a coordination class cannot have well-defined boundaries. Fuzzy boundaries make the question of whether or not a person "has" the concept very difficult to answer. It becomes more sensible to investigate the range of situations in which a person's knowledge system meets the performance specifications of a particular coordination class, and how the knowledge system behaves differently in situations where it does not meet those performance specifications. In particular, it may be interesting to determine the circumstances under which a person's knowledge system behaves like an expert's and the circumstances under which it does not. Differences between one person's knowledge system and another's, or between the person's knowledge system and an idealized coordination class, can be described in terms of readout strategies, the causal net, integration, and invariance.

DiSessa and Sherin (1998) leave open the question of whether novices, or even experts, have well-integrated and invariant coordination classes. They provide no term for a knowledge system that coordinates observations to infer other information but that fails to meet the reliability specifications that would make it a coordination class. The term *coordination system* will serve this purpose in this dissertation. The term should be understood as inclusive, in the sense that all coordination classes are coordination systems, but some coordination systems would not qualify as coordination classes. A coordination system has the component parts of readout strategies and a causal net. The coordination system can be described in terms of those components and in terms of limits on its capability for maintaining integration and invariance.

Changes in a coordination system may occur through changes in readout strategies or in the causal net (diSessa & Sherin, 1998). Changes in one component should often be driven by the other. For example, if a person believes two quantities are related, then that person might develop techniques for observing one of those quantities in order to infer the other; the causal net has driven the development of a new readout strategy. On the other hand, a person might notice something in the world and discover that it violates a relationship the person believes to be true. If this causes a change in the person's understanding of that relationship, then a readout has driven a change in the causal net.

2.3.3 The causal net for intuitive physics

DiSessa and Sherin claim that the causal net for intuitive physics has been described in earlier work by diSessa (1988; 1993), as the foundation of his *knowledge in pieces* framework. As described in this framework, the causal net for intuitive physics is a weakly organized network of primitive knowledge pieces that have been abstracted from experience. DiSessa refers to these knowledge pieces as *phenomenological primitives* (or *p-prims*). They are phenomenological in the sense that they are abstracted from phenomena that an individual has perceived. They are primitive in the sense that they are basic--*p-prims* are so obvious and self-explanatory to those who use them that they need no justification. Students implicitly use *p-prims* to invent a causal explanation for events when the *p-prims* are recognized in the situation surrounding the event. Different situations, that physicists might see as similar, may be seen as very different to novices. For a novice, features of the situation seen by the expert as unimportant may have a large effect on the strength with which particular *p-prims* are cued. For a novice, then, problems with invariance in coordination may result from making unnecessary distinctions among situations as well as from not making necessary distinctions.

DiSessa (1993) has catalogued several *p-prims*. Two *p-prims,* related to balance and equilibrium, are *dynamic-balance* and *abstract-balance*. *Dynamic-balance* is cued in situations where a person perceives that influences acting in opposite directions happen to nullify each other. For instance, the *dynamic-balance p-prim* may be cued for some novice physics students in explanations of an object in circular motion, when they claim that the action of some agent trying to pull the object inwards (gravity, or a string for example) is balanced by an outward acting centrifugal force. The *abstract-balance p-prim*, mentioned in conjunction with the inappropriate application of energy conservation in section 2.2, relates to situations where quantities are abstractly required to balance each other. Students' learning of conservation laws, such as conservation of energy, may be aided by the *abstract-balance p-prim*. Situations in which conservation laws are mis-applied may sometimes be explained, from the knowledge-in-pieces perspective, in terms of the *abstract-balance p-prim*. DiSessa (1993) describes a situation involving weights balancing at equal heights, for which students tend to apply conservation of energy inappropriately. DiSessa claims that the students recognize *abstract-balance* in the spatial symmetry of the situation and believe that a conservation law must explain the result.

P-prims are seen as resources that can be productively appropriated for learning school physics, and as remaining helpful in the causal nets of even expert physicists (diSessa, 1988, 1993; Smith et al., 1993/1994). The *p-prims* themselves are neither correct nor incorrect, but they may be recognized in situations for which they are appropriate or inappropriate from an expert physicist's viewpoint. Learning school physics is partially a matter of re-arranging the cueing structure for *p-prims*, so that they are recognized in appropriate situations and not in inappropriate ones. For example, the dynamic balancing *p-prim* is productive in understanding the forces on a book resting on a table--the upward contact force of the table on the book does, in fact, happen to balance the downward force of gravity on the book so that the book does not accelerate. The abstract balancing *p-prim* is productive in understanding situations for which conservation laws can be appropriately applied.

2.3.4 Coordination examples

DiSessa and Sherin (1998) provide several examples of coordination. These serve to illustrate properties of coordination class components and to suggest that the idea of coordination can be useful for understanding student behavior. Selected examples are reviewed below.

2.3.4.1 Coordination depends on purpose

Having just met somebody for the first time, you may wish to learn about that person's personality. Your readout strategies may focus on how the person speaks and how the person reacts to you and others. Your inferences about the person may be accomplished with a causal net that relates a person's actions and words to his or her intentions. The sorts of readouts and inferences you can make depend on the situation--

different judgments will be possible if you are playing tennis with the person, as opposed to administering a job interview.

On the other hand, consider having just met a person and then searching for that person at a party. Your readout strategies will be focused on determining the person's location by sight or sound. Readout strategies will still depend on the situation (consider searching at a masked ball as compared to a small dinner party) but will be very different than those useful for making judgments about personality.

2.3.4.2 Integration and identifying useful observations

DiSessa and Sherin (1998) use an example from Piaget's studies of children's understanding of conservation. When liquid is poured from a short wide container into a tall narrow container, young children often claim that there is more liquid in the tall container than there was in the short one. In another circumstance, the same children will claim that there is "more" in a wider container. One feature in each situation seems to dominate the readout strategies, so that there is neither integration of different possible readouts within one situation nor invariance of volume determination across situations. Children eventually learn to coordinate their readouts of width and height so that they can estimate volume in a more integrated and invariant way. In the case of pouring liquid from one container to another, the children will also learn that container shape is not nearly so reliable a readout--for deciding if the amount of liquid has changed--as is paying attention to whether any liquid is lost or added. Determining which sets of features may be reliably used to aid a particular judgment in a particular situation is a central task for a coordination system.

2.3.4.3 P-prims and context dependence in coordination

The most extended example used by diSessa and Sherin (1998) revolves around transcripts of interviews in which a student, "J", attempts to coordinate information related to forces. In one episode, the topic is a finger pushing a book across a table at constant speed. At a certain point J has explicitly stated her belief that the force of the finger pushing the book forward is greater than the force of friction pushing the book backwards. Bringing J's attention to Newton's second law, $F = ma$, the interviewer sets up a conflict. J correctly interprets the equation to mean that an unbalanced force would cause an acceleration and deduces that this, combined with the idea that unbalanced force is necessary for motion, implies that constant velocity motion is impossible. J directs her attention to the possibility that the book is accelerating, and decides that it is not. To resolve the problem, she decides that $F = ma$ must not apply in this case, saying, "you know, those darn equations aren't applicable to every single thing."

This episode highlights the idea that equations cannot be equated with the causal net. The idea that an unbalanced force is necessary for motion is identified by the authors as a *p-prim--imbalance implies motion.* In this case, J thoughtfully indicates that the *p-prim* is more relevant to her coordination of force in this situation than is Newton's second law. DiSessa and Sherin claim that *p-prims* form the causal net for naive physics. The use of *p-prims* is strongly affected by context, which causes difficulty with invariance across situations. A few minutes before, in fact, J had used a different *p-prim* (*contact conveys motion*) and had claimed that forces were unnecessary for describing the movement of a piece of paper under the book.

2.3.5 Prior use of the coordination class construct

Although it represents progress toward a perspective useful for understanding what it means to learn and use scientific concepts, the only extended use of the construct except for the original article is Wittmann's (2002) analysis of student reasoning about waves. Wittmann's investigation focused on the readout strategies and reasoning resources students bring to their interpretation of wave phenomena. It was found that many student behaviors can be understood in terms of their inappropriately applying readout strategies and resources that have been productive for seeing and understanding the behaviors of objects--referred to by Wittmann as the "object coordination class"--to the study of waves, which should more properly be regarded as interactions among objects. Wittmann found that students combine the use of wave-appropriate and wave-inappropriate resources in seemingly contradictory ways. Two explanations were suggested for students' apparent self-contradiction. The first is that students piece their reasoning resources together "on-the-fly," using and discarding pieces quickly and easily. The second is that students are unaware of their use of the object coordination class, and are therefore unable to abandon it when appropriate.

Many questions are unanswered about coordination classes and how they can be useful for investigating student reasoning. Researchers making use of coordination classes must, therefore, make several decisions. For instance, implicit in Wittmann's (2002) discussion of whether students' coordination classes are robust, how students' coordination classes are created, and how students shift among different coordination classes is the assumption that students do in fact possess coordination classes. Making this assumption is taking a stance on an open question; diSessa and Sherin (1998) point out that whether novices, or even experts, possess knowledge systems that meet the performance criteria of integration and invariance has yet to be determined.

Given the apparent inconsistencies among individual students' judgments in the tasks described in this dissertation, it seems likely that the coordination systems used by many students were not invariant across the one-ball and two-ball situations. The specific findings about physics novices reported in section 2.2 provide some cues for what types of inconsistencies to expect--they are used in chapter 3 to aid descriptions of the various animations, and in later chapters to interpret students' behaviors. The tasks in this study are well-suited to investigation with the coordination class construct because they require selective readouts and inferences about motion in a limited variety of familiar settings. A coordination class analysis, however, requires several decisions about how best to apply the coordination class construct to the specific data available. Many of these decisions are addressed in chapters five, six, and seven.

CHAPTER 3—STIMULI

In the studies described here, students responded to the stimuli of computer animations depicting balls rolling on tracks. This chapter provides a detailed description of the stimuli, which is essential for making sense of students' judgments. The chapter can function as a reference for the interpretation of student behaviors described in later chapters.

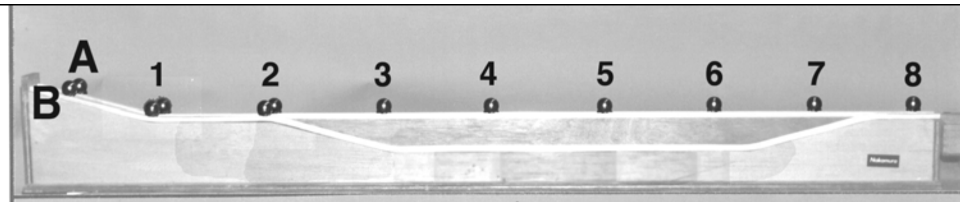
The chapter begins with a description of the process of inventing distractor motions for the non-realistic animations. This is followed by a description of some technical aspects of generating the two-ball animations. Section 3.2 begins with a set of standard labels for the sections of each track. A set of descriptions for each two-ball animation comprises the bulk of section 3.2. The creation of one-ball animations is described in section 3.3. Section 3.4 is a collection and re-description of unrealistic features found in each animation. The chapter closes with a list of the three different animation orderings, which were intended to alleviate potential ordering effects in administrations of the one-ball and two-ball tasks

One-ball and two-ball animations lend themselves to somewhat different readout strategies. The one-ball animations depict motions of ball B along the valley track, with a static background. The two-ball animations depict essentially the same motions of ball B as their one-ball counterparts, in addition to the (realistic) motion of ball A along the flat track. Students, therefore, were forced to judge the one-ball animations based solely on observations of ball B. In the two-ball animations, students had the additional opportunity to observe the relative motions of balls A and B. As discussed in the literature review, previously reported findings (Trowbridge & McDermott, 1980) indicate that novices may experience difficulty when given the opportunity to infer speed information from observations of relative motion. Both a kinematic and a comparative description are provided for each motion in section 3.2, to highlight the two readout possibilities.

3.1 GENERATING TWO-BALL ANIMATIONS

Before designing computer animations, we asked introductory physics students to complete the strobe diagrams shown in Figure 3.1. Students were told that the ball rolling across track A was shown in each strobe diagram at regular time intervals, and were asked to indicate, with numbered dots, positions for the ball on track B at times corresponding to those shown for the ball on track A (times 3-8 for the flat-valley apparatus, and times 2-8 for the V-valley apparatus). Twenty three students taking a one-semester conceptual physics course and 156 students taking the second semester of an algebra-based physics course completed the diagrams. (These students were not involved in later parts of the study.) Most responses fell into one of four categories. The names for these four categories--similar for the two sets of tracks, and based on features of ball B's motion relative to ball A--have persisted as labels for the distractor motions: (1) slow-lose [sl], (2) fast-slow-lose [fsl], (3) fast-slow-tie [fst] and (4) constant-horizontal-velocity [constvx]. The distractor motions are described in detail in section 3.2.

Flat-valley apparatus



V-valley apparatus

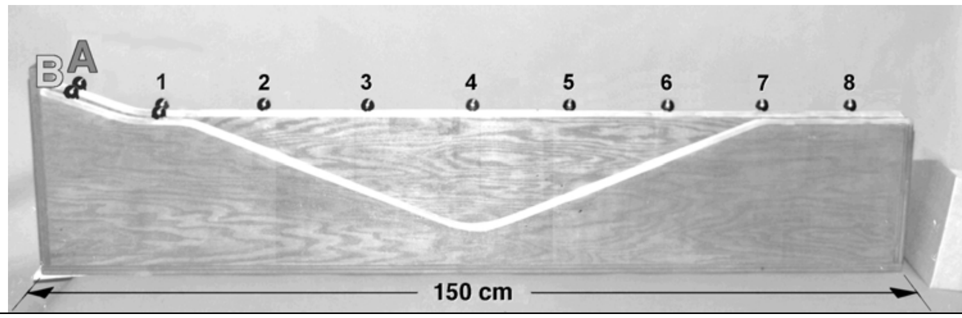


Figure 3.1 Partially completed strobe diagrams.

Two-ball animations, each depicting a motion with features of one of the four categories named above, in addition to an animation depicting realistic motion, were created for each apparatus. Each animation is a Quicktime digital movie. To make each frame of a movie, images of the ball were placed on digitally scanned photos of the tracks, using Photoshop 3.0. The movies were stitched together from the individual image-frames with QuickMovie 1.1, a Macintosh shareware application. The animations are approximately 22-cm wide on the computers used for the student tasks. For each motion, there is an animation that plays at a regular speed of 40 frames per second, and one that plays in slow motion at 20 frames per second. Ball A takes just less than two seconds to reach the end of its track in each of the regular speed animations (77 frames for the flat-valley apparatus, and 69 frames for the V-valley apparatus). Animations are viewed in a web-browser window, with a button to activate each one. Animations can be paused or stepped frame-by-frame. At the time of this writing, the animations can be accessed on the internet at <*http://www.physics.unl.edu/directory/koch/animations/*>.

3.2 ANIMATION DESCRIPTIONS

This section consists of a description of each motion for each apparatus. To standardize descriptions of ball motions, standard names for the sections of each track, shown in Figure 3.2, will often be used. Strobe diagrams, composites of several frames from each two-ball animation with numbers added to indicate increasing time, are shown in Figure 3.3 on page 38 and Figure 3.4 on page 41. Note that all interviews were conducted using the computer animation depictions of the motions represented here as strobe diagrams. In order to get a better understanding of the environment of the student interviews, the reader is urged to view the computer animations, available at <*http://www.physics.unl.edu/directory/koch/animations/*>.

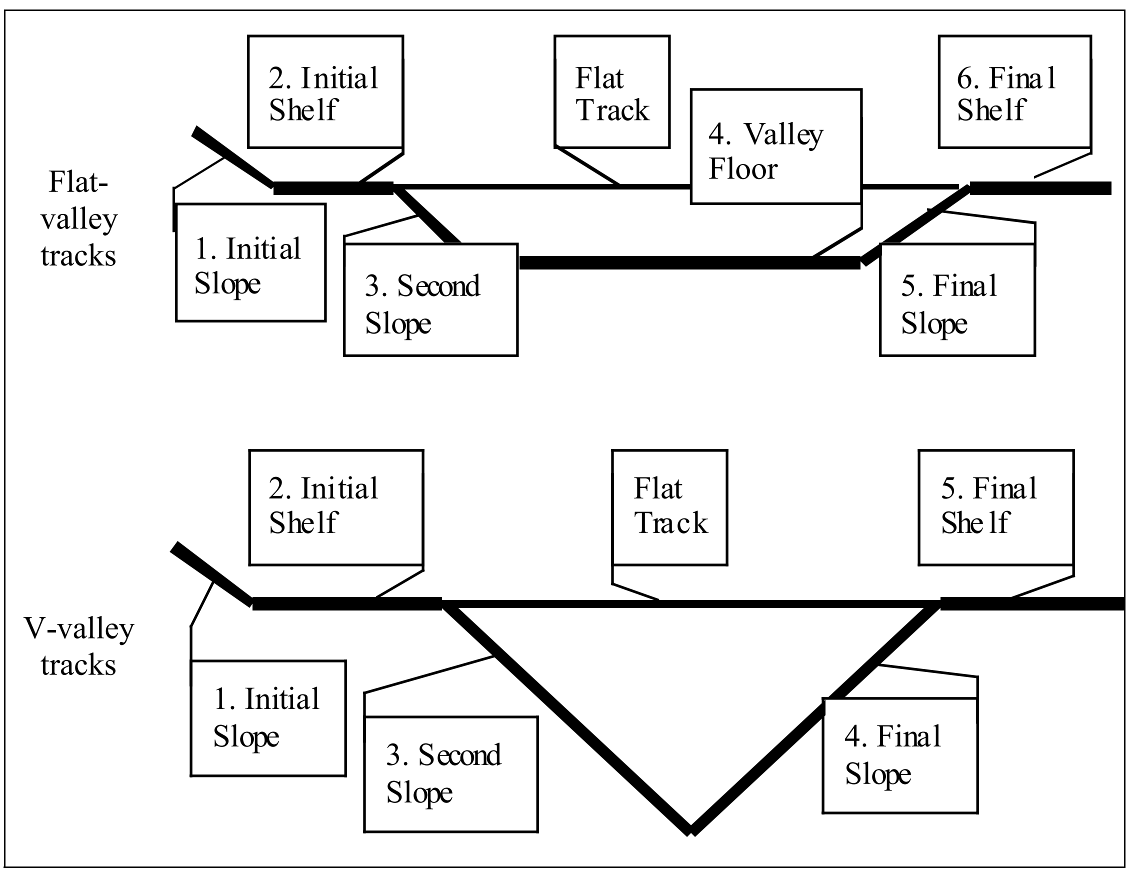


Figure 3.2 Labeled track sections.

Ball A has the same motion in all two-ball animations for each apparatus; only the motion of ball B is varied from one animation to another. In each animation, the two balls begin at rest and accelerate down the initial slope together. Ball A continues at constant speed across the flat track. Ball B continues at constant speed across the initial shelf. After the beginning of the second slope, ball B moves differently in different animations. When a ball reaches the end of its track, the animation stops.

Animation names were based on the characteristics of the corresponding categories of student-generated diagrams, as described above. The names convey a sense of ball B's progress relative to ball A. For example, in the flat-valley "fast-slow-tie" animation ball B moves *faster* than ball A at the beginning of the valley, then becomes *slower* than ball A towards the end of the valley floor, and is finally *tied* with ball A after the end of the final slope. The exception to this naming heuristic is "real", which corresponds to realistic motion of ball B on each set of tracks and is not based on student-generated diagrams.

To reflect the possibility that students may pay attention to the relative motions of balls A and B in the two-ball animations, the features of each animation are described in two complementary ways. The *comparative description* focuses on the position of ball B relative to ball A as they move across the tracks. The *kinematic description* is based solely on the speeds and speed changes of ball B.

1 "slow-lose" [sl]

2 "fast-slow-lose" [fsl]

3 "fast-slow-tie" [fst]

4 "constant v_x" [constvx]

5 "real" [real]

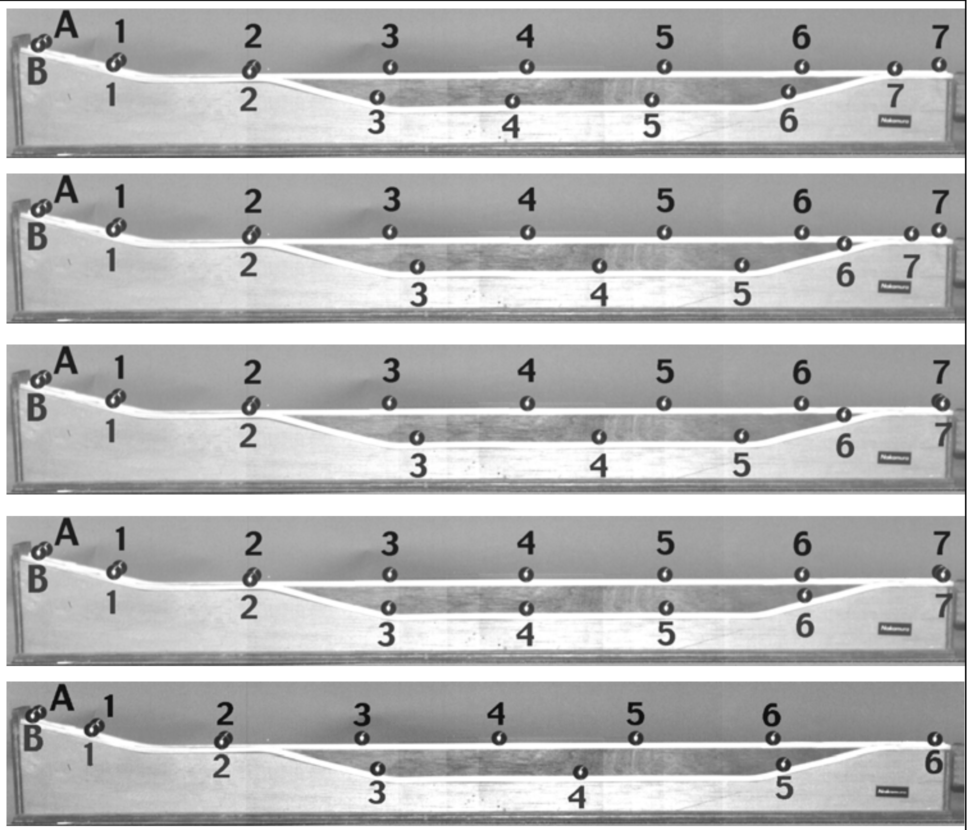


Figure 3.3 Two-ball flat-valley strobe diagrams. Gaps between ball positions correspond to ten frames in the computer animations.

3.2.1 Flat-valley-1 "slow-lose" [sl]

Comparative Description--Ball B falls behind ball A on the second slope. Across the valley floor, the separation between the two balls is constant, but the horizontal separation increases as ball B moves up the final slope. At the end of the tracks, ball A is ahead of ball B and moving slightly faster.

Kinematic Description--Ball B moves with a constant speed down the second slope and across the valley floor. Its speed decreases slightly, with a constant acceleration, as it goes up the final slope, and it moves with a constant speed across the final shelf.

3.2.2 Flat-valley-2 "fast-slow-lose" [fsl]

Comparative Description--As ball B rolls down the second slope into the valley, it speeds up and moves ahead of ball A. Ball B increases its lead across the first part of the valley floor, but slows down so that ball A is catching up as ball B moves towards the end of the valley floor and up the final slope. The two balls are tied at the end of the valley. Ball B moves more slowly than ball A across the final shelf, so that ball A wins the race.

