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.