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.