Kinematic Description--The speed of ball B increases, with a constant acceleration, as it rolls down the second slope. The magnitude of this acceleration is matched to that of ball B down the initial slope, but adjusted for the slightly shallower angle so that the motion is realistic until ball B reaches the valley floor. Upon reaching the valley floor, ball B has an acceleration of constant magnitude directed against its motion until the end of the final slope, so that it moves increasingly slowly. Ball B rolls across the final shelf at constant speed.

3.2.3 Flat-valley-3 "fast-slow-tie" [fst]

Ball B moves in the flat-valley [fst] motion exactly as it does in the flat-valley [fsl] motion, until the two balls meet at the end of the final slope.

Comparative Description--After meeting at the end of the final slope, balls A and B finish the race together, moving at the same speed.

Kinematic Description--At the end of the final slope, there is a discontinuity in the speed of ball B; its speed increases abruptly. Ball B continues with its new speed until the end of the track.

3.2.4 Flat-valley-4 "constant v_x" [constvx]

Comparative Description-- During the entire motion, the horizontal positions of ball A and ball B are approximately equal, so that the two balls are continually tied in their race.

Kinematic Description--The horizontal component of ball B's velocity is approximately constant after the initial slope.

3.2.5 Flat-valley-5 "real" [real]

Ball B moves in the flat-valley [real] motion exactly as it does in [fsl] and [fst] until it reaches the beginning of the valley floor. It continues to move as a real metal ball does on a real metal track with negligible frictional losses, as described below.

Comparative Description--Ball B is ahead of ball A at the beginning of the valley floor, and the horizontal separation increases as ball B crosses the valley and moves up the final slope. As ball B travels across the final shelf, the separation between the two balls remains constant, with ball B ahead by a considerable margin.

Kinematic Description--Across the valley floor, the speed of ball B is constant. Moving up the final slope, ball B slows down with a constant acceleration, which is matched to its earlier acceleration as adjusted for the angle of the slope. At the end of the final slope, the speed of ball B has returned to approximately the speed it had before the valley. Ball B moves with constant speed across the final shelf.

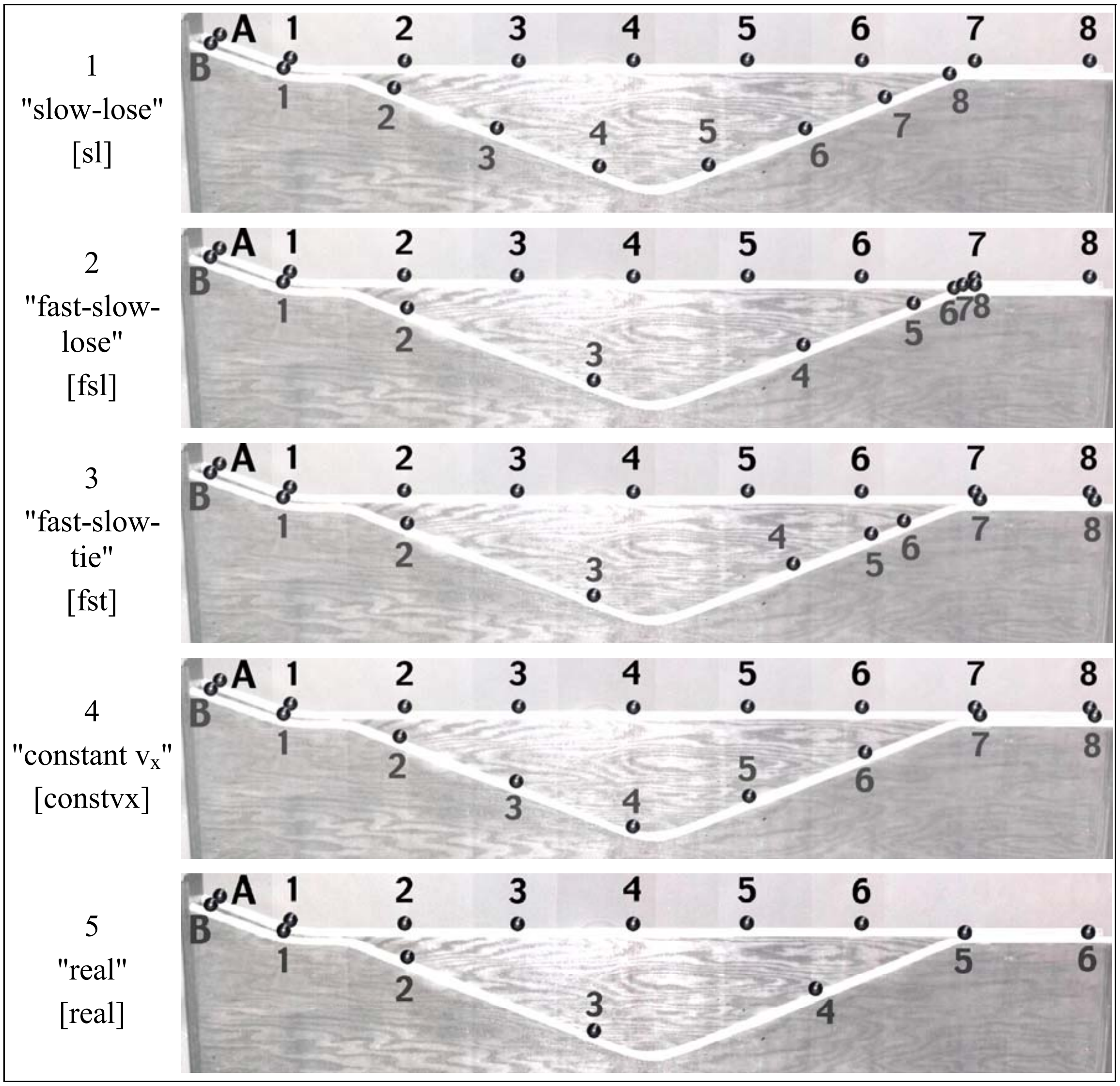


Figure 3.4 Two-ball V-valley strobe diagrams. Gaps between ball positions correspond to eight frames in the computer animations.

The five V-valley animations are similar to their flat-valley counterparts, with larger speed changes in most cases and more elaborate acceleration schemes for the [fsl] and [fst] animations.

3.2.6 V-valley-1 "slow-lose" [sl]

Comparative Description--As ball B rolls down the second slope into the valley, it falls behind ball A. The horizontal separation increases as ball B rolls up the final slope. Ball A reaches the end of the tracks just as ball B reaches the end of the final slope.

Kinematic Description--Ball B rolls with constant speed down the second slope into the valley. Its speed decreases slightly, with constant acceleration, as it goes up the final slope.

3.2.7 V-valley-2 "fast-slow-lose" [fsl]

Comparative Description--Ball B speeds up and moves ahead of ball A as it moves down the second slope into the valley. As ball B moves up the final slope, the horizontal separation between the balls initially increases; it reaches a maximum when ball B is approximately two-thirds of the way up the slope. After that point, the horizontal separation decreases until the balls meet at the end of the final slope. Ball A then leaves the much slower ball B behind and wins the race to the end of the tracks.

Kinematic Description--The speed of ball B increases, with a constant acceleration, down the second slope into the valley. The magnitude of this acceleration is matched to that of ball B down the initial slope, but adjusted for the steeper angle so that this motion is realistic until the end of the second slope. Rolling up the final slope, ball B has a time-dependant acceleration, opposite its direction of motion, that continues until it reaches the top edge of the valley. The magnitude of the acceleration at the beginning of the slope is much larger than that of the acceleration down the second slope. The magnitude of the acceleration decreases linearly in time to zero at the top of the ramp, so that the two balls are tied just as ball B reaches the end of the valley. At the end of the final slope, ball B has a small velocity directed up the slope. After the end of the final slope, the speed of ball B discontinuously jumps to a value approximately twice as large as its value at the end of the valley. The visual effect is one of ball B momentarily pausing at the end of the hill and suddenly speeding up by a very small amount.

3.2.8 V-valley-3 "fast-slow-tie" [fst]

In the V-valley [fst] motion, ball B accelerates down the second slope exactly as in [fsl]. After reaching the bottom of the slope its motion differs from that in the [fsl] animation, as described below.

Comparative Description--Ball B is ahead of ball A at the bottom of the valley, and moving much more quickly. As ball B rolls up the final slope, the separation between the balls continues to increase until the separation reaches a maximum with ball B approximately half way up the slope. After that point, the horizontal separation decreases until the balls meet at the end of the final slope. The two balls travel together at the same speed across the final shelf, and are still tied at the end of the race.

Kinematic Description--As it rolls up the final slope, ball B has a time-dependant acceleration. This acceleration was designed so that the two balls would reach the top of the valley at the same time and at the same speed. The magnitude of the acceleration at the beginning of the slope is much larger than that of the acceleration down the second slope, and larger than the corresponding acceleration in the [fsl] motion. The acceleration is initially directed against the direction of ball B's motion, but the acceleration has a constant time derivative along the direction of motion. By the time ball B reaches the end of the final slope, the acceleration is along the direction of motion. The effect on ball B's speed is that it slows down to a minimum speed near the top of the ramp, and then speeds up again while still rolling uphill. After the valley, ball B rolls with a constant speed approximately equal to its speed just before entering the valley. The visual effect is that ball B slows down quickly on the final slope and then quickly but smoothly speeds up again, while still rolling uphill.

3.2.9 V-valley-4 "constant v_x" [constvx]

Comparative Description-- During the entire motion, the horizontal positions of ball A and ball B are approximately equal; neither ball is ever ahead of the other.

Kinematic Description--The horizontal component of ball B's velocity is approximately constant after the initial slope.

3.2.10 V-valley-5 "real" [real]

In the V-valley [real] motion, ball B accelerates down the second slope exactly as it does in the [fsl] and [fst] animations. Upon reaching the bottom of the second slope slope, it continues as a real metal ball would roll on a real metal track with negligible frictional losses, as described below.

Comparative Description--As ball B rolls up the final slope, it is ahead of ball A, and the horizontal separation between the balls increases. As ball B travels across the final shelf, the separation between the two balls is constant, with ball B ahead by a considerable margin.

Kinematic Description--Moving up the final slope, ball B slows down with a constant acceleration, which is matched to its earlier acceleration and adjusted for the angle of the slope. When it leaves the valley, the speed of ball B has returned to approximately the speed it had before the valley. Its speed is constant across the final shelf.

3.3 ONE-BALL ANIMATIONS

A one-ball animation (showing only ball B) was created for each motion by removing ball A from each frame-image of the two-ball animations and compiling new Quicktime movies. Because each two-ball animation ends when the first ball reaches the end of its track, and ball A reaches the end of its track before ball B in the [sl] and [fsl] motions, a number of entirely new frames had to be created so that ball B could make it to the end of its track in the one-ball versions of these animations. (See Figure 3.5 for strobe diagrams of these four one-ball animations.) For each of these four animations except the one-ball V-valley [fsl] animation, the ball continues with constant speed to the end of the track.

In the V-valley [fsl] animations, the speed of ball B at the end of the final slope is extremely slow. In order for the animation to finish in a reasonable period of time, the ball's speed is discontinuously increased to approximately four times its speed at the end of the final slope, and the ball then accelerates so that its speed at the end of the track is approximately twice again as great--nearly nine times its speed at the end of the final slope. (Note that this is still less than half the ball's speed on the initial shelf.) The visual effect is that the ball slows down so much near the end of the final slope that it nearly pauses, abruptly speeds up at the beginning of the final shelf, and then accelerates slightly across the final shelf. Ball spacings from time 8 to time 13 of the one-ball V-valley [fsl] strobe diagram in Figure 3.5 clearly indicate these unrealistic speed changes.

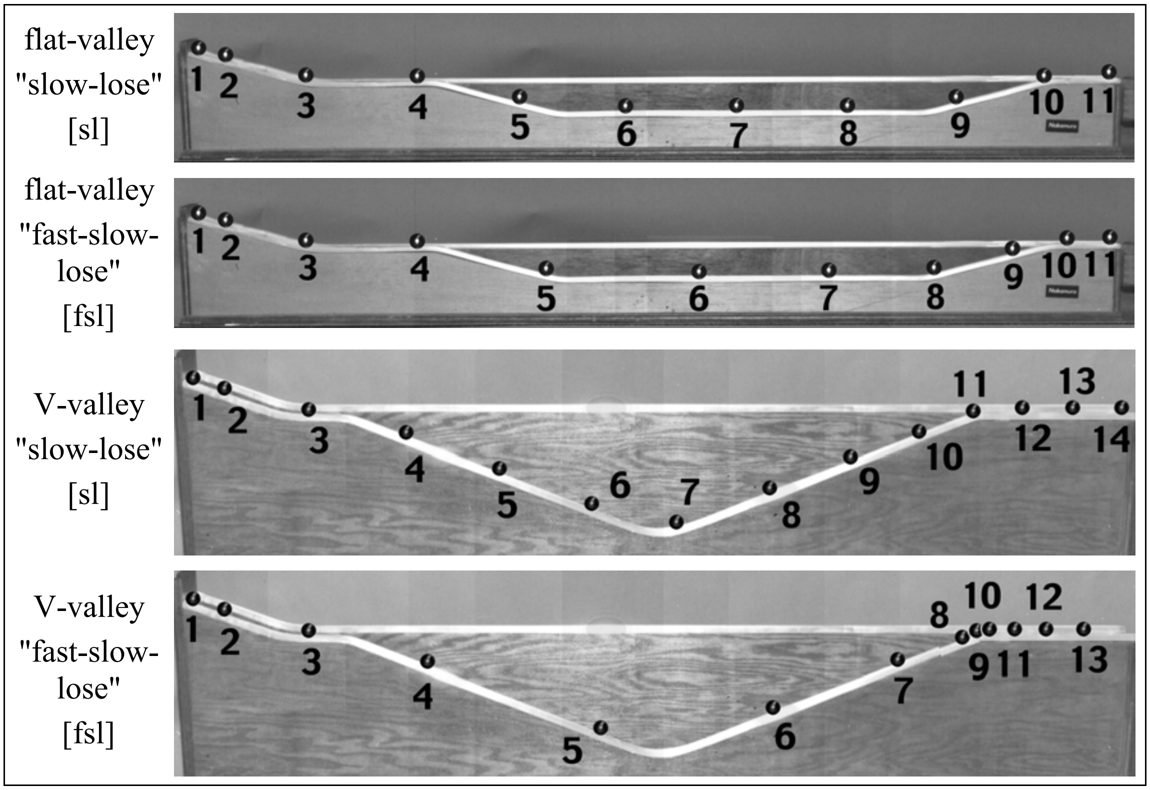


Figure 3.5 Strobe diagrams for one-ball animations with added frames.

3.4 UNREALISTIC SPEED CHANGES

Table 3.1 and Table 3.2 list the unrealistic speed changes in each animation to summarize some of the information presented above and to facilitate comparison of the motions in different animations.

Motion	Unrealistic speed changes
flat-valley [sl]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope.
flat-valley [fsl]	• Rolling across valley floor--speed decreases. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope and second slope.
flat-valley [fst]	• Rolling across valley floor--speed decreases. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope and second slope. • At beginning of final shelf--speed increases suddenly.
flat-valley [constvx]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--speed is approximately constant.
flat-valley [real]	• No unrealistic speed changes.

Table 3.1 Unrealistic speed changes in flat-valley animations.

Motion	Unrealistic speed changes
V-valley [sl]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--magnitude of acceleration is too small compared to acceleration on initial slope.
V-valley [fsl]	• Rolling up final slope--magnitude of acceleration is initially too large compared to accelerations on initial slope and second slope. • Rolling up final slope--magnitude of acceleration gradually decreases to zero by the end of the slope. • At beginning of final shelf--speed increases suddenly. • (One-ball animation only) Rolling across final shelf--constant acceleration causes gradual speed increase.
V-valley [fst]	• Rolling up final slope--magnitude of acceleration is initially too large compared to accelerations on initial slope and second slope. • Rolling up final slope--acceleration changes sign, so that the ball's speed increases as it approaches the end of the final slope.
V-valley [constvx]	• Rolling down second slope--speed is approximately constant. • Rolling up final slope--speed is approximately constant.
V-valley [real]	• No unrealistic speed changes.

Table 3.2 Unrealistic speed changes in V-valley animations.

Some distractor animations share features with motion that would be encountered in an environment with considerable non-conservative rolling friction (as if, for example, the tracks were covered in felt). The [fsl] and [fst] animations for the flat-valley apparatus are somewhat similar to motion in such an environment--the ball speeds up as it rolls down the second slope, but then begins to slow down as it rolls across the valley floor. The V-valley [fsl] animations are also somewhat similar to motion in an environment with high rolling friction--the ball speeds up as it rolls down the second slope, and then slows down in an exaggerated way as it rolls up the final slope, so that it has nearly stopped by the end of the final slope. The speed of ball B increases discontinuously at the beginning of the final shelf in the V-valley [fsl] animations and the flat-valley [fst] animations, which would be, of course, unrealistic even in the presence of non-conservative rolling friction.

3.5 ANIMATION ORDERINGS

In order to alleviate potential ordering effects (for example, students might be inclined to identify the first or the last animation as realistic), three different orderings were created for the one-ball and two-ball animations, as shown in Table 3.3 and Table 3.4. The number in the "Button number" corresponds to the labels seen in the web browser window for each animation. Orderings were kept the same for particular students so that, for example, students experiencing Ordering A for the one-ball flat-valley animations also experienced Ordering A for the one-ball V-valley animations and for both sets of two-ball animations. Students were never exposed to the heuristic names (i.e. [sl] or [fsl]) of the different motions.

Button number	**Ordering A**	**Ordering B**	**Ordering C**
1	[constvx]	[sl]	[fst]
2	[fst]	[fsl]	[real]
3	[real]	[constvx]	[sl]
4	[sl]	[fst]	[fsl]
5	[fsl]	[real]	[constvx]

Table 3.3 One-ball animation orderings.

Button number	**Ordering A**	**Ordering B**	**Ordering C**
1	[sl]	[constvx]	[real]
2	[fsl]	[fst]	[constvx]
3	[fst]	[real]	[fst]
4	[constvx]	[sl]	[fsl]
5	[real]	[fsl]	[sl]

Table 3.4 Two-ball animation orderings.

CHAPTER 4—RESPONSE PATTERNS

For the coordination class construct to be useful, features of student response patterns must appear plausible when viewed from a coordination class perspective. Response patterns from 646 students are presented here. Student samples are separated into two groups, described as Less Technical (LT) and More Technical (MT), depending on the course from which they were drawn; section 4.1 begins with a description of each student sample. Task administration procedures are also described in section 4.1. Response data are presented in section 4.2, with emphasis on the features of animations popular and unpopular with students from each group. The response data raise a number of issues related to the coordination class analysis to be pursued in later chapters. The chapter concludes with a discussion of several of these issues.

4.1 SAMPLES AND PROCEDURES

Student samples and the procedures used for gathering responses to the four tasks from each set of students are described in this section. Two sets of procedures were used in the study, those for large groups of students in a large classroom (listed as "lectures" in Table 4.1) and those for individual students (listed as "interviews"). Among the differences in procedure were that students in large classrooms were shown the animations a limited number of times in a particular order before making decisions, while students in interviews were allowed to view animations within a set repeatedly and in any order. Details, including variations within the large classroom and interview procedures for different sets of students, are provided below.

4.1.1 Samples

As shown in Table 4.1, students in two sets of interviews and in five different lecture classrooms completed the tasks. Subjects in the Less Technical group were drawn from psychology courses and an algebra-based physics course. Subjects in the More Technical group were drawn from calculus-based physics courses. All subjects were students at the University of Massachusetts-Amherst at the time of their participation.

Group	**Subgroup**	**Responses**
(LT) Less Technical	Psychology (Educational Psychology lecture)	130
	Health Science (Algebra-based Physics lecture)	173
(MT) More Technical	Engineering A (Calculus-based Physics lecture)	70
	Engineering B (Calculus-based Physics lecture)	171
	Majors (Calculus-based Physics lecture)	52
LT	Psychology (interviews)	26
MT	Honors Engineering (interviews)	24
LT Group Total		*329*
MT Group Total		*317*
Grand Total		**646**

Table 4.1 Complete responses gathered from each set of students.

Students included in the educational psychology lecture sample answered demographic questions, completed all parts of the tasks, and indicated that they had not previously seen the two-tracks demonstrations. Fifty one of the students had never taken a physics class, 69 reported taking at least one semester of physics in secondary school, and 22 reported having taken at least one semester of physics in college. One hundred of the students were female and 30 were male. Fifteen participants classified themselves as freshmen, 53 as sophomores, 34 as juniors, 26 as seniors, and 2 as graduate students.

Physics 132 is the second semester of the algebra-based 131/132 sequence, taken by pre-medical students and those majoring in other fields related to health science. Although students from a wide variety of majors, not all related to health science, take the course, this is referred to as the Health Science group. The Health Science group was split approximately evenly by gender. The projector used in the Health Scientists' course was dim, making it difficult to see the ball clearly in the flat-valley animations from some seats in the lecture hall. Animations for the V-valley tracks were clear.

Physics 151 is the first semester of the calculus-based 151/152 sequence for scientists and engineers. This is labeled the Engineers' course, although students from a variety of majors take the course. The tasks were administered in two sections of the Engineers' course, referred to here as A and B. Physics 172, labeled the Majors' course is the second semester of the calculus-based 171/172 introductory sequence taken by physics majors. Students in section A of the Engineers' course completed the tasks during the first week of the semester, before any physics content had been covered. Several weeks before completing the animated one-ball vs. two-ball tasks for this experiment, the majority of subjects from section B of the Engineers' course had completed a static (strobe diagram) version of the one-ball vs. two-ball task. In each section of a calculus-based physics course, approximately 75% of respondents were male.

At the time of the task administration, the two-tracks demonstration had not been used in any of the physics courses from which students were drawn, and it had not been used in the previous semester of either the Health Scientists' or the Majors' sequence. Students in section A of the Engineers' course had not encountered, at least in a post-secondary physics course, any of the physics content necessary for analyzing the two-tracks situations. Students in the other three sections had completed units covering kinematics, Newton's laws, and conservation of energy either in their current semester (in the case of section B of the Engineers' course) or in a previous semester (in the case of the Health Scientists' and the Majors' courses.) These units include an array of concepts that could be used to analyze motion in the two-tracks situations.

Nineteen males and five females from the honors section of the first semester calculus-based physics course volunteered to be interviewed. This was the honors section of the Engineers' course, described above. All interviews took place late in the semester, after the students had studied kinematics, Newton's laws, and conservation of energy. Six males and twenty females taking a psychology course volunteered to be interviewed. Twenty psychology students had completed at least one semester of physics in either high school or college, and six had not. Two additional physics interviews and one psychology interview are not included in the data set because the students involved had previously seen the two-tracks demonstration in a physics course.

4.1.2 Large classroom procedures

For each set of students, the two-tracks apparatuses were described first. Either the actual apparatuses were shown, with no balls available for rolling, or a picture of each apparatus was displayed using an overhead projector. The presenter pointed out that the two tracks in each apparatus had the same beginning height and the same ending height, and that the tracks and balls were made of metal. Students were told that they would be shown several computer animations of balls rolling on each apparatus, and asked to identify the animations depicting motion most like what real metal balls would do on the real tracks. Choices for most realistic animation were gathered for the four sets of animations in the following order: one-ball flat-valley, one-ball V-valley, two-ball flat-valley, and two-ball V-valley.

In the large classroom administrations of the tasks, computer animations were projected on a screen at the front of a lecture hall. Within a set, each of the five animations was played at the regular speed first. After they had all been played, the slow speed animation was played for all five, and then the regular speed animation was played again for all five motions. Students responded individually, with an electronic classroom communication system in some classes and bubble sheets in others. This procedure took approximately fifteen minutes. Demographic information was collected from the educational psychology students.

Psychology student participants received research participation credit. Students in physics classes were not compensated for their participation in the study. The author and four physics professors presented the tasks to large lecture classes.

4.1.3 Interview procedures

Interviews were semi-structured and open-ended. The introduction to the interview tasks was similar to that for the large lecture tasks, using a picture of each demonstration apparatus to describe its features. After describing the first task, the interviewer pointed out controls for the animations and demonstrated their use. Students were given a chance to ask questions, and were then given control of the computer. Students were encouraged to think aloud as they looked through the computer animations and made their decisions.

In contrast to the large classroom procedure, where the presenter controlled the order and pace of animation viewing, interviewed students could run animations within a set (for example, the one-ball flat-valley set of animations) as many times as they liked and in any order. They were provided with no physical resources for record keeping, although interviewers occasionally helped students keep track of which animations they had ruled out. Students were not allowed to change responses after moving on to a new set of animations.

Students were asked, either during the process of making decisions or afterward, to explain their reasons for choosing or rejecting particular computer animations. Because too much thinking out loud could distract some students, interviewers made judgments for each student about how much to prod for reasoning. A rule of thumb was that the student should have indicated reasons for (a) ruling out four of the five animations as less realistic than the fifth, or (b) "ruling in" one of the five animations as realistic. Interviewers were careful not to indicate whether student reasoning was correct or incorrect. Students were often asked to provide a description of, repeat, or elaborate on their reasoning about particular animations.

Physics students (from the honors section of the Engineering course) received nominal monetary compensation for their participation, and psychology student interviewees received research participation credit. The author and two physics professors conducted interviews with physics students, and a senior undergraduate physics major conducted interviews with psychology students.

Interviewers took brief notes about each student's decision-making and recorded the final choice for each task. Only these notes are available for the first twelve physics student interviews; the twelve subsequent physics student interviews, and twenty four of the twenty six psychology student interviews, were recorded on audio tape and transcribed.

4.2 FINDINGS

The purposes of this section are to present response patterns and to point out some issues related to coordination classes. Emphasis is placed on animation features and comparisons between one-ball and two-ball response patterns for the LT and MT groups. Discussed in particular detail are the fractions of students from each group choosing animations in which two balls reach the ends of their tracks simultaneously. The final sub-section points to several issues to be addressed in later chapters with the coordination class analysis of interview transcripts.

4.2.1 Flat-valley response patterns

Response patterns for the flat-valley tasks, for Less Technical and More Technical students, are presented in Figure 4.1. To facilitate the making of connections between computer animation features and student choices, a chart of selected unrealistic features for each flat-valley animations is provided in Table 4.2. Qualitatively unrealistic speed changes (for instance, accelerations with unrealistic directions) are included in Table 4.2. Accelerations with realistic directions but unrealistic magnitudes (for instance, the small magnitude of the acceleration on the final slope in the [sl] animation) are excluded from the chart. With the exception of race results, one-ball and two-ball flat-valley animations with the same label contain the same deviations from realistic motion.

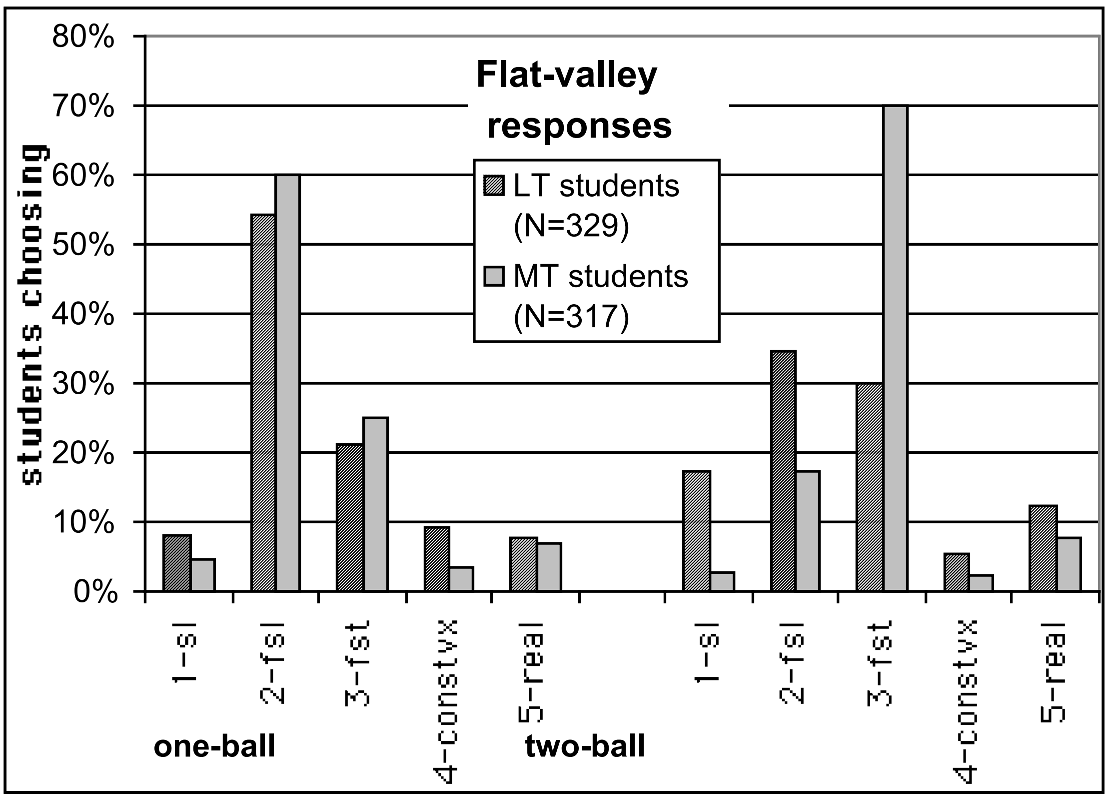


Figure 4.1 Responses to one-ball and two-ball flat-valley tasks.

As shown in Figure 4.1, the [fsl] and [fst] motions were much more popular than the other three motions in the one-ball flat-valley task, with [fsl] much more popular than [fst]. LT and MT response patterns were similar for the one-ball task. In the two-ball task, the same two animations were popular, but the number of students choosing each is roughly reversed from the one-ball task. In contrast to the LT response pattern, the two-ball response pattern for MT students is highly peaked on the [fst] animation.

Flat-valley motion	**1-sl**	**2-fsl**	**3-fst**	**4-constvx**	**5-real**
One-ball task, percent of all students choosing	7%	57%	23%	6%	7%
Two-ball task, percent of all students choosing	10%	26%	50%	4%	10%
Deviations observable in one-ball and two-ball animations					
Speed fails to increase on second slope	X			X	
Speed fails to decrease on final slope				X	
Speed decreases on valley floor		X	X		
Sudden speed increase, beginning of final shelf			X		
Slower on final shelf than on initial shelf	X	X			
Deviations observable only in two-ball animations					
Ball A wins race	X	X			
Balls A and B tie			X	X	

Table 4.2 Selected deviations from realistic motion: flat-valley animations.

As shown in Table 4.2, the only feature unique to the consistently popular flat-valley motions ([fsl] and [fst]) is that the speed of ball B decreases as it rolls across the valley floor. The popular motions also depict increasing speed when ball B rolls down the second slope and decreasing speed when it rolls up the final slope, but they share these features with the consistently unpopular [real] motion. In the two-ball flat-valley task, the two "tying" animations were identified as realistic by very different numbers of students. Similarly, [fsl] was much more popular than [sl], even though the two animations showed ball A winning the race.

4.2.2 V-valley response patterns

Response patterns for the V-valley tasks are presented in Figure 4.2. A chart of selected unrealistic features for each V-valley animation, similar to that for flat-valley animations in the previous section, is provided in Table 4.3. One-ball and two-ball V-valley animations with the same label contain the same deviations from realistic motion, with the exceptions of race results for all motions and the gradual speed change across the final slope for the one-ball [fsl] animation.

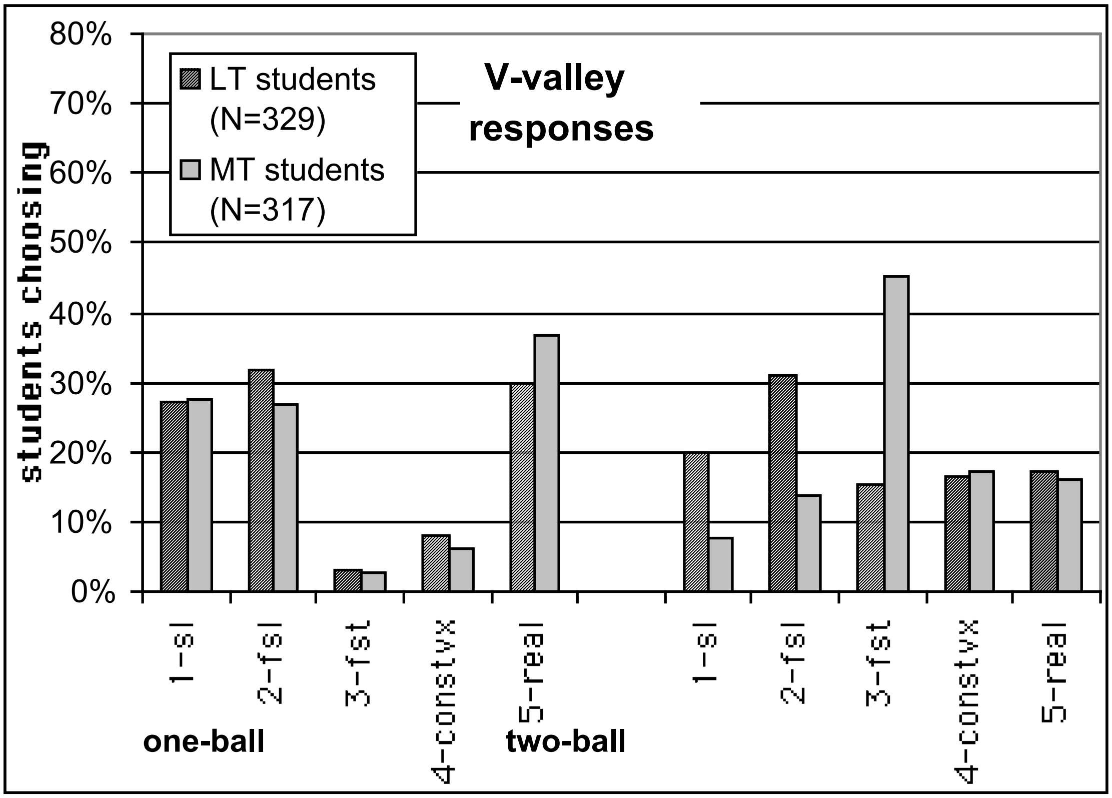


Figure 4.2 Responses to one-ball and two-ball V-valley tasks.

As shown in Figure 4.2, a small fraction of students identified the one-ball V-valley [fst] or [constvx] animations as most realistic. The majority of one-ball responses for LT and MT students were divided, approximately evenly, among the other three animations. In the two-ball V-valley task, response patterns were flatter than those in the other three tasks, with only about twice as many students choosing the most popular animation ([fst]) as the least popular ([sl]). There were differences between the two-ball response patterns for students in the LT and MT groups, however, with many more MT than LT students choosing [fst], and many more LT than MT students choosing [sl] and [fsl].

V-valley motion	1-sl	2-fsl	3-fst	4-constvx	5-real
One-ball task, percent of all students choosing	27%	29%	3%	7%	33%
Two-ball task, percent of all students choosing	14%	23%	30%	17%	17%
Deviations observable in one-ball and two-ball animations					
Speed fails to increase on second slope	X			X	
Speed fails to decrease on final slope				X	
Speed increases near end of final slope			X		
Sudden speed increase, beginning of final shelf		X			
Speed increases across final shelf		X†			
Slower on final shelf than on initial shelf	X	X			
Deviations observable only in two-ball animations					
Ball A wins race	X	X			
Balls A and B tie			X	X	

Table 4.3 Selected deviations from realistic motion, V-valley animations.

As shown in Table 4.3, no single feature is uniquely shared by the three most popular one-ball V-valley animations. Each of the two unpopular animations, however, contains a unique deviation from realistic motion on the final slope--speed fails to decrease as the ball rolls up the slope in the [constvx] motion, and speed increases near the end of the slope for the [fst] motion.

The most popular two-ball V-valley animation, [fst], includes the same deviations from realistic motion that apparently made the one-ball [fst] motion so unpopular, with the additional features that balls A and B cross the final shelf at the same speed and reach the end of the tracks at the same time. As was true for the flat-valley, the two V-valley "tying" animations and the two animations in which ball A won the race were identified as realistic by very different numbers of students. Differences in MT and LT response patterns for the two-ball V-valley task were also similar to those for the two-ball flat-valley task, with more MT students choosing tying animations and more LT students choosing animations in which ball A won.

4.2.3 Two-ball tying responses

As reported in sections 4.2.1 and 4.2.2, the fraction of students who chose tying motions in each task was lower for the LT group than for the MT group. As shown in Figure 4.3, there were also substantial differences in tying choice frequencies within the groups; students from more mathematically rigorous physics courses were more likely to choose a tying motion, especially for the two-ball V-valley task. The LT group consists of the first three student subgroups in Figure 4.3 (Psychology interviews, Psychology lecture, and Health Science algebra-based physics lecture). The MT group consists of the final four student subgroups in the figure (Engineering A, Engineering B and Majors calculus-based physics lectures, and Honors Engineering interviews).

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† In the two-ball V-valley [fsl] animation, ball B has constant speed after the beginning of the final shelf.

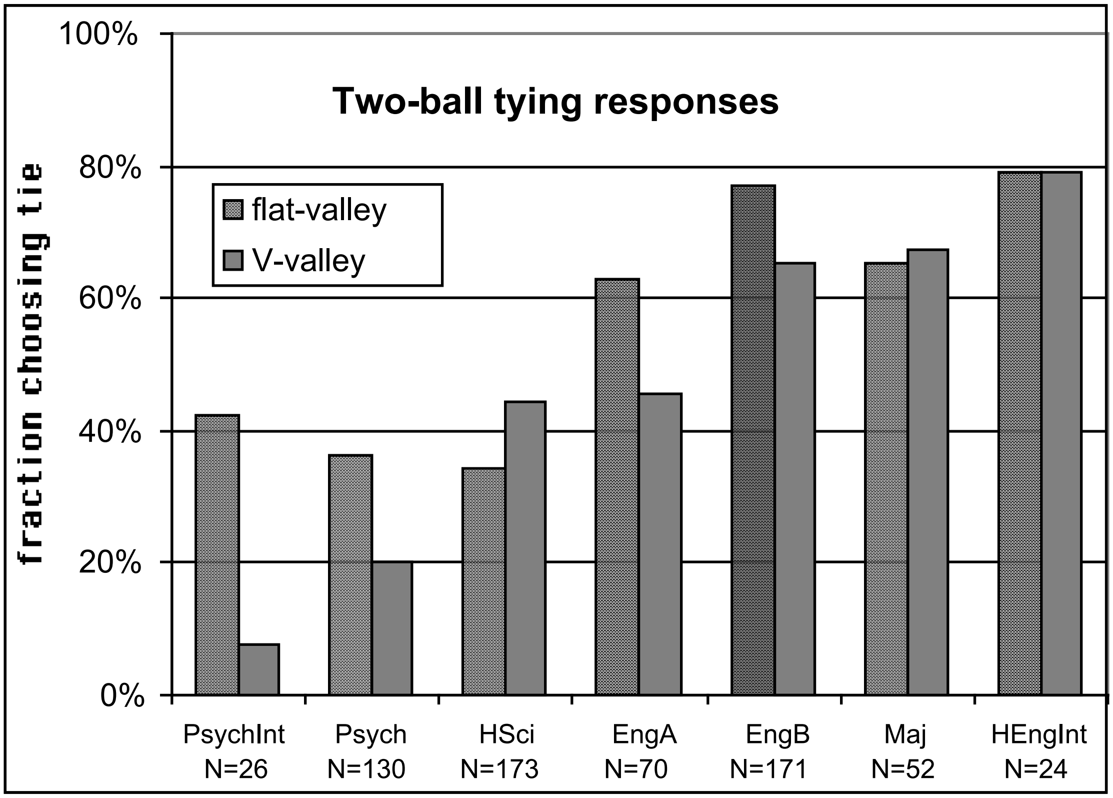

Figure 4.3 Fraction from each sub-group choosing a tying motion ([fst] or [constvx]) for each two-ball task.

The [fst] motion was relatively popular in the one-ball flat-valley task but very unpopular in the one-ball V-valley task, and the [constvx] motion was very unpopular in each one-ball task. The popularity of tying motions in the two-ball V-valley task is thus potentially more puzzling than the similar phenomenon for the two-ball flat-valley task.

4.2.4 Issues to be addressed

The structure found in the response patterns suggests that different students may have found similar ways to discriminate among the different animations. However, most students did not identify the [real] animations as depicting realistic motion. The goal of the analysis presented in the next three chapters is to understand the decision-making processes of interviewed students in terms of the coordination class construct. Among the general issues about students' coordination to be addressed are the following:

- How did students "rule in" or "rule out" animations as realistic or unrealistic? In particular, how did so many students rule out the [real] animations in favor of other animations which included deviations from realistic motion?
- To what extent does similar judgment in a task correlate with similar coordination in the task? In other words, if two students choose the same animation, do they necessarily use the same causal net elements and readout strategies, or are there distinct sets of coordination elements and processes that can lead to identical judgments?
- Can a coordination systems approach make plausible the variety of student responses?

Several comparisons of response patterns revealed differences. Between the one-ball and two-ball flat-valley tasks, the fraction of students choosing the two most popular animations ([fsl] and [fst]) was essentially reversed. The [fst] animation was chosen by a very low fraction of students in the one-ball V-valley task, but [fst] was the most popular two-ball V-valley animation. In the one-ball tasks, response patterns for the LT group were similar to those for the MT group, but this was not the case in the two-ball tasks. Students taking more mathematically-oriented physics courses were more likely to choose tying motions in the two-ball tasks, and this difference was more pronounced for the V-valley animations. Two-ball animations with the same race outcome were chosen by different fractions of students. These comparisons raise several issues, which will be addressed in the following chapters. Among these are the following:

- Did LT and MT students use similar decision-making processes in the one-ball tasks?
- How did the addition of a second ball change students' decision-making processes? Was the change more pronounced for MT students than for LT students? How can choosing animations with different features for the one-ball and two-ball tasks be understood in terms of integration and invariance?
- Did students judge two-ball animations based on the race outcome? Can exposure to school physics be used to explain an increased propensity to identify tying motions as realistic? Were some processes in students' two-ball decisions similar to processes in their one-ball decisions?
- Can a coordination systems approach make plausible the similar one-ball response patterns for MT and LT groups, while simultaneously making plausible the groups' different two-ball response patterns?

CHAPTER 5—ELEMENTS OF COORDINATION

In this chapter, transcripts of student interviews are analyzed to identify student utterances related to the two structural parts of coordination classes: causal nets and readout strategies. Some of the questions raised in chapter four can be addressed here; others are addressed in chapters six and seven.

This chapter reports the first part of an analysis of interviews with 24 students from a psychology class and 12 students from a physics class. These interviews were audio taped and transcribed, as reported in chapter four. In section 5.1, the causal net and readout strategies, discussed at length in chapter two, are re-described in terms of the present study and the analysis in this chapter. Transcript analysis related to the causal net is discussed in section 5.2. Students described several expectations about realistic motion for balls on the two-tracks apparatuses. These expectations are described and identified as causal net elements. Transcript segments are related to the various expectations, and distributions of student utterances coded for each expectation are discussed. Transcript analysis related to readouts and readout strategies is discussed in section 5.3. Students described several observations about the motion of balls. Example student descriptions of accurate and inaccurate observations are presented and related to two general strategies for observing characteristics of motion. Several students made holistic or experiential statements that inextricably combined properties of causal net elements and readouts. Examples are discussed in section 5.4. Section 5.5 provides a summary of the major findings of this chapter, addresses selected questions from chapter four, and raises new questions about how students judge the realism of animated depictions of motion on the two-tracks apparatuses.

5.1 ELEMENTS

To determine that one computer animation depicted motion more realistic than the others from each set, students had to develop expectations about realistic motion and judge motions depicted in animations against their expectations. The coordination class construct, described in chapter two, includes structural parts that highlight both students' expectations and their strategies for observing animations. Those parts, the causal net and readout strategies, are discussed in this chapter. (Interactions among causal net elements and readout strategies in decision-making, including the performance specifications of integration and invariance, are discussed in chapter six.)

The causal net can be described as "the set of inferences that lead from observable information to the determination of things that may not be directly or easily observable" (diSessa & Sherin, 1998, p.1174). In this chapter, instances in which students indicate their expectations for realistic motion are identified. Such expectations can be understood as providing pathways from observable information (a speed change, for example) to something not directly observable (whether or not motion is realistic). It may be that students develop expectations for motion on these particular tracks from other knowledge. For some of the expectations described in this chapter, evidence pointing to other knowledge is available in transcripts, but this is often not the case. In this analysis, identification and description of students' apparent expectations about realistic motion are emphasized over making claims about the sources of particular causal net elements.

DiSessa and Sherin describe the utility of readout strategies as dealing "with the diversity of presentations of information." They point out that the job of readout strategies in quantity-like coordination classes "amounts mainly to determining the value of the quantity in a particular situation" (diSessa & Sherin, 1998, p.1176). To be effective, readout strategies for tasks in this study must provide students with information they can use to determine whether or not motions depicted in animations are realistic--in other words, observations that can be compared with their expectations for realistic motion. In the interviews, students provided reports of several readouts about the animations, but provided little description of the methods (or *strategies*) they used to make those readouts. Some deductions may be made about students' readout strategies from their statements and from common errors. In this analysis, examples of students' readout reports about speed changes will be presented, and two general types of readout strategies will be identified.

5.2 THE CAUSAL NET

After initial transcript analysis, a list of expectations was created to capture the ideas most prominent in students' decision-making. Statements in which physics students indicated ideas similar to those in the expectation list were coded. Coding was carried out in a similar way for psychology student interview transcripts. Statements made by psychology students were sometimes difficult to code with a small list of expectations, as described in section 5.4. In this section, the list of expectations codes is described, and transcript excerpts coded for each expectation are presented. Counts of students whose transcripts were coded with each expectation in each task are also provided.

5.2.1 Causal net elements

The list of expectations presented in Table 5.1 represents categories of relatively common and clearly described considerations that appeared to influence student judgments about individual animations. These were divided into four major categories: speed changes across sections of the tracks, sudden speed changes, race outcomes, and miscellaneous ad hoc expectations.

Label	Brief description
Expectations about speed changes	
DECELUP	Speed should decrease when rolling uphill.
ACCELDOWN	Speed should increase rolling downhill.
CONSTFLAT	Speed should remain constant on horizontal section of track.
DECELFLAT	Speed should decrease on horizontal section of track.
SAMESPEED	Ball B should have the same speed before and after the valley.
Expectations about relatively sudden speed changes	
NOGAIN	Speed should not increase without an apparent cause.
PAUSETOP	Ball B should pause upon reaching the top of a hill.
Expectation about the balls' relative positions at the end of the race	
TIE	The balls should reach the end of their tracks simultaneously.
VALLEYWINS	The valley ball (ball B) should win the race
VALLEYLOSES	The valley ball (ball B) should lose the race
Ad hoc expectations	
MAKEITUP	Ball B should convincingly roll as if it could make it up the slope.

Table 5.1 Common student expectations (causal net elements) for realistic motion.

The DECELUP and ACCELDOWN expectations involve speed changes on slopes. The next two, CONSTFLAT and DECELFLAT are conflicting expectations about speed changes on a horizontal segment of a track. SAMESPEED involves a comparison of speeds before and after the valley. The second category of expectations, NOGAIN and PAUSETOP, deals with speed changes that occur within a short time span. The third category of expectations applies to the race outcome, with all three possible outcomes represented.

The final category in this list represents a different sort of expectation, not so clearly defined as the others. The only entry in the final category of Table 5.1 is MAKEITUP, although others could have been included (see section 5.4 for more discussion of expectations with a different character than those discussed in this section.) Statements in which students described their feelings that some motions should result in the ball rolling back down the final slope, although it was shown continuing, were categorized as relating to the MAKEITUP expectation.

The set of tables from Table 5.2 to Table 5.9, on pages 73 to 80, consist of prototypical student statements illustrating each expectation listed in Table 5.1. Each statement is identified by the pseudonym of the student who made the comment, the set of interviews (physics or psychology) in which the student participated, the task during which the statement was made, and the particular animation (if any) to which the statement refers. When students referred to specific animations they did so by number; because the same number corresponded to different animations in different tasks, the animation's abbreviated label has been added for ease of interpretation. Because it is often impossible to disentangle readout reports from statements indicating expectations, formatting has been added to the statements to help clarify where an expectation is indicated. Student's words are *italicized*. Phrases that apparently relate to expectations are also *underlined*, and phrases that apparently relate to readout reports are printed in ***boldface***. Phrases that apparently relate to both are printed in ***underlined, italicized boldface***.

ACCELDOWN and DECELUP
• Stephen, psychology, one-ball V-valley [constvx]: "*I expect it to get faster on the way down and slower on the way up…*"
• Emilio, physics, one-ball flat-valley [constvx]: "*…this **looks like it's got, um, pretty constant speed**, like it should pick up speed coming down the ramp and lose speed going up the ramp, and **it doesn't look like it does that**.*"
• Phyllis, psychology, two-ball flat-valley [fsl]: "*...number four [fsl] was the most realistic because **it gained momentum down the first hill and lost momentum going up the second hill**.*"

Table 5.2 Transcript excerpts indicating the ACCELDOWN and DECELUP expectations.

As shown in Table 5.2, students often expressed the ACCELDOWN and DECELUP expectations in close proximity, although this was not always the case. As Emilio did, students often indicated expectations for realistic motion when they believed they had been violated. The statement from Phyllis describes changes in momentum rather than speed changes, but she seemed (un-problematically, in this case) to treat speed changes and momentum changes as equivalent. Her claim that particular momentum changes make the [fsl] animation "realistic" transform her readout report about momentum changes into an indication of expectations for realistic motion; the combination also indicates a judgment about the [fsl] animation.

CONSTFLAT and DECELFLAT
• Gina, physics, one-ball flat-valley [fsl]: "... *number 2[fsl]* *is wrong because* ***it slows down on the flat part*** *and it shouldn't do that, or* ***it slows down too much*** *if it was essentially frictionless*."   • Paul, psychology, one-ball flat-valley [sl]: "*I'd expect* *it um, um like the um, um,* ***be able to visualize more that it slows, slow, almost slow down on this flat part***."

Table 5.3 Transcript excerpts indicating the CONSTFLAT and DECELFLAT expectations.

Gina's statement in Table 5.3 indicates the CONSTFLAT expectation. She apparently tied this expectation to school physics knowledge about friction as a potential cause for speed change, and appropriately expected friction to have a small effect on the valley floor. Paul's statement, on the other hand, indicates the DECELFLAT expectation. He apparently observed that the ball rolled across the valley floor at constant speed, violating his expectation. Paul did not explicitly tie his expectation to other knowledge. The DECELFLAT expectation is consistent with previous findings, discussed in the literature review, which have shown evidence for a naive expectation (or a P-prim) that motion dies away on its own in some situations (see for example, diSessa, 1993).

SAMESPEED
• Brook, physics, one-ball flat-valley (general statement): "… *my intuition tells me that it's gonna have a certain velocity at this horizontal point and a certain higher velocity at this horizontal point. And then at this point it's going to approach, call this v1 and this v2, it's gonna approach v1 again*."
• Emilio, physics, two-ball V-valley [fsl]: "*Number 2[fsl] I don't like because* ***the ball that went down and up the ramp pretty much loses all its speed once it gets to the top of the ramp*** *it should have the same speed as it did at the beginning before it went down the ramp*."

Table 5.4 Transcript excerpts indicating the SAMESPEED expectation.

In Table 5.4, Brook and Emilio indicate ideas consistent with the SAMESPEED expectation, that the ball should have the same speed before and after the valley. From the surrounding context (not shown here) it is clear that Brook intended to describe speeds on the initial shelf, the valley floor, and the final shelf of the flat-valley apparatus. Neither Brook nor Emilio indicate ties between the SAMESPEED expectation and other knowledge in these excerpts, but in other parts of their interviews both students made reference to conservation of energy as providing information about speeds at different heights. Physics students often indicated the SAMESPEED expectation and psychology students only rarely did so. Connections between the SAMESPEED expectation and energy conservation knowledge are consistent with previous findings about the two-tracks apparatus (Leonard & Gerace, 1996) and with diSessa's (1993; 1996) claims about student recognition of the "abstract balance" P-prim and application of the "narrative" of energy transformations in situations that involve height changes.

NOGAIN
• Brook, physics, one-ball flat-valley [fst]: "***It looks like it accelerates again when it gets to the top****, which is very weird. Like there's a magnet on the end or something*."
• Rosemarie, psychology, one-ball V-valley [fst]: "*2[fst] is not realistic, because it wouldn't just* ***start going fast, up hill***."
• Samantha, psychology, one-ball V-valley [fst]: "*On number 2[fst] slow,* ***it just seems like right as it almost gets to the top, something gives it a little push up****. I don't think, I don't know, unless a wind came by*."

Table 5.5 Transcript excerpts indicating the NOGAIN expectation.

In Table 5.5, student statements indicate the NOGAIN expectation, apparently in reaction to observations about sudden speed changes depicted in the flat-valley and V-valley [fst] animations. Brook's and Samantha's suggestions that the observed speed changes could be caused by an outside force missing from the two-tracks situations (such a force could be supplied by "a magnet" or "a wind") suggest connections between the NOGAIN expectation and an underlying expectation that sudden speed changes do not occur in realistic situations unless something causes them.

PAUSETOP
• Emilio, physics, one-ball V-valley [fsl]: "…*when* ***it pauses right at the top of the ramp it looks like it's got just enough, um, forward momentum to keep going, yeah once it gets to the flat level****, so I like 5[fsl]*"
• Jackson, physics, one-ball V-valley [fsl]: "*This one is right because* ***it accelerates as it's go down the gradual ramp and it accelerates more as it goes down the steep ramp, and it shows a constant deceleration as it goes up the steep ramp, a momentary stop at the point where, um, the steep ramp joins the level track and then it travels at the slower but constant speed****.*"
• Patricia, psychology, one-ball V-valley [fsl]: "*I don't know. I'm trying to picture…I mean* ***it seems like the hesitation shouldn't be as much as it is****. But I know there should be a little, I mean it's coming to, to the top of something....*"

Table 5.6 Transcript excerpts indicating the PAUSETOP expectation.

In Table 5.6, Emilio and Jackson appear to accept the "pause" or "stop" they observe at the end of the final slope in the one-ball V-valley [fsl] animation as realistic, as part of a description of the motion depicted in the animation. Physics students never indicated the PAUSETOP expectation except in the context of accepting this particular animation as realistic--for instance they never explicitly judged an animation to be *un*realistic because it was missing such a pause. By contrast, Patricia's statement seems to indicate that she expects a "hesitation" when a ball comes to "the top of something," although she was apparently concerned that the pause depicted in the one-ball V-valley

[fst] animation might be exaggerated. Interactions of readouts and expectations in student judgments of this animation are discussed further in chapter six.

TIE
• Felix, physics, two-ball flat-valley [fst]: "... *ideally, since, you know there's no real change in height because it drops and then it comes back up they should finish the same velocity at the same time*."   • Gina, physics, two-ball V-valley [fsl]: "... ***even though the ball in the front looks ok, for the same reason as the last video****, they should finish at the same time because they're both starting off with the same amount of energy ....*"

Table 5.7 Transcript excerpts indicating the TIE expectation.

In Table 5.7 are statements from two physics students indicating the TIE expectation. Felix mentions his TIE expectation in connection with observations about height changes and the SAMESPEED expectation (perhaps, again, related to the "abstract balance" P-prim and the narrative of energy conservation (diSessa, 1993, 1996)). Gina indicates a judgment that an animation is unrealistic, "even though [the motion of] the ball in the front looks ok," because the balls should tie. Neither Felix nor Gina mention their apparent assumptions that ball A, on its flat track, continues with a constant speed after the initial slope. Interactions of readouts and expectations associated with judgments related to the TIE expectation are discussed further in chapter six.

VALLEYWINS and VALLEYLOSES
• Kent, physics, two-ball flat-valley [real]: "*up to the point where they break apart they have to be going the same speed, and then* ***as it goes down the speed for the ball that goes down gets faster and faster, so for this area, it's when the whole time the balls are apart … the one that goes down is going faster, but when it comes back to here, the ball is going the same speed as the other one****, so if it was going faster for that time, then it would definitely have to be ahead of the other one*."   • Samantha, physics, two-ball flat-valley [constvx]: "*I think that the bottom one actually has further to travel, than the top one, so I think that the top one would get there first, and would be a little faster.*"

Table 5.8 Transcript excerpts indicating the VALLEYWINS and VALLEYLOSES expectations.

In Table 5.8, a physics student indicates the rare and appropriate expectation that ball B should win the race to the end of the tracks. Kent's expectation that ball B should win was connected to the SAMESPEED expectation, as was Felix's TIE expectation in Table 5.7, but with a more careful logical connection between the expectations and a different prediction for the race outcome. Samantha, a psychology student, indicates the VALLEYLOSES expectation, common among psychology students interviewed but rare for physics students interviewed, in connection with her observation that track B is longer than track A.

MAKEITUP
• Don, physics, one-ball flat-valley (general comment): "***some of the other ones seem to die down about midway through***, *and if they die down that early it wouldn't make sense for them to be able to have enough energy to get back up the ramp at the end.*" • Samantha, psychology, one-ball flat-valley [sl]: "*Yeah, that one [sl] just* ***seems like the pace is a lot slower than number 5[fsl] was***. *And uh, if it would be slower than number 5[fsl], it wouldn't make it up that ramp. Whereas* ***number 5[fsl] just barely made it up that ramp***." • Sharon, psychology, two-ball V-valley [fsl]: "*... it should have enough speed coming down the hill to get it right up over the next bump and it,* ***stopping right on the angle***, *it seems like it would fall back down too*."

Table 5.9 Transcript excerpts indicating the MAKEITUP expectation.

In each of the statements in Table 5.9, a student has described his or her judgment that the ball is not moving in such a way, in some animation, that it could realistically be expected to roll up the final slope. The MAKEITUP expectation, that the ball ought to move so it could realistically make it up the final slope, is different from the other expectations in Table 5.1. The others provide inferences that connect the realism of the motion depicted in an animation to the presence or absence of some relatively concrete motion feature--a speed change or a race outcome. The inference inherent in MAKEITUP depends on a readout of whether the speed of the ball at some point is above a certain threshold (presumably, a subjectively determined threshold). A few expectations of this type, each appearing to provide inferences based on subjectively determined readouts, are discussed in section 5.4.

Student statements included in the tables above establish the plausibility of the idea that students developed expectations about realistic motion and that these expectations allowed students to make inferences about the realism of animations based on their observations. The ability to make such inferences is a primary feature of a causal net.

5.2.2 Expectation distributions

In the previous section, the plausibility that students developed expectations about realistic motion was established. It was suggested that many expectations were relatively similar across different students. Further indications that different students expressed similar expectations, and that individual students expressed similar expectations across different tasks, are presented in this section.

The transcripts of recorded interviews were coded for the expression of the expectations listed in Table 5.1. Table 5.10, below, indicates the number of students from each group of interviews coded as having expressed each expectation in each of the four tasks. Students were not always so explicit about their ideas as they were when making the statements in the tables above, and coding student utterances often required interpolation among what a student said about expectations, what the student reported as a readout about a particular animation, whether the student judged a particular animation to be realistic or not, and what the student had said about other animations. Coding, therefore, was somewhat subjective, and counts of coding instances must be taken as somewhat approximate. Note also that students may have held expectations that they failed to express, either in an individual task or over the four tasks as a whole.

	Frequencies (Psychology interviews / Physics interviews)				
Expectation	**1-flat**	**1-V**	**2-flat**	**2-V**	**overall**
DECELUP	71% / 92%	83% / 83%	75% / 100%	58% / 83%	92% / 100%
ACCELDOWN	71% / 92%	79% / 92%	79% / 100%	75% / 100%	96% / 100%
CONSTFLAT	8% / 33%	0% / 0%	13% / 58%	0% / 0%	21% / 75%
DECELFLAT	25% / 0%	0% / 0%	13% / 8%	0% / 0%	33% / 8%
SAMESPEED	0% / 42%	13% / 50%	4% / 25%	0% / 50%	13% / 67%
NOGAIN	29% / 58%	83% / 100%	4% / 0%	75% / 25%	92% / 100%
PAUSETOP	0% / 0%	21% / 33%	0% / 0%	4% / 0%	25% / 33%
TIE	0% / 0%	0% / 0%	46% / 83%	29% / 92%	50% / 100%
VALLEYWINS	0% / 0%	0% / 0%	0% / 17%	8% / 8%	8% / 17%
VALLEYLOSES	0% / 0%	0% / 0%	25% / 0%	8% / 0%	25% / 0%
MAKEITUP	17% / 8%	33% / 17%	4% / 0%	25% / 8%	50% / 17%

Table 5.10 Fractions of students in recorded Psychology interviews (N=24) and Physics interviews (N=12) coded as expressing common expectations about realistic motion during each task, and during the entire interview.

Table 5.10 presents several patterns. The ACCELDOWN, DECELUP, and NOGAIN expectations were expressed in most psychology and physics interviews, and in both one-ball and two-ball tasks. Some expectations were expressed by a much larger fraction of students from one group than the other--CONSTFLAT, SAMESPEED, and TIE were expressed in a larger fraction of physics interviews, while DECELFLAT, VALLEYLOSES, and MAKEITUP were expressed in a larger fraction of psychology interviews. The NOGAIN expectation was expressed by physics students in the one-ball V-valley task far more often than in the two-ball V-valley task, while a large fraction of psychology students expressed the expectation in both.

5.3 READOUT STRATEGIES

One function of readout strategies is to serve as the interface between the outside world and a students' causal net. In this capacity, readout strategies act as an active filter, capturing and encapsulating information from the outside world so that elements of the causal net can operate on that information. As presented in the previous section, students were often concerned with judging whether or not speed changes presented in animations were realistic. Their readout strategies were, not surprisingly, often focused on gathering information about speed changes depicted in animations.

Students provided much more information about their readouts than about the methods (*strategies*) they used to obtain those readouts. Students' statements suggest that their strategies for reading out information about speed changes can be separated into two major categories: those that produce "fixed-referent" readouts and those that produce "relative motion" readouts. In the one-ball tasks, the fixed background of the two-tracks apparatus was the only reference that students had to work with for judging speed changes; students were therefore limited to making fixed-referent readouts in the one-ball tasks. In the two-ball tasks, students had the additional option of judging one ball's motion relative to the other; in the two-ball tasks, students were presumably free to make either fixed-referent or relative motion readouts.

5.3.1 Fixed-referent readouts

Table 5.11 presents examples of readout reports from four students. These reports must refer to fixed-referent readouts, because they describe students' observations of one-ball animations. Several more examples of fixed-referent readout reports can be found in the tables in section 5.2.1.

Fixed-referent readouts
• Huan, physics, one-ball V-valley [real]: "***Definitely goes faster, it's, it's going fastest at the bottom of the hill, the bottom of the V.***"
• Phyllis, psychology, one-ball flat-valley [fsl]: "…***it picked up a little bit of momentum there and then it slowed down again going up the hill….***"
• Gina, physics, one-ball V-valley [constvx]: "***it speeds up as it goes up again,*** *which is wrong,* ***when it comes up the V****….* "
• Carol, physics, one-ball flat-valley [sl]: "***Number 3 [sl] looks like it slows down when it's going down the second hill***….."

Table 5.11 Student statements indicating fixed-referent readouts.

Fixed-referent readouts are apparently sometimes accurate and sometimes inaccurate. Readouts reported by the first two students in Table 5.11, Huan and Phyllis, are accurate. Readouts reported by the second two students in the table, Gina and Carol, are inaccurate. What are collectively described here as fixed-referent readouts are likely the result of somewhat different readout strategies, some of which may be more reliable than others in particular situations or when employed with particular attention to detail. Student statements provide little information to fuel speculation about the precise nature of their fixed-referent readout strategies.

5.3.2 Relative motion readouts

Table 5.12 presents three examples of readout reports. The wording of these reports strongly suggests that students' readouts about speed changes were affected by observations of the relative positions of balls A and B. The examples also suggest patterns of accuracy and inaccuracy that may be attributable to inferences about speed changes based on observations of relative motion.

(Likely) relative motion readouts
• Emilio, physics, two-ball flat-valley [constvx]: "*All right, it's not 4[constvx], because* ***the two balls are always at the same, um, I guess I'll call it 'x' value, they're always at the same position going down the ramp*** *and they shouldn't be. When the ball's going down the ramp it should be going faster than the ball going straight so it should be further along the ramp*." • Sharon, psychology, two-ball flat-valley [sl]: "**the top ball stayed a little bit ahead of the one that went down the ramp** and the one that went down the ramp seems like it should pick up at least some momentum to get ahead of it at some point." • Lauren, physics, two-ball flat-valley [fst]: "…*I chose 2[fst] because I thought that the balls, um,* ***the speed of the ball that was going down on the incline should be, um, at a different speed at certain points in going down and up than the ball that, on the straightaway, but that they should meet at the end*** *because their velocity, after that ball goes down and goes up it should have the same velocity as it did before*."

Table 5.12 Student statements suggestive of relative motion readouts.

In the first two examples in Table 5.12, Emilio and Sharon make accurate inferences about the speed of ball B on the second slope, apparently based on the observation that when ball B does not move ahead of ball A on this slope, its speed has not increased. In this case, the inference is appropriate because the two balls had the same speed and position before ball B reached the second slope.

In the final example, Lauren reports appropriate expectations for speed changes, and relates them to an inappropriate expectation for relative position at the end of the race. Her description of velocity and relative position implies that when the balls have the same velocity at the end of the track they must also have the same position. It is unclear whether her claim that the balls had different speeds during the two-ball flat-valley [fst] animation was based on fixed-referent readouts, relative motion readouts, or some combination of the two.

The first two examples in Table 5.12 provide particularly clear examples of students making inferences about speed changes from observations of relative positions. In many descriptions of speed changes in two-ball animations, students were not so explicit about the inferences they made. They often made mistakes similar to those in Lauren's description of the two-ball flat-valley [fst] motion, suggesting the possibility that, although they did not describe relative motion readout strategies explicitly, they may have used relative motion readout strategies or some combination of relative motion and fixed-referent readout strategies.

As described in the literature review, Trowbridge and McDermott (1980) report characteristic mistakes made by students in situations where students might use information about the relative positions of two objects to judge the relative speeds of the objects. Students' readout reports in the present study suggest that students may have used strategies similar to those reported by Trowbridge and McDermott: treating "getting ahead" as equivalent to "getting faster", treating "losing ground" as equivalent to "slowing down", and appearing to treat "same position" as equivalent to "same speed". These strategies, each appropriate in some circumstances, are inappropriate in other circumstances and can lead to mistaken readouts of speed changes. Potential effects of relative motion readout strategies on student judgments are pursued in chapter six.

5.4 EXPERIENTIAL AND HOLISTIC MOTION DESCRIPTIONS

Several student statements combined elements of readout strategies and causal net elements. For some of these statements, straightforward decomposition in formal physics terms might do injustice to the intent with which the students made them. Such statements were made more often by psychology students than by physics students. Statements such as those in the tables in this section appeared useful to the students who made them, and almost certainly contain information about the students' attempts at coordination. They are, however, difficult to interpret unambiguously and are not generally pursued in the coordination class analysis beyond the discussion here.

This type of statement is separated into two broad categories. Statements presented in Table 5.13 are classified as experiential descriptions, because they appear to directly relate motion in an animation to motions students have experienced. Statements presented in Table 5.14 are classified as holistic descriptions. They appear to be the result of judgments about the *overall* speed of the ball in an animation, rather than judgments based on the presence or absence of particular speed *changes*.

Experiential descriptions of motion
• Teresa, psychology, one-ball V-valley (general comment): "*If you think about it like a bowling alley, it still comes up and doesn't really slow down ....*" • Rosemarie, psychology, one-ball V-valley (general comment): "*This kind of reminds me of riding my bike up a hill.*" • Samantha, psychology, two-ball V-valley [real] and [fsl]: "*…number 5[real] seemed* ***kind of like a sling shot****, kind of thing ... once* ***it goes it just goes whsht****, you know? ... we go mini golfing sometimes, and they have the little ... green[s], and there is one and it has little bumps on it, like little waves, but they're pretty big. But, that one, the ball just kind of goes, and* ***it just seems to fly like the whole way through, like number 5[real]*** *... and then another one it goes straight, drops down a lot and comes up and,* ***I would definitely, relate that the ball would lose its momentum as it goes back up. But, I think that one kind of compared to number 2[fsl]****.*"

Table 5.13 Examples of experiential motion descriptions.

There is nothing inappropriate about basing judgments of motion on experience. Teachers often encourage students to relate experiences in physics classes to their daily lives. Samantha demonstrates one of the pitfalls of an experiential approach, however, when she appears to have experience with different types of motion, and exhibits difficulty in deciding which experience is useful for the task at hand. Without principles to guide the choice of an appropriate experience on which to base expectations, and to guide the choice of readout strategies, such an approach may lead to idiosyncratic and context specific coordination, resulting in low levels of integration and invariance.

Holistic descriptions of motion
• Patricia, 368, 2122, 2-V [real]: "***The bottom ball seems way too fast***. *Now I'm gonna try to concentrate more on the top ramp ball.* ***Which also seems like it's going kind of fast***."
• Sharon, 370, 1125, 2-V [sl]: "*And 5[sl] it just seems that* ***the ball that goes down the ramp is just too slow***."

Table 5.14 Examples of holistic motion descriptions.

The statements included in Table 5.14 appear to be judgments based on the overall speed of the ball. Expectations for what is a "reasonable" speed must be based on something, but it is difficult to judge what that is or whether it is appropriate. Again, an approach based on judging the overall speed of the ball may lead to idiosyncratic and context specific coordination with low levels of integration and invariance.

5.5 DISCUSSION

The analysis in this chapter suggests that a large fraction of interviewed students had some causal net elements in common, and that many of the students consistently brought some of these elements to bear across the different contexts presented by the four tasks. There were also, however, variations in the frequencies with which particular expectations were expressed, across different tasks and across different students. Yet to be addressed are the questions of how such patterns in causal net elements should affect the invariance of coordination episodes for individual students and how they should affect similarity of coordination episodes across different students. A key task for this analysis is, of course, to determine whether students with these expectations could plausibly produce features of the response patterns described in chapter four.

The analysis in this chapter suggests that students interviewed made both accurate and inaccurate readouts of features of motion depicted in the computer animations. Although the precise nature of students' readout strategies cannot be determined from interview transcripts, students attempting to read out speed change information from animations apparently had access to at least two different classes of readout strategies. One class of strategies was based on fixed-referent observations, and the other was based on observations of the relative motion of two balls. Patterns of success and failure associated with different types of readout strategies may have implications for interpretation of the integration and invariance of students' efforts at coordination.

It was found in chapter four that students often judged two-ball animations depicting a tying race outcome to be realistic, when they had judged the one-ball animation depicting the same motion to be unrealistic. One reason for this difference, in terms of coordination classes, might be that different causal net elements or readout strategies are brought to bear in the one-ball and two-ball situations. A detailed discussion of the possibilities is premature at this point, but some preliminary patterns can be pointed to. First, the pattern of expectations expressed by students suggests that in the two-ball tasks many students held onto the same set of expectations they had used for the one-ball tasks, but added expectations about the race outcome. (A potentially telling exception to this pattern is that fewer physics students expressed the NOGAIN expectation in the two-ball V-valley task than in the one-ball V-valley task.) Second, students had access to relative motion readout strategies in the two-ball tasks that had been unavailable in the one-ball tasks. Chapter six is devoted to further interview analysis and an exploration of how causal net elements and readouts can interact to produce judgments about animations; a more complete discussion of student coordination, including coordination that could lead to identification of tying animations as realistic, is presented there.

CHAPTER 6—COORDINATION PROCESSES

The response patterns presented in chapter four raised several questions about how students judge the realism of animated motions. As a first step in addressing those questions, several causal net elements and two general types of readout strategies were identified in chapter five. In this chapter, the production of students' judgments about computer animations is explored. Special attention is paid to judgments that are apparently inconsistent with students' expectations for realistic motion.

The processes described in this chapter are essentially methods for interpreting students' apparent progression from sets of expectations about realistic motion to identifications of animations depicting realistic motion. When a student accurately makes the readouts implied by the student's expectations, this progression may be straightforward, and the student may make a choice that appears consistent with the student's expectations. In interviews, however, students often chose animations whose features were inconsistent with their expressed expectations for realistic motion. In these cases, connections between students' expectations and choices cannot be so straightforward.

This chapter extends the interview analysis begun in chapter five. In section 6.1, the integration and invariance senses of coordination, described at length in chapter two, are re-described in terms of the present study and the analysis in this chapter. Students' animation choices are compared with expectations for realistic motion in section 6.2; this comparison motivates the search for processes that could explain apparently inconsistent choices. Incorrect readouts are explored as a cause of inconsistent choices in section 6.3. Feedback between readout strategies and the causal net is explored as a cause for inconsistent choices and changes in coordination systems in section 6.4. Processes of coordination are used to explore differences between physics and psychology students' judgments about the [fst] animations in section 6.5. The final section summarizes the major findings of the chapter.

6.1 INTERACTIONS

When a student makes a judgment about the realism of the motion in an animation, it may be understood as the result of interactions among the student's causal net, the student's readout strategies, and the animations. These interactions constitute the student's coordination. The purpose of this chapter is to delineate some particular types of interactions.

DiSessa and Sherin state that "coordination classes include strategies of selecting attention and strategies of determining and integrating observations into the requisite information." This description places emphasis on making useful readouts available for the causal net, and potentially combining observations from several readouts. DiSessa and Sherin describe coordination in the sense of *integration* to emphasize that "within a given situation, multiple observations or aspects may need to be coordinated to determine the necessary information." (diSessa & Sherin, 1998, p.1172). A person with a coordination class, then, could assess a situation, make multiple observations within that situation, and integrate the results to create a single judgment. In the tasks presented here, integration might consist of recognizing and making several different observations about a particular animation in order to judge the realism of the animation's motion. A student with integration problems might base a judgment on the first observation to present itself, rather than using especially reliable observations or integrating information from several different observations. A student with integration problems might also make several observations that lead (through the student's causal net) to conflicting conclusions, leaving the student unable to integrate readouts from the various observations to make a single coherent judgment.

DiSessa and Sherin describe an additional sense of coordination, which they label *invariance*, to emphasize that "across instances and situations, the knowledge that accomplishes readout of information must reliably determine the *same* information. Otherwise we might count the [coordination class] as confused or incoherent." (diSessa & Sherin, 1998, p.1172, emphasis in the original). A person with a coordination class for a particular quantity, then, could reliably determine that quantity in several different circumstances, even if such determinations required the use of different observations and different inferences in different situations. In the tasks presented here, a student who coordinates invariantly should make the same judgments about one-ball and two-ball animations depicting the same motion for the same apparatus, even if those judgments are based on somewhat different features and inferences. A student with invariance problems might make conflicting readouts, or be led to use conflicting causal net elements, in different circumstances.

Judgments are one result of interactions between the causal net and readout strategies. Such interactions may also result in learning--changes in students' coordination systems. "In general, readout strategies and the causal net should co-evolve as learning occurs. There should be episodes of 'conceptual bootstrapping', where causal assumptions drive the learning of new readout strategies. On other occasions, 'noticings'--for example, that something surprisingly affects something else--may drive reformulations in the causal net." (diSessa & Sherin, 1998, p.1177). Most of the evidence in the present study for change in readout strategies or the causal net suggests that the changes were situation specific, and could not in themselves be characterized as useful learning.

6.2 COMPARING CAUSAL NETS WITH CHOICES

Most of the expectations described in chapter five can be related to animation features, in the sense that each animation could be judged to meet or violate each expectation. Students often chose animations apparently incompatible with their expectations. Connections between expectations and animation features are examined in this section. Table 6.1 summarizes the relationships between commonly expressed expectations and animations, indicating (with "NO") which animations contain features apparently incompatible with particular expectations.

	Animation type				
Expectation	*1 [sl]*	*2 [fsl]*	*3 [fst]*	*4 [constvx]*	*5 [real]*
DECELUP (A)				**NO**	
ACCELDOWN (A)	**NO**			**NO**	
CONSTFLAT (A)		flat **NO**	flat **NO**		
DECELFLAT (I)	flat **NO**			flat **NO**	flat **NO**
SAMESPEED (A)	**NO**	**NO**			
NOGAIN (A)		V **NO**	**NO**		
PAUSETOP (I)	V **NO**		V **NO**	V **NO**	V **NO**
TIE (I)	2-ball **NO**	2-ball **NO**			2-ball **NO**
VALLEYWINS (A)	2-ball **NO**	2-ball **NO**	2-ball **NO**	2-ball **NO**	
VALLEYLOSES (I)			2-ball **NO**	2-ball **NO**	2-ball **NO**
MAKEITUP (??)	??	??	??	??	??

Table 6.1 Incompatibilities between animation features and common expectations.

The main features of Table 6.1 can be indicated with specific examples. The "NO" in the DECELUP-[constvx] cell indicates that all four [constvx] animations (one- and two-ball flat- and V-valley) violate the DECELUP expectation, because the ball fails to slow down on the final slope in all four [constvx] animations. The "flat NO" in the CONSTFLAT-[fsl] cell indicates that only the flat-valley [fsl] animations violate the CONSTFLAT expectation; the V-valley [fsl] animations do not violate CONSTFLAT. Each of the race-outcome expectations (TIE, VALLEYWINS, and VALLEYLOSES) can, of course, be incompatible only with two-ball animations; this is indicated with "2-ball NO". The MAKEITUP expectation differs from other expectations in that a student's judgment of whether the ball could reasonably make it up the final slope cannot be objectively evaluated in kinematic or race-outcome terms. MAKEITUP (and other holistic or non-kinematically described expectations expressed by some students) appear to influence students' reasoning about particular animations, but are not systematically useful for comparing expectations described by students with their final choices. This is indicated in the table with question marks, "??". Each expectation listed in Table 6.1 is marked with either an "(A)" or an "(I)", to indicate that it is an Appropriate or Inappropriate expectation for motion on either two-tracks apparatus. (MAKEITUP is not classified as either Appropriate or Inappropriate, as indicated by the question marks.) Only Inappropriate expectations, of course, are violated by features of [real] animations.

A particular student may express expectations that are consistent with only one animation from a set. Such a group of expectations can be described as "well-determining," whether or not the single animation consistent with the expectations is the realistic [real] animation. In contrast, expectations may be "over-determining" or "under-determining." An over-determining group of expectations is inconsistent with all five animations from a set; an under-determining group of expectations is consistent with more than one animation from a set. If a student's causal net is under- or over-determining, even complete knowledge of that student's expectations is not sufficient to predict which animation the student will identify as depicting realistic motion. A student who makes accurate readouts appropriate to a set of expectations that is not well-determining will likely face problems with integration.

Even when a student's causal net is well-determining, the student's expectations and choices may be inconsistent with each other. To illustrate this, consider two quotations from the one-ball V-valley task portion of the interview with Gina, a physics student, as presented in Figure 6.1. In her first statement, Gina expresses the NOGAIN expectation--the ball should not speed up without an apparent cause. In her second statement, Gina's description of why she found [fsl] to be realistic indicates the use of three different expectations: ACCELDOWN, DECELUP, and SAMESPEED. These four expectations are appropriate; Table 6.1 indicates that taken together they are well-determining and compatible only with the [real] animation. Gina chooses the [fsl] animation, however, indicating an apparent mismatch between her expectations and the features of her one-ball V-valley choice. Despite this apparent mismatch, her remarks demonstrate a high level of integration--several readouts about the [fst] and [fsl] animations lead her to the coherent conclusion that the [fsl] motion depicts more realistic motion.

- *"Number 4[fst] it* ***looks like it, stops three-quarters of the way up the V and then accelerates again before it goes over the bump****, so that's wrong."*

  …later in the same task…

- *"I liked number 2[fsl] because it started off to,* ***it started off getting a little bit faster as it went down the first ramp, and then as it went down the V it got a lot faster and as it went up the V it slowed down a little bit, and then when it got to the level part at the end it pretty much had the same speed as the little part of level part at the beginning****.* <Interviewer: And that's good?> *Uh huh.* <Interviewer: Why do you like that, why do you think it's …> *Um, because they're at the same height, so they should have the same speed, pretty much if it's frictionless, or, whatever."*

Figure 6.1 Gina, a physics student, discussing two different one-ball V-valley animations[†].

Taking a student's choices into account implies four categories of expectation/choice comparisons, suggested by the three expectation categories and Gina's example. In a "well-determined" comparison, a student's expectations are compatible only with the animation chosen. Note that "well-determined" does not imply "correct", but rather that expectations expressed by a student appeared to be compatible with only a single animation, which was identified by that student as realistic. In a "differently-determined" comparison, the expectations are compatible with only a single animation, which happens *not* to be the one chosen--as was the case for Gina. In an "under-determined" comparison, the expectations are compatible with more than one animation.

In an "over-determined" comparison, a student's expectations are compatible with no single animation. For all expectation/choice comparison categories except well-determined, some mechanism is needed to explain how a student could have ruled out an animation consistent with expectations, *failed* to rule out an animation *in*consistent with expectations, or both.

The transcript for each of the 36 recorded interviews was coded, statement-by-statement, with the expectations that students appeared to be describing or using to judge an animation. For each student, the set of animations compatible with the coded expectations for each task were determined and compared with that student's choice for the task. See Table 6.2 for the results of these comparisons. (Coding of expectations is necessarily subjective, so these counts provide only rough estimates.) Across all four tasks, only a third of expectation/choice comparisons were well-determined, indicating that in most cases knowledge of the expectations expressed by a student during a task did not provide information sufficient to predict that student's choice in the task. The ratios varied by task; in the one-ball flat-valley task, 69% of expectation/choice comparisons were under-determined; in the two-ball V-valley task, 50% were well-determined.

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† Student quotations in this chapter are formatted to indicate ***readout reports*** and <u>*expressions of expectations*</u> as in chapter five.

Causal net / choice comparison	Percent of all choices
well-determined	33%
differently-determined	17%
under-determined	30%
over-determined	20%

Table 6.2 Causal net / choice comparison for choices in all recorded interviews.

In the majority of small-scale judgments--for example, comparing a readout with an expectation to temporarily rule an animation "in" or "out"--students made successful comparisons. For the most part, students appeared to successfully integrate more than one observation to make a small-scale judgment, as Gina did above. Students appeared to apply expectations such as ACCELDOWN and DECELUP consistently across the four tasks. The consistent use of at least some expectations could be classified as a step toward invariance, although full invariance would obviously result in making the same judgment about each motion in each task. The majority of students' final decisions, however, involved identifying an animation as realistic even though it was apparently incompatible with one or more expectations expressed by the student. Processes that can lead students to judgments apparently incompatible with their expectations are discussed in the following sections.

6.3 INACCURATE READOUTS

Often, in describing their judgments of animations, students reported inaccurate readouts. They had apparently attempted to make readouts appropriate for comparing animation features with expectations, but had failed to make accurate readouts. Readout problems could either lead students to rule out animations consistent with their expectations, or to accept animations as realistic even though the animations were *in*consistent with one or more of their expectations. Presented in section 6.3.1 is a pattern that could lead students with apparently appropriate expectations to rule out a [real] animation as unrealistic. Presented in section 6.3.2 is a pattern that could lead students with apparently appropriate expectations to accept an [fsl] animation as realistic.

6.3.1 Inaccurate readouts limiting choices

When a student's expectations were under- or differently- determined, the student must have ruled out one or more animations apparently compatible with the expectations coded for that student in that task. Because approximately one-half of students' choices in recorded interviews were under- or differently- determined by their coded expectations, a model of student decision-making must provide a method by which this could occur. One possibility is that students could make inaccurate readouts about an animation, and mistakenly determine that the animation violates an expectation.

A particular example of this phenomenon is presented in this section. Several students apparently made inaccurate readouts about the [real] animations and determined that they violated the DECELUP expectation. This example provides a clear case in which students can describe appropriate expectations for realistic motion, but describe inaccurate readouts to rule out a realistic animation. It also provides a model for understanding how so many students with apparently appropriate expectations could rule out the [real] animations.

In Figure 6.2, different students claim that different [real] animations do not depict realistic motion. Four of the five students appeal directly to the DECELUP expectation, claiming that the ball does not slow down on the final slope. For one-ball animations (Sarah and Allison), the claims were necessarily based on fixed-referent readouts. For two-ball animations (Phyllis and Brook), the claims may have been based on fixed-referent or relative motion readouts. In either case, the claims were very similar. In a slight variation, Isaac appeals to the SAMESPEED expectation, claiming that the ball has a different speed on the final shelf than it had on the initial shelf.

- Sarah, psychology, one-ball flat-valley [real]: *"The fifth one* ***gains momentum as it goes down, but it doesn't lose a whole lot, of momentum when it goes up****."*
- Allison, physics, one-ball V-valley [real]: *"That didn't seem to me,* ***there is no deceleration going up the ramp*** *so that's not it"*
- Phyllis, psychology, two-ball flat-valley [real]: *"...****it gained a lot of momentum going down the hill, but it didn't seem to lose any going back up it****."*
- Brook, physics, two-ball V-valley [real]: *"I don't think so because* ***the one that falls down the lowest doesn't seem to slow down it seems to keep its final velocity."***
- Isaac, physics, one-ball V-valley [real]: *"the ball here should have the same velocity as it does here.* <Int: So you're pointing to the, the two flat parts.> *Right, 'cause they're at the same level.* **But they don't***."*

Figure 6.2 Students claiming that [real] animations are unrealistic.

This effect of this particular incorrect readout on excluding consideration of [real] animations for students whose coded expectations were compatible with [real] appeared to be widespread. As shown in Table 6.3, in each of the one-ball tasks, students in more than half of the recorded interviews chose some animation other than [real]. Of those students not choosing [real], more than half expressed expectations that were apparently compatible with [real]. Many of those students apparently followed the pattern described in this section--as shown in the final row of Table 6.3, a large fraction of students with [real]-compatible expectations not choosing [real] reported that ball B failed to slow down on the final slope in the [real] animation. Although students reported similar readouts about speed changes in the two-ball tasks, the high frequency of [real]-compatible expectations was not repeated in the two-ball tasks, where the common TIE expectation was incompatible with [real] animations.

	one-ball flat-valley	**one-ball V-valley**
Of total, students NOT choosing [real]	30 / 36 (83%)	20 / 36 (56%)
Of above, with [real]-compatible Causal Net	21 / 30 (70%)	11 / 20 (55%)
Of above, claimed [real] violated DECELUP	14 / 21 (67%)	8 / 11 (73%)

Table 6.3 Ruling out one-ball [real] animations with inaccurate readouts.

6.3.2 Inaccurate readouts extending choices

When a student's expectations were over- or differently- determined, the student had to choose an animation apparently incompatible with the expectations coded for that student in that task. Because approximately one-third of students' choices in interviews were over- or differently- determined by their coded expectations, a model of student decision-making must provide a method by which this could occur. One possibility is that students could make inaccurate readouts about an animation, and mistakenly determine that the animation does not violate a particular expectation.

A particular example of this phenomenon is discussed in this section. Some students apparently made inaccurate readouts about the one-ball [fsl] animations and determined that they were compatible with SAMESPEED and/or CONSTFLAT expectations. This example provides a clear case in which students describe appropriate expectations for realistic motion but describe inaccurate readouts, and identify an animation depicting unrealistic motion as realistic. It also provides a model for understanding how many students whose expressed expectations were compatible only with the motion in [real] could identify [fsl] animations as depicting realistic motion.

In Figure 6.3, two students claim that one-ball [fsl] animations meet their expectations. Emilio describes appropriate expectations for realistic motion with a mixture of accurate and inaccurate readouts about the one-ball flat-valley [fsl] animation--"picks up speed going down the ramp" (ACCELDOWN, accurate readout); "loses it going up" (DECELUP, accurate readout); "it has the same speed on, um, on this first flat straightaway as the second one" (SAMESPEED, inaccurate readout); and "it's got a constant speed on the middle straightaway" (CONSTFLAT, inaccurate readout). In a similar way, Isaac judges that the one-ball V-valley [fsl] animation meets the ACCELDOWN (accurate readout), DECELUP (accurate readout), and SAMESPEED (inaccurate readout) expectations. Inaccurate readouts enable Emilio and Isaac to judge that the [fsl] animations meet their appropriate expectations for realistic motion.

- Emilio, physics, one-ball flat-valley [fsl]: *"I like 5[fsl] because, um, it* ***picks up speed going down the ramp and loses it going up*** *and it* ***looks like it has the same speed on, um, on this first flat straightaway*** *as the second one,* ***as the ending rather****, and* ***it's got a constant speed on the middle straightaway there****."*
- Isaac, physics, one-ball V-valley [fsl]: *"Well, number 2[fsl], well, what I was looking for in each one, there has to be,* ***some sort of acceleration that's heading downhill, and it's got to decelerate when it's going uphill,*** *um, similar to the same, like, energy argument that I uh used before, and* ***at points where it's the same, uh at the same point, the velocity would have to be the same****."*

Figure 6.3 Students claiming that [fsl] animations meet their expectations.

6.3.3 Inaccurate readouts and integration

In the examples above, students were led to make judgments that were apparently inconsistent with their expectations. This means that students made inferences based on inaccurate information, but does not necessarily imply that they had difficulty integrating information from several observations to make a coherent conclusion--students in the examples often described several readouts supporting judgments about animations. On the other hand, integration associated with successful coordination sometimes requires the comparison of different readout strategies. Students who based judgments on inaccurate readouts either did not realize that their readout strategies were not sensitive enough to make accurate readouts in some cases, or lacked the knowledge necessary to execute more sensitive readout strategies (for instance, stepping through an animation frame-by-frame in order to infer speed changes from changes in the frame-to-frame distances between ball images).

6.4 FEEDBACK: ADJUSTING READOUTS OR THE CAUSAL NET

Students sometimes rejected all five animations from a set. Having made readouts about every animation that were incompatible with their expectations, they were still required to identify one animation as depicting realistic motion. Students in this situation were left with two options, each involving feedback between readouts and the causal net. They could adjust their causal net so their expectations would be consistent with all readouts about one animation, or they could adjust their readouts about one animation to fit all expectations about realistic motion.

Examples in which students appear to adjust their readouts or their expectations are provided in the following subsections. The examples demonstrate strong interactions between student's readouts and their causal nets, interactions apparently strengthened by their acceptance of the notion that one of the animations presented in the task does in fact depict realistic motion.

6.4.1 Adjusting readouts to fit expectations

Isaac, whose final description of the one-ball V-valley [fsl] animation is presented in Figure 6.3 on page 100, gradually shifted his description of that animation, (in this case, *away* from an accurate description of the [fsl] motion) to fit his expectations for realistic motion. His earlier descriptions, presented in Figure 6.4, differ significantly from his final description of the same animation.

- Isaac, physics, one-ball V-valley [fsl]: *"...****it um accelerates down that, that first part of the V, but it barely gets over, barely gets over that hump,*** *which wouldn't happen because the uh, the starting point was higher than that, than this point right here, which when it gets to its final flat part."*

    …later, after objecting to all five one-ball V-valley animations…

- Isaac, physics, one-ball V-valley [fsl]: *"Well, going through all of them, it at first didn't seem like, any of them would work, but now looking back at number 2[fsl] again,* **it accelerates downhill and then decelerates uphill**, *but the only point I'm considering is at that point right where the V ends, and it goes over onto the uh flat part.* ***It seems to just barely get over it****, which at first I didn't think would happen, but it still does,* ***but it's not just barely getting over there, it's getting over there with some velocity, too, it's still moving****."*

Figure 6.4 Isaac's early descriptions of the one-ball V-valley [fsl] animation.

In the earliest description, Isaac objects to the ball's motion on the final shelf. By the time he makes the second description in Figure 6.4, Isaac has objected to all five of the one-ball V-valley animations. He points out that the [fsl] animation meets the ACCELDOWN and DECELUP expectations before referring to the troublesome area ("where the V ends") and re-describes the motion at that point in a way that may be closer to full compatibility with his expectations than his first description. In his final description, in Figure 6.3, Isaac has eliminated any question about the realism of the motion. He describes the motion on the final shelf as if it matches the SAMESPEED expectation. It is almost as if Isaac, having decided what he wanted to see, gradually convinced himself that he had seen it.

6.4.2 Adjusting expectations to fit readouts

The episode in which Sarah, a psychology student, reports her decision that the two-ball V-valley [real] animation is realistic demonstrates an apparent shift of expectations to fit the readouts for a particular animation. The episode is presented in Figure 6.5.

- Sarah, psychology, two-ball V-valley [constvx]: *"... **the speed of the ball stays the same the entire time**. You would think it would speed up and slow down."*

  …finally, after rejecting all but the [real] animation…

- Sarah, psychology, two-ball V-valley [real]: "*I think number 3[real] is the most realistic.* <I: Uh huh> *Even though **they end at different places**.* <I: Yeah that bothers you though, right?> *Yeah. But this--it seems like it would, since it's going so fast it's kind of like a ramp effect.* <I: Uh huh> *That makes it go, it doesn't slow down as much because it go- it slants down so severely.* <I: Uh huh> ***It's kind of like a ramp when it flies off and, leaves it going faster.****"*

Figure 6.5 Sarah's acceptance of the two-ball V-valley [real] animation.

In her rejection of the [constvx] animation, Sarah clearly expresses the DECELUP expectation. Discussing the [real] animation, she reveals that she has had to adjust two related expectations about realistic motion to determine that [real] is realistic. She has let go of a TIE expectation to accept [real], in which the valley ball wins the race. Her explanation for that change is expressed in terms of another change; the DECELUP expectation does not apply to this particular case in the way she might have expected it to. ("[The ball] doesn't slow down as much because [the track] slants down so severely.") Sarah's label for this phenomenon is "ramp effect", which apparently signifies a relationship between her readouts about the shape of the V-valley track, readouts related to the motion depicted in the [real] animation, and remembered experiences with the motion of real objects.

6.4.3 Feedback, learning, and invariance

Isaac and Sarah, in the examples discussed in this section, appeared to bend their readout strategies or causal nets in order to accept particular animations as realistic. The changes seemed to be localized and situation specific, rather than systematic. It did not appear that the changes would have systematic impacts on their coordination systems that could be considered meaningful learning or conceptual change. The students' coordination systems may have flexible and not highly interconnected, so that systematic change was unlikely.

Tolerance for isolated exceptions to causal nets or readout strategies reduces the chances for invariant coordination. If a student develops a unique readout strategy or expectation to evaluate a particular animation and then reverts to a different set of readout strategies or expectations to evaluate other animations, with no justification for the switch, then there is no way for the student to assure him- or her-self that the same kinds of information have been read out from the different animations.

6.5 A STUDY IN INTEGRATION AND INVARIANCE: [FST] ANIMATIONS

Many students coded with essentially appropriate expectations for realistic motion in the one-ball tasks (ACCELDOWN, DECELUP, NOGAIN, and sometimes CONSTFLAT and/or SAMESPEED) express the expectation that the balls should TIE in at least one of the two-ball tasks. The TIE expectation is, of course, inappropriate for realistic motion on either apparatus. As shown in Table 6.1, the tying two-ball animations ([fst] and [constvx]) are not consistent with all three of the ACCELDOWN, DECELUP, and NOGAIN expectations--[constvx] animations violate ACCELDOWN and DECELUP, and [fst] animations violate NOGAIN. Most of the recorded physics students and several of the recorded psychology students appeared to hold TIE and the other three expectations. As described in chapter four, the [constvx] animations were relatively unpopular and the [fst] animations were much more popular in the two-ball tasks than in the one-ball tasks.

The number of students from each group of interviews who chose the [fst] animation in each task is presented in Table 6.4. Group similarities and differences in the fractions choosing [fst] foreshadow similarities and differences in coordination related to the [fst] motion. The largest differences occurred for the two-ball V-valley task.

Students choosing [fst] animations	one-ball flat	one-ball V	two-ball flat	two-ball V
Physics students (N = 24)	2 (8%)	0 (0%)	19 (79%)	15 (63%)
Psychology students (N = 26)	2 (8%)	0 (0%)	11 (42%)	0 (0%)

Table 6.4 Numbers of interviewed students identifying the [fst] animation as depicting realistic motion in each task.

Trends in how students coordinated readouts and causal net elements related to the one-ball and two-ball [fst] animations are presented in this section. Students' fixed-referent readout strategies for one-ball tasks resulted in different patterns of accurate and inaccurate readouts than did relative motion readout strategies, which were possible only in two-ball tasks. These patterns, central to understanding patterns of student coordination, are discussed in section 6.5.1. Although students from both the psychology and physics classes expressed the expectation that the balls should reach the ends of their tracks simultaneously, physics students provided much more specific reasoning for the TIE expectation than did psychology students. This is discussed in section 6.5.2. Readouts about the [fst] animations made by students from each group are discussed in section 6.5.3. Students' coordination of judgments about the [fst] animations is summarized in terms of integration and invariance in section 6.5.4.

6.5.1 Patterns of success and failure: Fixed-referent and relative motion readout strategies

As described in chapter five, students' readouts of speeds and speed changes in the one-ball animations must have been based on fixed-referent readout strategies. Ball A's presence in the two-ball animations invited the use of relative motion readout strategies. The two types of readout strategies seemed to have somewhat different patterns of success and failure for detecting different types of speed change. These patterns are summarized in Table 6.5, and described below.

Expectation	Fixed-referent readouts	Relative motion readouts
ACCELDOWN	good sensitivity	good sensitivity
DECELUP	poor sensitivity for [real] motions	systematic error for [real] motions
CONSTFLAT	poor sensitivity	poor sensitivity
NOGAIN	good sensitivity for V-valley [fst] motion; otherwise variable across students and animations	poor sensitivity
SAMESPEED	poor sensitivity	systematic error for [real] motions
race outcome	not applicable	good sensitivity

Table 6.5 Patterns of success and failure for Fixed-Referent and Relative Motion readout strategies.

Students neither described nor gave other evidence for awareness of the inferences involved in making fixed-referent readouts. Errors in fixed-referent readouts seemed to be errors of sensitivity. In reference to the DECELUP expectation for the one-ball flat-valley animations, for instance, students routinely reported the accurate observation that [fsl] and [fst] were consistent with DECELUP. The speed change depicted on the final slope of the flat-valley [real] animation was smaller than that in [fsl] and [fst], however, and students routinely *failed* to observe that [real] was consistent with DECELUP. The fixed-referent readout strategies used by many students apparently lacked the sensitivity necessary to resolve the speed change on the final slope for [real]. In a similar way, students' fixed-referent readout strategies were nearly always sensitive enough to detect the NOGAIN violation depicted in the one-ball V-valley [fst] animation. In contrast, several students *failed* to report the NOGAIN violation depicted in the one-ball flat-valley [fst] animation. Some students may simply not have had fixed-referent readout strategies sensitive enough to detect the sudden speed change in the one-ball flat-valley [fst] animation.

When reporting readouts for the two-ball animations, students sometimes indicated awareness that they had used relative ball positions as cues for inferring information about the speed of ball B. Presumably it is easier to judge that one ball is ahead of, tied with, or behind another ball than it is to judge the ball's speed directly. Students were universally successful at making readouts about the race outcome.

Focusing on relative positions during the race, however, seems to have introduced systematic errors into students' readouts about speed changes.

One problem for students using relative motion readouts was that focusing on relative positions may have reduced students' sensitivity to sudden speed changes related to the NOGAIN expectation, because the sudden speed changes depicted in the [fst] motions did not result in sudden changes in the relative positions of the two balls. This may be thought of as a problem with integration. Students took several observations of relative position into account when judging the [fst] motions to make a consistent judgment--demonstrating successful integration. At the same time, the students failed to make use of speed-change information that could have been obtained with other strategies--demonstrating a failure of integration. Differences in integration between students' coordination of the one-ball and two-ball V-valley [fst] animations often resulted in lack of invariance between their judgments of the two animations.

Another set of problems for relative motion readouts was created by students' inferences relating "ahead" to "faster", "tied" to "same speed", and "ball A catching up" to "ball B slowing down." In the animations used for this study, the two balls moved together before ball B entered the valley, so equating "ahead" with "faster" happened to result in appropriate judgments of whether animations were consistent with the ACCELDOWN expectation. In contrast, students' observations and inferences resulted in systematic errors for judging whether or not the two-ball [real] animations were consistent with the DECELUP and SAMESPEED expectations--[real] animations are consistent with the two expectations, but ball A never catches up to ball B. (Note that these problems are not inherent in focusing on relative motion to infer speed changes, but result from the use of inappropriate relationships between relative position and relative speed.) Curiously, lack of sensitivity in fixed-referent readout strategies and systematic error in relative motion readout strategies produced similar (incorrect) DECELUP-related readouts for [real] animations--several students appeared to judge the [real] animations invariantly (but inaccurately) across the one-ball and two-ball situations, even though they employed different readout strategies in the two tasks.

6.5.2 Causal net differences: The TIE expectation

Even among students coded with the TIE expectation, there were characteristic differences between the expectations described by physics students and those described by psychology students. Physics students tended to support the TIE expectation with physics-like reasoning apparently related to energy conservation and the SAMESPEED expectation. Psychology students expressing the TIE expectation tended to be more tentative about it, and not to support it with other reasoning. These differences are illustrated with examples from student transcripts in Figure 6.6 and Figure 6.7.

- Emilio, physics, one-ball flat-valley [fst]: *"...the height is the same, so it gains, um ... there's a change in energy from the top to the bottom it should be the same when it gets back up to the top so the speed should the same. I hope. If not I've been doing my entire semester wrong, so ..."*
- Emilio, physics, two-ball V-valley [fst]: *"Because when it goes down the ramp, um, it's picking up speed, and when it goes back up the ramp it's losing speed, but it's also at the same time changing height and energy, and so, and that's, one way to find the speed is by the energy of the ball, by finding the, by using height, so when it gets back up to the same height it should have the same energy and speed as it did at the beginning, and since the ball in the back is always at the same height, um, when the ball going up and down the ramp gets to the point where it meets up with the ball in the back it should get there at the same time."*

Figure 6.6 A physics student describing reasoning to support the SAMESPEED and TIE expectations.

Emilio, the physics student whose words appear in Figure 6.6, describes reasoning for the SAMESPEED expectation in the one-ball flat-valley task, saying that the height is the same on each side of the valley (the initial and final shelves), which means that the ball has the same energy on each side of the valley, which means that it should have the same speed on each side of the valley. This is a loose characterization of an energy conservation argument, and Emilio's conclusion (an expression of the SAMESPEED expectation) is appropriate for the situation at hand.

The second excerpt in Figure 6.6 is Emilio's explanation for why the balls should tie, as stated at the end of the two-ball V-valley task. As he had earlier, he connects energy and speed to the ball's height appropriately (although again without a complete argument). Emilio apparently leaps from an (appropriate) SAMESPEED expectation that despite their different paths the two balls should have equal speeds when they have the same elevation to the (inappropriate) TIE expectation that despite their different paths the two balls should be tied in the race when they have the same elevation. This leap is reminiscent of inferences described for students' relative motion readout strategies.

Several physics students described both the SAMESPEED expectation and the TIE expectation in terms similar to Emilio's, essentially substituting the idea of the balls being in the *same place* for the balls having the *same speed*. Most seemed, as Emilio did, to sense a strong connection between expectations about the race outcome and other expectations about realistic motion. Such a connection is inappropriate for this situation: an appropriate energy conservation argument can be used to predict that the balls have the same *speed* (but not necessarily the same position) when they have the same elevation.

- Teresa, psychology, two-ball flat-valley [fst]: "*I think it probably would **roll faster** but then eventually it would have to **slow a little bit going up**, so I think that is why I choose 3[fst].*"

  …and later, in the same task…

- "*I think that they would end up together but I could be wrong.*"

Figure 6.7 A psychology student describing the TIE expectation.

Teresa, a psychology student, expresses the TIE expectation with apparent trepidation in Figure 6.7. She offers a description of what she likes about the two-ball flat-valley [fst] animation, in terms of the ACCELDOWN and DECELUP expectations, but does not describe connections between the TIE expectation and other reasoning. Psychology students who expressed the TIE expectation presented it rather weakly--similar to Teresa's presentation--as a free-standing idea, and not as something strongly integrated with other parts of their causal nets related to realistic motion.

6.5.3 Readout differences: NOGAIN-related readouts

In addition to characteristic differences in causal nets, physics and psychology students coded with the TIE expectation described characteristically different readouts about the two-ball V-valley [fst] animation. Only a small number of recorded physics students reported NOGAIN-related readouts for the two-ball V-valley [fst] animation; the majority of physics students identified the [fst] animation as realistic, reporting readouts related to the ACCELDOWN, DECELUP and TIE expectations, and sometimes the SAMESPEED expectation. Nearly all of the psychology students reported readouts for that animation related to the NOGAIN expectation; they rejected [fst] as portraying unrealistic motion near the end of the final slope. Numbers of recorded physics and psychology students reporting NOGAIN-related readouts for the [fst] animation in each task are shown in Table 6.6.

Counts of NOGAIN-related readouts	one-ball flat	one-ball V	two-ball flat	two-ball V
Physics students (N = 12)	7 (58%)	11 (92%)	0 (0%)	3 (25%)
Psychology students (N = 24)	6 (25%)	19 (79%)	1 (4%)	17 (71%)

Table 6.6 Numbers of recorded students reporting NOGAIN-related readouts for [fst] animations in each task.

Physics and psychology students reported characteristically different readouts for the two-ball V-valley [fst] animation, but readouts reported by many students in the two groups for the [fst] animations in the other three tasks were remarkably similar. These similarities and differences are illustrated by transcript excerpts in Figure 6.8 and Figure 6.9. The excerpts presented in Figure 6.8 and Figure 6.9 are typical for interviewed physics students, and for those psychology students who expressed the TIE expectation.

- Isaac, physics, one-ball flat-valley [fst]: "*...it looks like in number 4[fst],* ***it accelerates right at the very end***."
- Isaac, physics, one-ball V-valley [fst]: "*It accelerates at,* ***once it gets, it goes down this V and then goes back up, it seems to accelerate right here****.* <I: So just to record, you're pointing about two thirds of the way up this second part of the V.> *Yeah.* ***It seems to slow down and then for some reason it picks up some speed****.*"
- Isaac, physics two-ball flat-valley [fst]: "... *number 2[fst] looks the best, because* ***they start at the same point at the same velocity****, and then when they go to the point where they break,* ***the one that goes downhill accelerates*** *like it should, so* ***it's slightly ahead of the one that's just at constant velocity****. But then* ***at the point where it goes uphill it decelerates and they meet up here and finish at the same time****.*"
- Isaac, physics, two-ball V-valley [fst]: "... *the balls start at the same height and then are released; at the point where they split,* ***the one that goes down the V accelerates so that it um is a little bit ahead*** *of the ball that is on the flat track linearly, but then* ***when it goes up the uh, the uphill part of the V it decelerates again to the point where um, it meets with the the uh ball that was, that was just on the flat track*** *because they have the same um amount of energy and should uh be together because they were at the same height; it doesn't matter that it went down and then went back up, the uh acceleration and deceleration should cancel each other out.*"

Figure 6.8 A physics student describes readouts for [fst] animations.

In the first two excerpts in Figure 6.8, Isaac (a physics student) reports NOGAIN-related readouts for both one-ball [fst] animations, commenting on unrealistic speed changes in each. Isaac's descriptions of the flat-valley and V-valley two-ball [fst] animations are similar to each other, and different from his one-ball descriptions. Rather than reporting NOGAIN-related readouts in either two-ball case, he reports readouts related to the balls' relative positions and to the ACCELDOWN, DECELUP, and TIE expectations.

Note that Isaac clearly connects speed-change readouts for the two-ball animations to the relative positions of the two balls when ball B is in the valley and when it reaches the end of the valley: in the flat-valley task, "…accelerates like it should, so it's *slightly ahead* … decelerates and *they meet up here*...." and in the V-valley task, "accelerates so that it um *is a little bit ahead* … decelerates again *to the point where um, it meets*…." There is no logical problem with Isaac's inference that ball B should move ahead of ball A when its speed increases, since the two balls had equal speeds before the increase in ball B's speed. There is, however, a logical problem with the inference that the distance between the balls should decrease when ball B's speed decreases from a speed higher than ball A's to a speed equal to ball A's; the speed of ball B is always at least as great as that of ball A, so the distance between the two balls should never decrease. (More precisely, the horizontal component of the velocity of ball B is always at least as large as the horizontal component of the velocity of ball A, so the horizontal component of the displacement between the two balls should never decrease.)

Isaac's reasoning about the balls' relative positions after the end of the valley is flawed. His strong expectations about relative positions appear to support the speed change inferences he makes from readouts about relative positions. His readout strategies appear to be focused on verifying that the balls' relative positions at certain points during the race meet his expectations. His readout strategies for the two-ball [fst] animations apparently fail to supply him with information relevant to the NOGAIN expectation.

- Todd, psychology, one-ball flat-valley [fst]: "*I think 1[fst],* ***it starts fast,*** *and like,* ***only when it reaches the top it slows down*** *like it has a,* ***the speed is increasing all the way*** *and I don't think that is correct."*
- Todd, psychology, one-ball V-valley [fst]: "*I think 1[fst] is wrong because it's, before it goes on the flat area again, it cannot go but* ***it is like jumping****."*
- Todd, psychology, two-ball flat-valley [fst]: *"Ok, I believe that correct is 3[fst] because,* ***although they cover the same difference, they cover it differently****. ... Yeah, I would say it is 3[fst] because the one that goes on a straight line, it only gets some acceleration by going down here, so,* ***it speed, it starts to decrease as it goes to the end*** *but then, but we see the ball that goes, on the curved line, that it will accelerate faster, but then since it loses speed to climb up, they will eventually reach at the same time in the end."*
- Todd, psychology, two-ball V-valley [fst]: *"it shows that* ***it has a difficulty in the end****, like again it just,* ***so that it's equal****."*

Figure 6.9 A psychology student describes readouts for [fst] animations.

In the first excerpt in Figure 6.9, Todd (a psychology student) reports an idiosyncratic readout for the one-ball flat-valley [fst] animation, in which he fails to point out the unrealistic speed increase at the end of the final slope. Todd's readout report for the one-ball V-valley [fst] animation is apparently related to the unrealistic speed change near the end of the final slope. Todd's readout reports for the two-ball flat-valley [fst] animation in the third excerpt from Figure 6.9. are remarkably similar to Isaac's reports for the same animation in Figure 6.8, although Todd is not so explicit about making connections between speed changes and relative ball positions as Isaac. Todd reports readouts related to the balls' relative positions at the end of the valley and to the ACCELDOWN, DECELUP, and TIE expectations. For the two-ball V-valley [fst] animation Todd apparently recognizes the unrealistic speed change near the end of the final slope, in sharp contrast to Isaac's identification of this animation as realistic.

6.5.4 Invariance and integration: [fst] judgments

A student with a coordination class useful for judging the realism of motion depicted in the [fst] animations would, by definition, coordinate in a way that integrates several useful observations for each animation and invariantly results in the same judgment for the one-ball and two-ball tasks. Students' attempts to coordinate information about the [fst] animations in the one-ball and two-ball tasks are discussed from the perspective of integration and invariance in this sub-section.

Many physics students describe an appropriate set of expectations for the one-ball tasks (ACCELDOWN, DECELUP, NOGAIN, and sometimes SAMESPEED and/or CONSTFLAT). They describe expectations for realistic motion in the two-ball tasks as if they were similar to the set for one-ball tasks, with the addition of a TIE expectation. Despite the logical inconsistencies between physics students' expectations for the motion of ball B in the valley and the TIE expectation, they seem to have a sense that their causal nets are consistent and well-connected. In fact, they often treat the TIE expectation as if it were equivalent to the SAMESPEED expectation. They also act as if they are discussing equivalent information about speed changes, whether they talk about them in terms of fixed-referent readouts (for one-ball animations) or in terms of the relative motion of two balls. As Isaac's interview demonstrated, this is often not the case; many physics students described violations of the NOGAIN expectation in the one-ball [fst] animations but did not describe those violations, for the same motions, in the presence of the second ball.

Physics students acted as if their two-ball judgements were the same as their one-ball judgments, indicating that they had a sense of invariance across the two tasks. They acted as if they were using the information available in the one-ball and two-ball situations to make coherent judgments about realism of depicted motions, indicating that they had a sense of integrating different observations. In contrast to their apparent sense of invariance, most physics students demonstrated a lack of invariance by making different judgments about the realism of the [fst] animations in the one-ball and two-ball cases. In contrast to their apparent sense of integration, most physics students demonstrated a lack of integration by failing to use the NOGAIN-related information available from fixed-referent readouts to appropriately evaluate the two-ball [fst] animations.

Psychology students who expressed the TIE expectation did not act as if it were closely connected to other parts of their causal net about realistic motion for the two-tracks situations--their sense of having a tightly woven and self-reinforcing causal net for realistic motion in the two-ball animations may not have been as strong as that of many physics students. For the flat-valley tasks, at least, the levels of integration and invariance in these psychology students' judgments of the [fst] animations may have been similar to those of physics students.

Physics students tended to make similar judgments about the two-ball flat-valley and V-valley [fst] animations. In contrast, psychology students tended to make similar judgments for the one-ball and two-ball V-valley [fst] animations. Their V-valley judgments were invariant in a way that physics students' judgments were not. Without a web of reasoning to support the TIE expectation, most psychology students seemed willing to ignore the TIE expectation during the two-ball V-valley task; after all, no single animation fit both the TIE expectation and their other expectations about realistic motion. Their judgments for the two-ball V-valley [fst] animation may not have been well-integrated (although they happened to be correct); psychology students who expected that the balls should tie were forced to *ignore* expectations and readouts related to the race outcome in choosing an animation other than [fst], rather than finding an animation that met their expectations about the race outcome as well as all other expectations. Where physics students apparently made use of readout strategies related to the TIE and SAMESPEED expectations but failed to take NOGAIN-related readouts into account, many psychology students apparently made use of readout strategies related to the NOGAIN expectation but discounted the importance of race outcome-related readouts.

6.6 DISCUSSION

This chapter has been devoted to an exploration of interactions between causal net elements and readouts. Little space went to description of interactions that led to judgments about animated motion that were apparently consistent with students' expectations. This is not because such judgments were rare--in fact, the majority of students' judgments about individual computer animations appeared to be consistent with their expressed expectations. Instead, it is because they are relatively easy to understand. Students most often attempted readouts that would detect motion violating their expectations, and they were often successful.

Most students made some judgments that were apparently inconsistent with their expectations for realistic motion. Against the background of successful judgments, the interactions that led students to inconsistent judgments are especially interesting. Students' choices for each task were the ultimate output of their efforts at coordinating information about each set of computer animations, and inconsistent judgments had a large effect on students' choices.

Judgments that were inconsistent with a students' expectations can be explained by readout problems and by feedback between readouts and the causal net. Inaccurate readouts apparently led students to errors of inclusion and exclusion; sometimes they mistakenly claimed that an animation violated their expectations, and sometimes they *failed* to detect that an animation was inconsistent with their expectations when they should have done so. Students' fixed-referent readout strategies sometimes suffered from a lack of sensitivity. Students using relative motion readout strategies sometimes failed to make use of information that may have been more easily acquired with fixed-referent readout strategies. Students using relative motion readout strategies also made systematically flawed inferences that led them to incorrect conclusions about speed changes for ball B.

Students who had apparently detected expectation violations in every motion from a set sometimes changed their readouts or their expectations in order to accept one animation from the set as realistic. The changes students made appeared to be localized and situation-specific, so that they often resulted in apparent mismatches between the students' expectations and their choices.

When judging the two-ball V-valley [fst] animation, different sorts of interconnections within causal nets appeared to have robust effects on the coordination of information about that animation, and on the judgments made by physics students and psychology students. Physics students appeared to support their TIE expectations with other expectations about realistic motion, and these interconnections in turn appeared to support their consistent use of relative motion readout strategies. Psychology students who expressed the TIE expectation appeared not to have strong interconnections to support it; although they held many expectations in common with the physics students, they made different readouts and different judgments about the animation.

CHAPTER 7—COORDINATION PATTERNS

The discussion in this chapter illustrates one way that the coordination class construct can be used to make sense of the decision-making processes of different students--processes that are complex even for the relatively bounded tasks studied here. Students' judgments are compared and contrasted at a group level, in terms of the expectations and coordination processes discussed earlier. Causal net elements (expectations for realistic motion) and readout strategies that students brought to bear in the four tasks were discussed in chapter five. Coordination processes that led students to judgments of the computer animations were explored in chapter six. A quantitative visual description of some of the decisions reported by students in their interviews is presented in this chapter. It is suggested that the phenomenology of student decision-making presented here could provide a basis for understanding some of the response patterns presented in chapter four.

The decision path diagrams presented in this chapter display some of the decisions students reported in their interviews. Decisions are represented by nodes in the diagrams, and choices are represented by arrows. Arrows lead from a node to another node (another decision) or to a final identification of one animation as most realistic. The diagrams are based on the coordination pieces from chapters five and six, as well as on the numbers of interviewed students who reported making particular choices for particular decisions. The diagrams present some of the complexity of students' decisions in a way that allows for comparisons among students and among groups. Of course, much of the complexity inherent in student coordination is hidden; the decision path diagrams make some complexity digestible without hiding all of it. No claim is made that the diagrams directly represent students' coordination systems; however, they do represent the behavior of coordination systems for a pair of situations. This is useful in itself, and is useful as a step in exploring students' coordination systems.

Decision path diagrams will be presented for the one-ball and two-ball V-valley tasks. For each decision in the diagrams, the percentages of interviewed physics students and psychology students making each choice are presented. The diagrams highlight similarities in the coordination of physics students and psychology students for the one-ball V-valley task, and also with the coordination of psychology students for the two-ball V-valley task. In addition, the diagrams highlight the uniqueness of physics students' coordination in the two-ball V-valley task; their choices appear in a different part of the decision path diagram than do those of psychology students, a part of the diagram that was not accessible in the one-ball V-valley task. These similarities and differences in coordination echo similarities and differences in the response patterns presented in chapter four.

7.1 REVIEW: EXPECTATION / READOUT PAIRS

In chapter six, readouts were described as linking students' expectations about realistic motion to their judgments. The coordination process described most often by students was the observation of some feature of an animation (a readout) inconsistent with an expectation for realistic motion (a causal net element). This process allowed students to judge the animation as depicting unrealistic motion (judgments were sometimes overturned, or even forgotten, later). Several examples of this process, made with both accurate and inaccurate readouts, were described in chapter six. The description from chapter six is extended in this section with a list of the expectations most commonly expressed in the V-valley tasks and the readouts and judgments most commonly associated with each expectation for particular V-valley animations.

The following three tables consist of descriptions of how often each expectation was expressed by students in each group, the types of readouts associated with each expectation, and the negative judgments most commonly associated with each expectation. Table 7.1 includes expectations commonly expressed for both one-ball and two-ball V-valley tasks. Table 7.2 lists the three possible race outcome expectations. Table 7.3 includes two of the more common and easily interpreted subjective expectations for realistic motion. In section 7.2, many of these expectation / readout pairs will be implemented in decision path diagrams for the V-valley tasks.

Expectations commonly expressed for both V-valley tasks	
ACCELDOWN and DECELUP expectations for slopes	• Nearly universal for students with identifiable expectations. • Associated with fixed-referent and relative motion readouts. • Accurate readouts rule out [constvx] and [sl]; inaccurate DECELUP-related readouts rule out [real] animations.
NOGAIN	• Nearly universal in one-ball V-valley task; often not expressed by physics students in two-ball V-valley task. • Associated with fixed-referent readouts. • Accurate readouts rule out [fst] and [fsl] animations.
SAMESPEED expectation for initial and final shelves	• Common for physics students; rare for psychology students. • Associated with (sometimes imprecise) fixed-referent and (sometimes inappropriate) relative motion readouts. • Accurate readouts rule out [fsl] and [sl] animations. • Effect on two-ball judgments amplified by connection to TIE expectation and inappropriate relative motion readouts.

Table 7.1 Selected properties of expectations commonly expressed in one- and two-ball V-valley tasks, including potential effects of expectation / readout combinations on student judgments.

Students usually reported accurate ACCELDOWN-related observations. Readouts related to the DECELUP expectation were normally accurate for all animations except [real], which students often judged to violate the DECELUP expectation. Students'

NOGAIN-related judgments for the [fst] animations are described in chapter six; some students also reported NOGAIN-related readouts for the [fsl] animations. The SAMESPEED expectation was expressed by many more physics students than psychology students; SAMESPEED-related readouts were apparently imprecise for one-ball animations, so that even students expressing the SAMESPEED expectation were sometimes unable to rule out the one-ball V-valley [fsl] animation. Thus, the SAMESPEED expectation appeared to have a small effect on many students' judgments in the one-ball V-valley task. The SAMESPEED expectation apparently had a more robust effect on physics students' two-ball judgments, through its connection to the TIE expectation; several physics students spoke as if the two expectations were interchangeable.

Race outcome expectations	• Associated with robust relative motion readouts. • Rule out two-ball animations with other outcomes.
TIE	• Strongly expressed by most physics students. • Expressed weakly by some psychology students.
VALLEYLOSES, VALLEYWINS	• Rarely expressed during V-valley tasks.

Table 7.2 Selected properties of race outcome-related expectations.

Many students expressed expectations related to the race outcome for the two-ball tasks. Of the three possible outcomes, only the TIE expectation was commonly expressed for the two-ball V-valley task. As described in chapter six, the TIE expectation was more commonly and more confidently expressed by physics students than by psychology students. Many psychology students expressed no preference for the race outcome in the two-ball V-valley task.

Selected subjective expectations expressed during V-valley tasks	
PAUSETOP	• More common for psychology students than physics students. • Expressed when choosing [fsl] despite NOGAIN-related readouts.
MAKEITUP	• More common for psychology students than physics students. • Associated with readouts about several animations.

Table 7.3 Selected properties of subjective expectations sometimes expressed in one- and two-ball V-valley tasks, including potential effects on student judgments.

Several students, more commonly psychology students than physics students, expressed experiential or holistic expectations. Two of these expectations, in particular, were expressed in a relatively consistent manner by several students, and seemed to have an impact on their judgments about animations. The PAUSETOP expectation was most commonly expressed by students who noticed that ball B nearly stopped at the end of the final slope in the V-valley [fsl] animations, but still judged that motion to be realistic. The MAKEITUP expectation, that ball B should not be "too slow" to roll up the final slope as depicted, was expressed in relation to many different animations; its most important use from the perspective of this chapter was in finding V-valley [fsl] animations unrealistic on the grounds that ball B should roll back down the slope.

7.2 REPRESENTING STUDENT COORDINATION

In the course of choosing animations as "most realistic", interviewed students reported several judgments about individual animations. In this section, the judgments of students from the two groups of interviews (twenty six students from a psychology course and twenty four students from a physics course) are represented quantitatively as path diagrams. The decision path diagrams were built from the coordination processes reviewed in the previous section as well as the feedback process described in chapter six. Judgment patterns for the one-ball and two-ball V-valley tasks are presented here. Comparison of diagrams for the two tasks demonstrates how the addition of the second ball increased the complexity and variety of student judgments.

The set of connections implemented in each diagram was determined by analysis of the decisions reported by interviewed students, where such analysis was possible. (Some decisions were not reported explicitly enough to allow for confident analysis; in addition, the twelve interviews with physics students that were not tape-recorded were useful only for counting judgments about which the interviewer happened to write notes.) The diagrams take the form of nodes, which represent decisions, connected by arrows to other nodes and to boxes, which represent final animation choices. Each connecting arrow is annotated with an abbreviated description of the choice represented by the arrow and the percentages of students who apparently made that decision. The percentages reported for each connecting arrow represent the fractions of students reporting a particular decision for the judgment represented by a particular node, so that percentages sum to 100% for arrows pointing out from a node. The percentages reported in a box (final choice) are calculated as the product of percentages for all arrows in the path leading to that box. Percentages in each box represent the overall fractions of students reaching that box, so that the percentages in all of a diagram's boxes sum to 100%. Percentages for psychology students (physics students) are labeled LT (MT), consistent with the group labeling system from chapter four.

7.2.1 One-ball V-valley decision paths

Figure 7.1 summarizes the judgment patterns of students from each group in the one-ball V-valley task. Decision paths for all students begin at node A and end at a box, which represents a final animation choice. Paths are intended to indicate a series of decisions; a student following the path ABE[sl] will have reported different decisions than a student following the path ABCD[sl], even though the two students identified the same animation as depicting realistic motion. Paths are not intended to depict a time order for decisions; two students following the path ABCD[real], for example, will have reported similar decisions, but will not necessarily have made or reported them in the same order. Node D, however, which represents a decision that involves feedback, can only be reached after all five animations have been judged unrealistic. (To indicate that the decision at node D involves feedback, arrows leading from node D have dashed lines and are described with italicized text.)

As the description of the arrow from node A to node B indicates, all interviewed students who described observations about the [fst] animation expressed the NOGAIN expectation. Thus, the decision paths for all interviewed students follow the arrow from A to B, and no interviewed student identified the one-ball V-valley [fst] animation as realistic. The decision paths of students reporting accurate ACCELDOWN-related readouts about the [sl] and [constvx] animations follow the arrow from B to C. Some students did not object to the motion depicted on the slopes of the [sl] animation; their decision paths follow the arrow from B to E, and from E (with a DECELUP-related objection to the motion depicted on the final slope in [constvx]) to the box labeled [sl].

Students whose decision paths reached C fell into three categories. Some students did not object to the [real] animation and did object to [fsl] for one of several reasons (some students found [fsl] unrealistic due to NOGAIN-related readouts, some students found it unrealistic due to SAMESPEED-related readouts, and some student reports were coded as MAKEITUP-related judgments). Students in this first category identified the motion depicted in the [real] animation as realistic. Other students reported an inaccurate DECELUP-related readout for [real] and did not object to [fsl], leading them to identify [fsl] as depicting the most realistic motion. Still other students objected to motion depicted in both [real] and [fsl]. The decision paths of these students follows the arrow from C to D. A path through node D indicates that a student had objected to all five animations, so that choosing any animation as realistic required a process involving feedback. From node D, students revised either their readouts or their expectations of realistic motion to choose [sl], [fsl], or [real].

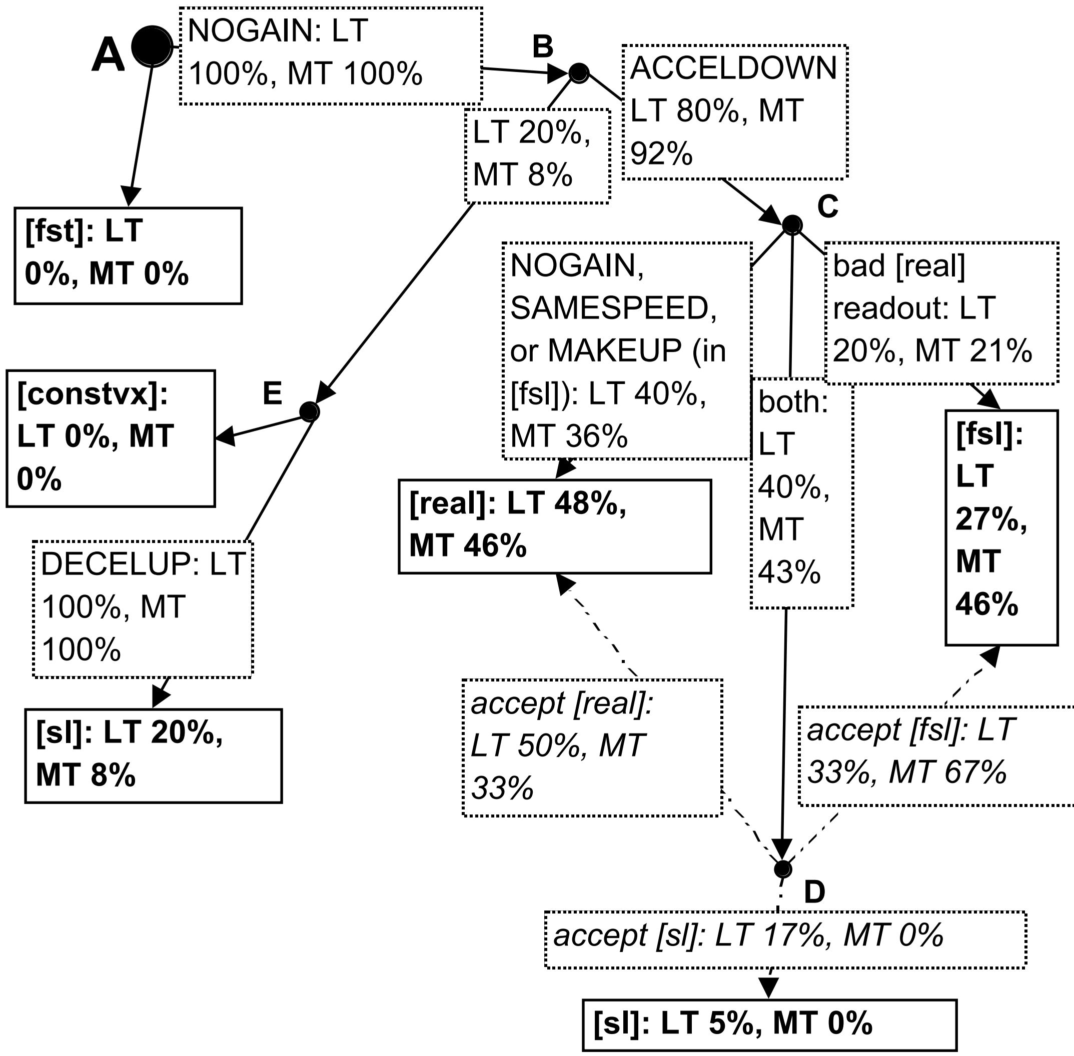

Figure 7.1 Decision paths for the one-ball V-valley task.

Illustrative quotations are provided in Table 7.4 below to demonstrate how the diagram in Figure 7.1 represents a particular student's decisions in the one-ball V-valley task.

Node progression	**Transcript excerpts from Felix, a physics student, in the one-ball V-valley task**
A → B (NOGAIN)	*Alright, that looks a little funny, because* ***it almost comes to a stop there and then picks up speed****.*
B → C for [sl] (ACCELDOWN)	*...seems like, oh, 3[sl]'s wrong.* <Interviewer: 3[sl]'s wrong?> *Well,* ***it looks like it doesn't pick up any speed on that slope****. It should...*
C → D → [fsl] (objects to [fsl] and presumably [real], but revises SAMESPEED expectation to choose [fsl])	*...Essentially number 4[fsl] again but still, I don't know, seems like it loses too much like* ***it almost comes to a stop, and <indecipherable> like perpetual motion once it comes to the top*** <Interviewer: So tell me what you like about 4[fsl]> *Um, the other ones it seem like, 'cause ideally when it comes to the top it should have the same velocity that it does right here...* <Interviewer: Why is that?> *Um, potential energy, gets transferred to kinetic energy, I mean the ball's rolling so you lose a little torque, but, um, it slows down considerably when it comes to the top of this, and that's ideally what it should do, so yeah, I guess let me say number 4[fsl] again.*

Table 7.4 Excerpts illustrating a physics student's progress through the one-ball V-valley decision path diagram.

The decision paths representing coordination by most psychology students (LT) and by most physics students (MT) are remarkably similar for the one-ball V-valley task. Except for a smaller percentage of LT than MT students reporting ACCELDOWN-related objections at node B, and somewhat different distributions of feedback-related judgments from node D, they are virtually identical when viewed at this level of detail. (Note, for example, that splitting the path from C to the [real] box into an arrow for each specific objection to [fsl] might reveal some finer-grained differences between path distributions for the two groups.) The coordination of the majority of students from each group led through node C (and for many students in each group, node D) to a final choice of [fsl] or [real].

7.2.2 Two-ball V-valley decision paths

Figure 7.2 summarizes the judgment patterns of students from each group in the two-ball V-valley task. Decision paths for all students begin at node A and end at a box, which represents a final animation choice. Node A represents the choice among race outcomes.

Two animations depict ball B losing the race, so that an expression of the VALLEYLOSES expectation did not narrow the field to one choice. Therefore, the "V-LOSE" arrow leads from A to B, where node B represents a choice between the [sl] and [fsl] animations. Students whose decision paths led to node B, and who made appropriate ACCELDOWN-related readouts and judgments, would follow the arrow labeled "slopes" to identify the [fsl] animation as depicting the most realistic motion; others might follow the arrow leading from B to the [sl] animation. Only one interviewed student for whom a decision path could be traced clearly expressed a belief that ball B should win the V-valley race. That student's decision path appeared to be AB[fsl].

Two interviewed students (one physics student and one psychology student) clearly expressed the VALLEYWINS expectation in the two-ball V-valley. Their decision paths appeared to follow the arrow labeled "V-WIN", and they identified the [real] animation as most realistic. Although these two students made specific motion-related objections to some animations, race outcome was apparently important to their decision, and they described ruling out some animations because of their race outcomes.

The majority of interviewed physics students (labeled MT in the diagram) and some psychology students (LT) clearly indicated their expectation that the two balls should tie in the V-valley race. Their decision paths led to node C. Three arrows lead from C, indicating the three choices observed among students who expressed the TIE expectation. Some students reported NOGAIN-related readouts for [fst] and no objections to [constvx]. The decision paths of these students followed the arrow labeled "NOGAIN" to the [constvx] box. Some physics students reported ACCELDOWN- or DECELUP-related objections to [constvx] but no objections to [fst]. Their decision paths followed the arrow labeled "slopes" to the [fst] box. Other students found the motions depicted in both [constvx] and [fst] to be unrealistic, so that their decision paths led to node D. Students reaching node D had ruled out each of the five animations as unrealistic, so that each arrow leading from node D represents a process involving feedback. To reach [constvx] from node D, a student had to align his or her expectations and readouts for [constvx] by revising expectations related to speed changes on the valley slopes or revising readouts related to speed changes in the [constvx] animation. Students who reached [fst] from D reported either distrusting their NOGAIN-related readouts or lowering their expectations about how realistic the motion depicted in even the "most realistic" animation should look. The third arrow, leading from D to G, indicates that some students lost confidence in the TIE expectation altogether, and re-considered the realism of non-tying animations.

The fourth arrow from A leads to E. This arrow indicates that some students (the majority of interviewed psychology students) expressed no clear preference for the race outcome. Nodes E through I in Figure 7.2 are very similar to nodes A through E in Figure 7.1. A slight deviation from a strict analogy is that students whose decision paths led from node G to the [real] box all reported NOGAIN-related objections to [fsl], rather than one or more of the objections encompassed by the arrow from C to D in Figure 7.1.

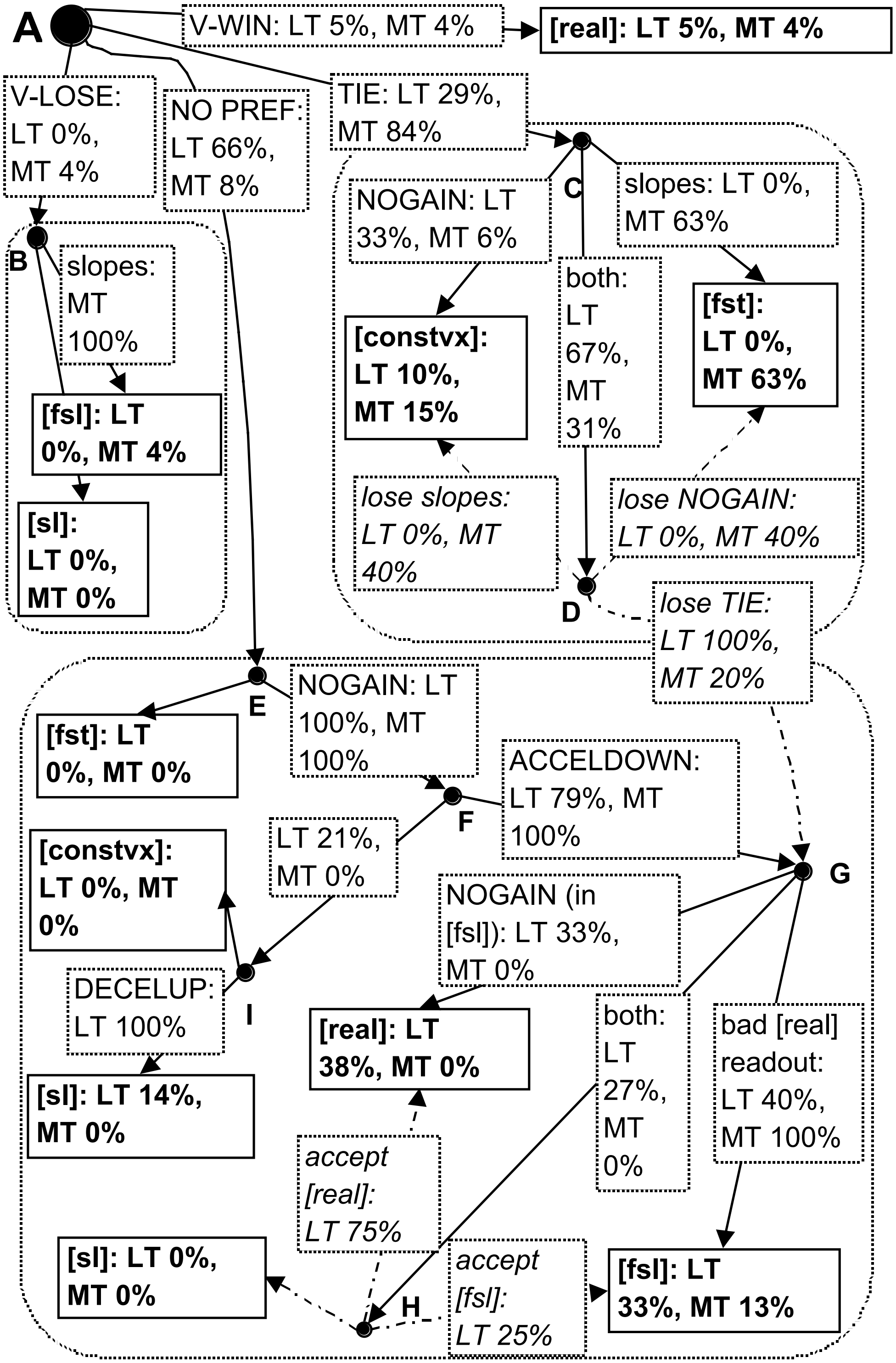

Figure 7.2 Decision paths for the two-ball V-valley task.

Illustrative quotations are provided in Table 7.5 below to demonstrate how the diagram in Figure 7.2 represents a particular student's decisions in the two-ball V-valley task.

Node progression	**Transcript excerpts from Stephen, a psychology student, in the two-ball V-valley task**
A → C and initially to [fst] (ACCELDOWN, DECELUP, TIE)	[in constvx]*...it doesn't seem that realistic to me that* ***they're at the same point all the way along****, I would imagine ... that it accelerates and decelerates* ... [in fst] ...***the top one seems to be going more at a steady speed while the bottom one goes faster and then slower and they end up pretty much at the same place that****, that seems realistic to me.*
DECELUP readout problem	[in real] *...that seems like the effect of* ***going up the hill doesn't really slow it down as much as I****...*
ACCELDOWN	[in sl]*...this one doesn't seem very realistic to me, number 4[sl], ...* ***going down that ramp it doesn't seem like that ball picks up really any spee****d.*
TIE	[in fsl] *... I still don't think that it would* ***slow down that much that it would, that the top one would pass it****, it doesn't seem as realistic to me.*
D → G NOGAIN causes feedback to lose TIE expectation	[fst again] *... I think I like ... 2[fst] ... hold on, hmm ... right* ***at the very end it seems to almost accelerate more than would be realistic*** *...* ***it's really almost stopped there*** *and what makes it get that last little push to get over the top? So, now I'm not sure about 2[fst].*
G → [fsl] DECELUP readout problem	*I guess it's between 3[real] and 5[fsl] ... I guess I would go more with 5[fsl] because it does,* ***it doesn't seem like it slows down coming up the ramp as much on 3[real]****.*

Table 7.5 Excerpts illustrating a psychology student's progress through the two-ball V-valley decision path diagram.

The resemblance between the decision paths for the group of interviewed psychology (LT) students, for the two-ball V-valley task in Figure 7.2 and the one-ball V-valley task in Figure 7.1, is remarkable. The coordination of the majority of interviewed psychology students in the two-ball V-valley task led through node G (and for many students in each group, node H) to a final choice of [fsl] or [real], just as their coordination in the one-ball V-valley task led to the analogous section of the one-ball V-valley decision path diagram. Most of those students expressed no clear preference for the race outcome, so that their decision paths led from node A to node G through nodes E and F. Even among psychology students expressing the TIE expectation, however, most decision paths did not end in the TIE-related section of the decision path diagram, but instead passed through nodes C and D to node G. The group of interviewed psychology students appears to have made similar coordinations for the one-ball and two-ball V-valley tasks. Although individual psychology students may not have coordinated invariantly across the two tasks, the collection of decision paths taken by the group as a whole did appear to be consistent across the two tasks. As a group, the interviewed psychology students were not particularly sensitive to the shift in context from the one-ball to the two-ball task. (Note that relative motion readout strategies could be implemented in the two-ball task but not in the one-ball task, so there may have been coordination differences, even for students completely free of race outcome expectations, that would not be apparent from the diagrams as constructed here.)

In contrast, the collection of two-ball V-valley decision paths for interviewed physics students differs markedly decision paths for the same group of students in the one-ball V-valley task. Decision paths for the majority of physics students in the two-ball V-valley task ended in the TIE-related area of the decision path diagram, leading through node C (and for some students, node D) to a final choice of [fst] or [constvx]. In the one-ball V-valley decision path diagram, there is no analogous section. The collection of decisions made by the group of interviewed physics students appears, from this point of view, to be highly sensitive to the one-ball to two-ball context shift.

7.3 COMPARING WITH LARGE N PATTERNS

In chapter four, V-valley response distributions were presented for large groups of students. Among the patterns found were that:

- LT and MT students produced similar response distributions for the one-ball task;
- MT response distributions for the two-ball task were very different from those for the one-ball task; and
- LT response distributions for the two-ball task were more similar to one-ball response distributions than to two-ball MT response distributions.

How do these patterns relate to patterns of coordination? Similarities and differences in response distributions do not necessarily correspond to similarities and differences in underlying coordination processes; Figure 7.1 and Figure 7.2 show that the same response can be reached through different coordination paths, while similar coordination paths can lead to choices of animations with different features. For lecture presentations of the tasks, no information about students' coordination is available. However, coordination patterns for interviewed students, presented in the previous section, can be summarized as a virtual echo of the response patterns described above. Among the patterns found were that:

- the decisions of LT and MT students were distributed over similar paths for the one-ball task;
- the decisions of MT students for the two-ball task were distributed very differently from those for the one-ball task; and
- the decisions of LT students for the two-ball task were distributed over paths more similar to one-ball decision paths than to two-ball MT decision paths.

The similarity in patterns raises the possibility that LT and MT students in the large group presentations of the tasks may have used coordination processes similar to those used by the interviewed students. Figure 7.3 and Figure 7.4 suggest that this may be the case. Each figure presents the response patterns of a large group of students alongside the percentages reaching each response in the path diagrams. (Note that the "path diagram" percentages are not identical to the response patterns for the complete groups of interviewed students. They represent only the 15-20 interviewed students from each group for whom decision paths could reasonably be determined.) Error bars proportional to the square root of the number reaching each response are shown, using a nominal sample size of N=20 for the path diagrams.

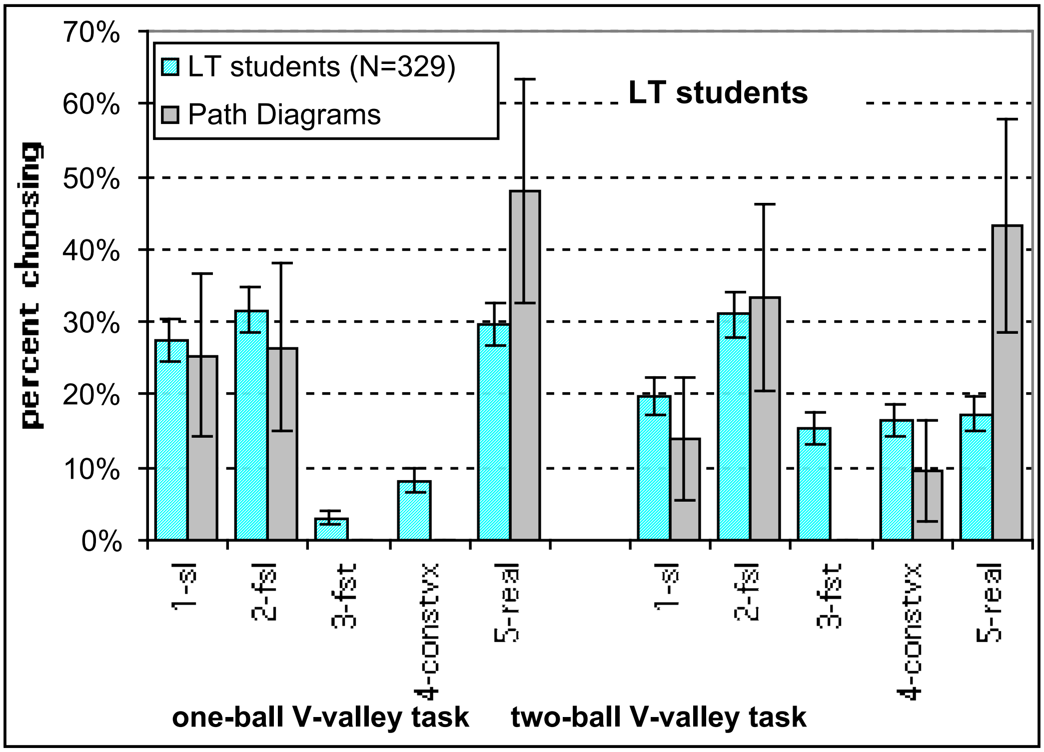

Figure 7.3 LT students: V-valley comparison charts for Path Diagrams vs. Large N data.

For LT students, the pattern of responses is similar for the large groups of students and for the path diagrams, although the path diagrams lead to the [real] animations with a higher frequency than did students in large groups.

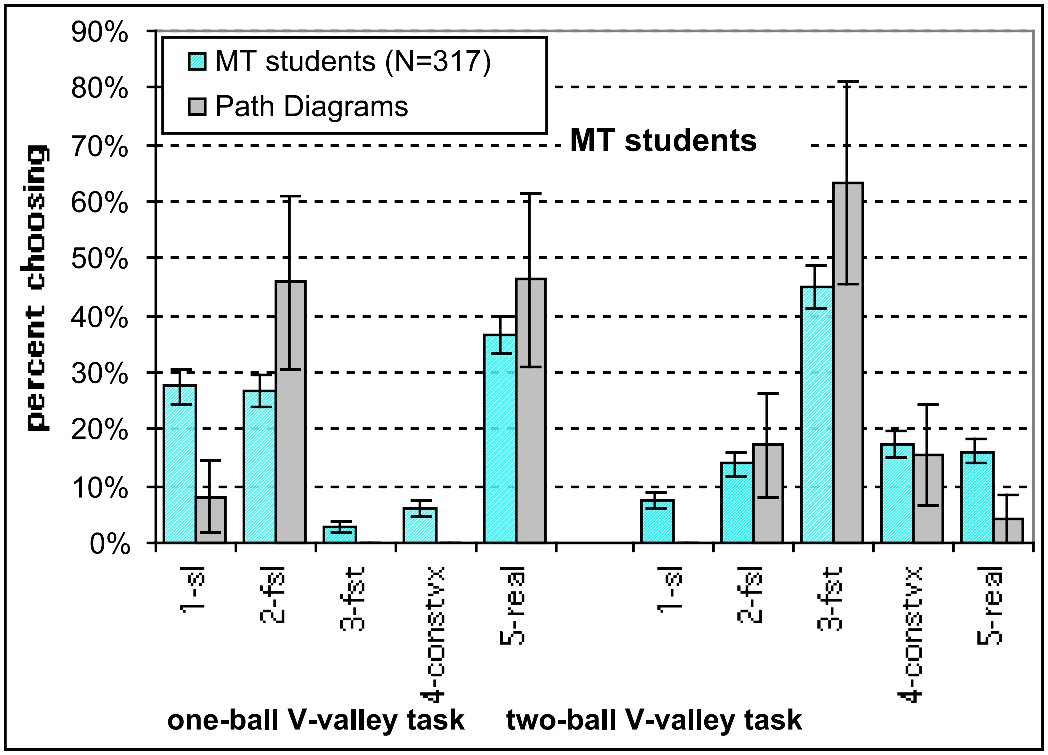

Figure 7.4 MT students: V-valley comparison charts for Path Diagrams vs. Large N data.

For MT students, response patterns are also similar for the large groups of students and the path diagrams, although the path diagrams lead to the one-ball [sl] animation with a lower frequency than did students in large groups.

CHAPTER 8—SUMMARY

The coordination class construct proved useful for the analysis of student decisions in the one-ball and two-ball tasks. When the tasks were administered to students in large lectures or in interviews, comparisons between the responses for Less Technical (LT) and More Technical (MT) groups of students revealed a pattern of similarities and differences. When the decision-making processes of the interviewed students were analyzed with the coordination class construct and decision path diagrams in chapter seven, comparisons between the *coordination* patterns of the LT and MT groups echoed comparisons between the groups' *response* patterns.

The elements of the coordination class construct -- readout strategies and the causal net -- were useful for describing the elements of student decision-making. Students' expectations about realistic motion fit naturally into the construct as elements of their causal nets, and their observations about animations fit naturally into the construct as the products of readout strategies. Interactions among these decision-making elements provided a way to describe the processes of student decision-making in the tasks. The performance criterion for the coordination class construct, extracting information from the world in an integrated and invariant way, provided a yardstick against which to measure students' decision-making processes.

Students' judgments about which computer animations depicted the most realistic motion for the two-tracks situations involved several decisions about features of the motions depicted. The coordination class analysis broke those complex judgments into simpler elements and processes. Description of decision-making processes in terms of the coordination class construct conveyed some of the complexity of those decision-making processes while allowing for comparison, across the several decisions reported by each student and also across decisions reported by different students.

Analysis with the coordination class construct suggested that a student's causal net was not necessarily the most important factor in a judgment. For the majority of final choices made by interviewed students, the collection of expectations expressed during a task did not uniquely single out the animation identified as depicting the most realistic motion. Students often made inaccurate readouts that led them to choices apparently inconsistent with their expectations. In particular, the majority of decisions against choosing the realistic [real] animations in the one-ball tasks were driven not by expectations incompatible with realistic motion but by faulty readouts about speed changes on the final slope.

Analysis with the coordination class construct facilitated comparisons among students' decision-making performances. Many of the ideas students expressed could be mapped to a small set of expectations about realistic motion, so that performances could be compared by whether students expressed this or that subset of expectations. Students' observations about animations implied two general classes of readout strategies with characteristic strengths and weaknesses, so that performances could be compared by students' methods of describing readouts as well as with the particular readouts they reported.

Most judgments appeared to involve patterns and processes of decision-making in which students searched for readouts that violated their expectations. Students sometimes found such violations in all animations from a set, in which case they made use of a variety of feedback paths to adjust readouts or expectations so that one animation could be identified as depicting realistic motion. Coordination class analysis made such similarities evident, and decision path diagrams facilitated quantitative comparison of decision-making processes for different samples of students. For the one-ball tasks, differences among the decision-making processes within the MT and LT groups were comparable to differences across the groups. For the two-ball V-valley task, group differences in judgment seemed to result from confident use of school physics knowledge by students in the MT group to support the TIE expectation, which in turn supported the use of relative motion readout strategies by students from the MT group.

The finding that in the two-ball V-valley task MT students were *more* likely than LT students to make mistakes characteristic of relative motion readouts stands in sharp contrast to the Trowbridge and McDermott (1980) finding, described in chapter 2, that students beginning more mathematically sophisticated introductory physics courses are *less* likely than students beginning less mathematically sophisticated courses to make these mistakes (in a simpler situation). From a coordination class perspective, the contrasting findings can be understood in terms of interactions among causal net elements and readout strategies in different contexts. MT students are likely to possess causal net elements that strongly relate the race outcome to the realism of the depicted motion; this leads them to rely heavily on relative motion readout strategies for making observations about the two-ball animations. LT students are *un*likely to possess causal net elements that strongly relate the race outcome to the realism of the depicted motion, leading them to try several different readout strategies for making observations about the two-ball animations. However, the situation presented to students in the Trowbridge and McDermott study was unlikely to differentially trigger connections to race outcome for different groups of students, so that more sophisticated students, presumably applying more sophisticated readout strategies and causal nets, were more likely to make correct judgments about the balls' relative speed.

Many other models of cognition treat concepts as essentially elementary units of cognition, and do not fare so well in explaining this pattern of contextual dependence. For example, some models of "misconceptions" imply that students use particular naive ideas consistently (Caramazza, McCloskey, & Green, 1981; McCloskey & Kohl, 1983). This is at odds with the finding that one type of student is likely to use a set of "misconceptions" about relative motion in one situation and unlikely to do so in a slightly different situation, while a group of "more advanced" students is more likely than the first type to use the "misconceptions" in the first situation, and less likely than the first type to use them in the second situation. To take a second example, consider some models of conceptual change, which imply that students' incorrect conceptions can be "replaced" by more appropriate conceptions (Hewson, 1985; Posner et al., 1982). Under these models, once students have learned a new conception, the old one has disappeared, making it very difficult to explain the comparative "absence" of a problematic conception about relative position and relative speed in presumably less sophisticated LT students as measured in the two-ball V-valley situation, in conjunction with the "recurrence" of the problematic conception in the same situation in so many, presumably more sophisticated, MT students. The coordination class model of cognition is more successful at explaining complex patterns of context dependence than these other models, largely because it does not posit a monolithic "concept" that students either apply or fail to apply in a given situation, but instead treats what the other models would describe as "concept use" as a series of processes involving elements (causal net elements and readout strategies) that must be understood at a smaller grain-size.

Analysis with the coordination class construct captured significant adaptability in students' decision-making processes. Individual students were seen to use sets of expectations that were logically inconsistent with one another. Individual students were also seen to use fixed-referent and relative motion readout strategies that sometimes gave conflicting readouts. When students altered readouts or their causal net to re-accept an animation they had previously rejected, the alterations seemed to take the form of local exceptions, rather than to result in global changes that could maintain coherence within their coordination systems.

The original specification of the coordination class construct (diSessa & Sherin, 1998) implies that a person with a coordination class would produce well-integrated and invariant readouts for a particular class of information within some reasonably broad set of circumstances. As demonstrated here, novices may not coordinate invariantly even across closely related contexts. The coordination class construct proved useful for analysis despite the fact that novice coordination attempts were generally *not* indicative of their possessing coordination classes. The term "coordination system" was introduced to facilitate description of students whose coordination systems do not meet the criteria specified for coordination classes. A coordination system is the collection of readout strategies, causal net elements, and processes with which a person coordinates; the system's performance can be characterized by its particular successes and failures of integration and invariance.

In the original specification of coordination classes, the distinction between a readout strategy and a coordination class is somewhat unclear. It is not clear whether the distinction between the two is simply based on scale, or if there are more qualitative differences. Consider the following chain of reasoning. One might describe very simple readout strategies useful for determining the position of an object in an animation. One might describe more complicated readout strategies that require inferences made from a few simpler observations, such as a strategy for reading out the relative speeds of objects from changes in their relative positions. This second strategy would, then, appropriate causal net elements -- presumably, relationships between relative position and relative speed -- to construct a class of information from multiple readouts -- presumably, observations of relative position. In the same spirit, one could describe a readout strategy (again including causal net elements) for something that requires an extended series of observations and inferences, such as determining which animation from a set depicts the most realistic motion. One could imagine extending this to describe readout strategies sufficiently complex to read out any particular class of information, but that is precisely the job of a coordination class. Is a coordination class, then, just a readout strategy that meets a certain set of criteria, or is there a qualitative difference between readout strategies and coordination classes? If there are qualitative differences between coordination classes and readout strategies, clarification of those differences will re-frame discussions of coordination classes and readout strategies.

The open-ended-ness of the interview methods in this study limited the precision with which students' readout strategies, causal nets, and coordination processes could be characterized. Students selectively described their reasoning in the course of the interviews, often providing incomplete and intricately interwoven reports of readouts, expectations, and decisions, so that interpretation of a student's statements frequently required the researcher to make subjective judgments about the student's intent. Students' statements provided insight about the reasoning behind some of their expectations (TIE, for example). More often, students reported their expectations as essentially fundamental units (ACCELDOWN, for example). These expectations may have been seen as fundamental by the students, or they may simply have felt no need to provide further details about their reasoning. In a similar way, students provided limited information about the strategies behind their readouts. Students may, in fact, have lacked the ability to describe their readout strategies. Structured questions and tasks designed with the coordination class construct in mind might allow a firmer understanding of the elements and processes involved in students' coordination.

Some inconsistencies in students' coordination could not be easily characterized as problems of integration or invariance. The existence in a coordination system of conflicting causal net elements, or pairs of readout strategies that produce mutually inconsistent results, can *lead to* invariance but does not in itself constitute invariance. Detecting conflicts within, say, a causal net containing the {ACCELDOWN, DECELUP, NOGAIN, SAMESPEED, TIE} set of expectations requires logical operations, rather than integration or invariance. This ambiguity makes it impossible to describe some shortcomings of coordination systems within the terminology provided by the specification of the coordination class construct. In addition, differences and similarities across students would not be appropriately characterized as integration or invariance, but terminology suitable for such characterization would be useful.

An understanding of the processes behind students' decisions is necessary for diagnosis of students' apparent difficulties with judgments. As the results of this study illustrate, different judgments do not imply different causal nets. Judgment differences were observed to result from differences in readout strategies or differences in coordination processes that were not necessarily linked to differences in expectations about realistic motion. This has obvious implications for research on student learning and for evaluation of student learning. For example, consider an instructor who observes a student making inappropriate judgments and intervenes with the assumption that the student needs to work on his or her causal net. The intervention may serve only to confuse a student whose difficulty stems from inappropriate readout strategies rather than from an inappropriate causal net. Consider many of the students in the present study. They clearly understood that rolling up and down slopes would result in speed changes, but they experienced serious difficulty observing whether or not the expected speed changes had occurred. Attempting to teach the students about what happens to balls on slopes would have been no help to them whatsoever; however, helping students learn reliable techniques for *reading out* the relevant speed change information might have greatly increased their accuracy in distinguishing realistic motion from unrealistic motion.

The coordination class construct has many implications for teaching, which differ from the implications of many "misconception" or "conceptual change" models. For instance, a coordination interpretation of students' reasoning could lead to increased communication with students about metacognition, in terms of helping students to recognize which causal net elements and readout strategies they use for decision-making in different situations, and to recognize potential problems with integration and invariance in their own coordination. The other models imply that a simpler "elicit", "confront", and "replace" method of teaching, in which incorrect conceptions can be rooted out and replaced with more appropriate conceptions, could be successful. Under such models, metacognition may not be very important. The coordination interpretation suggests that teaching cannot systematically take the form of confronting students with their incorrect conceptions, since there is no coherent unit of incorrect conception that could be confronted and then removed or replaced. Too many parts are involved in cognition, and the ways in which different parts work together are too complicated and context dependent, for any hope to survive of dealing with them as a single unit. Far from complicating the matter of instructors understanding student reasoning or students understanding their own reasoning, however, the coordination class model simplifies it by providing a useful guide to different parts of that reasoning, signified by readout strategies, the causal net, and coordination processes.

The results of this study illustrate that achieving invariant coordination is a substantial challenge. The processes and elements involved in coordination, even for the relatively limited task of recognizing realistic motion, proved to be complex and variable. When students were faced with a situation in which they had to adapt their coordination systems to identify an animation as depicting realistic motion, they tended to ignore global consequences of the adaptations; in so doing, they gained flexibility at the cost of losing invariance. Consider the example of Isaac, spread across several sections of chapter 6; in the feedback process of accepting the one-ball V-valley [fsl] animation as depicting realistic motion, he gradually lowered his standards for the SAMESPEED expectation, but in the process of accepting the two-ball [fst] animations as depicting realistic motion he re-asserted the importance of SAMESPEED-related coordination. Isaac offered no explanation for why such shifts were warranted, and in fact showed no awareness that any shift had taken place. The majority of interviewed physics students exhibited dramatic shifts in NOGAIN-related coordination across the one-ball and two-ball V-valley [fst] animations.

This suggests that appropriately incorporating school physics knowledge into a coordination system is difficult. Learning in one context might cause adjustments in the complex of causal net elements, readout strategies, and coordination processes that a student brings to bear in that particular context. If the student's coordination system is not tightly coherent, coordination in a slightly different context may very well remain unaffected, as if no learning had occurred. Alternatively, coordination in a different context may shift inappropriately, as seemed to be the case when many physics students applied the narrative of energy conservation to support the expectation that a realistic two-ball animation should result in a tie, in a way that psychology students (presumably less likely to have incorporated school physics knowledge into their coordination systems) did not.

Descriptions of cognition and learning in terms of coordination processes can guide the development and evaluation of instructional techniques. In addition to focusing on the causal net (which is perhaps the more obvious cause of conceptual problems) the coordination class construct and the findings reported here imply that instruction should aim to help students develop and consciously monitor readout strategies. Instructional strategies are also needed to help students develop techniques for maintaining and evaluating integration and invariance in their own coordination. This might take the form of instruction to create links from particular causal net elements to multiple readout strategies and to help students recognize when particular readout strategies and causal net elements can be appropriately applied. The process of feedback could be particularly powerful for learning, with the caveat that feedback often leads to local changes and inconsistent coordination rather than global changes in the coordination system.

There are many opportunities for continued study of student coordination, and of the utility of the coordination class construct. Targeted protocols are needed to allow more precise characterization of students' readout strategies, causal nets, and decision-making processes. An example, for studying readout strategies related to forces, might be to provide students with a set of situations and ask them to identify the forces present in each situation, and to provide the same students with a list of factors (i.e. contact, color, motion, …) and ask them to indicate which ones could be used to gain information about forces present in a situation. In addition to providing information about readout strategies, such an approach could provide information about students' conscious awareness of their readout strategies. To address questions about learning, study of the evolution of students' coordination during instruction, especially instruction designed with coordination classes in mind, would be relevant. To address questions about whether experts possess coordination systems that might actually be classifiable as coordination classes, and to aid in further clarification of the theoretical description of the coordination class construct, the characteristics of experts' coordination systems should also be studied.

This dissertation demonstrates that the coordination class model is worthy of further investigation. Coordination of readouts and causal net elements provides a more satisfactory model for understanding the reasoning students demonstrated in this study than would models that treat concepts as elemental units to be applied (or not) in their entirety. Adopting a coordination class perspective of student reasoning could allow researchers and instructors to see problems and possibilities difficult to see from other perspectives. For instance, the knowledge elements (causal net elements) involved in decision-making are much smaller than what would ordinarily be identified as a concept, and readout strategies can be at least as important to students' decisions as the causal net. Even more important, perhaps, are the coordination processes through which causal net elements interact with readout strategies to produce decisions. By helping to parse student decision-making into small elements and a series of processes, the coordination class perspective facilitated an understanding of the mechanisms behind the context dependence exhibited by different groups of students in the study, rather than just a phenomenological description of those context dependencies. This understanding appears natural within the coordination class perspective, but cannot easily be made compatible with many other models of cognition.

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