Uncommon Knowledge:
Student Behavior Correlated to Conceptual Learning

Ronald K. Thornton

Professor of Physics and Education
Center for Science & Mathematics Teaching
Tufts University-Medford, MA USA

Summary. – We have observed, over entire semesters, by direct observation and video analysis, groups of students learning force and motion (mechanics) concepts in introductory physics learning laboratories that use real time data-logging tools and the *RealTime Physics Mechanics* curriculum. This and many previous studies show that most students (75 to 90%) learn force and motion concepts in this situation. This paper will explore the behavior of students learning conceptually (or not). A detailed analysis has identified four behaviors that correlate strongly (positively or negatively) with learning conceptually. The behaviors are asking open or closed questions, giving explanations based on cause or principle, and using or linking multiple representations. Some of actual student behavior is "uncommon knowledge" for teachers since it is different from common expectations. We also find evidence for a conceptual development process that is most easily described in four phases.

PACS 01.40.Fk

1 – Introduction

In English, "common knowledge" is that which is generally believed to be true in a particular context by a particular group. Common knowledge is often accepted without careful examination and may or may not be true. "Less is more" is common knowledge among curriculum developers. "Less is more" among particle physicists leads to the common knowledge that "the vacuum is everything." "Uncommon knowledge" is not widely thought to be true. This paper will explore the behavior of students learning conceptually (or not learning) in an introductory university physics course. Much of actual student behavior turns out to be “uncommon knowledge” for teachers.

Collaborators in this work are Dr. Allan Risley (psychology & physics) of the Center for Science and Mathematics Teaching, Tufts University and Professor Maria Kozhevnikov (cognitive psychology & physics) now at Rutgers University but formerly at the Center. Detailed discourse analysis was done by Kevin O’Connor and Anna-Ruth Allen of the University of Wisconsin, Madison. Primary funding was provided by the National Science Foundation. *

2 – Research Questions

We have been exploring four primary research questions.

- Does the behavior of the students who learn concepts differ from those who do not?
- Do specific learning behaviors correlate with conceptual learning?
- Is there evidence for a conceptual development process?
- What kinds of group interactions are common and how do group dynamics affect the students in their effort to learn?

This paper will discuss some of what we have learned for the first three.

3 – Research Setting

We observed students who took a Tufts University second-semester calculus-based introductory physics course. (Most students take physics in the first semester.) The students are primarily engineers and future science majors. Most students are in their first year and are 18-19 years old. Tufts students are generally academically talented (11 applications for every place) but as is true for students in other selective universities, this does not mean they know physics concepts.

The course has traditional lectures three times per week and traditional end of the chapter problems are assigned. The weekly laboratories (about 2 hours) are non-traditional conceptual learning laboratories using the *RealTime Physics Mechanics* [1,2] lab curriculum that we developed. Students work in groups (usually 3) and use real-time data logging tools to collect and analyze data from the physical world. In the motion and force laboratories they primarily use motion detectors and force probes--*Vernier* interfaces and probes with *LoggerPro* software[3]. The curriculum is guided discovery and allows 80-90% of students to understand force and motion concepts.

* NSF Division of Research, Evaluation, and Communication. Project number REC9903309

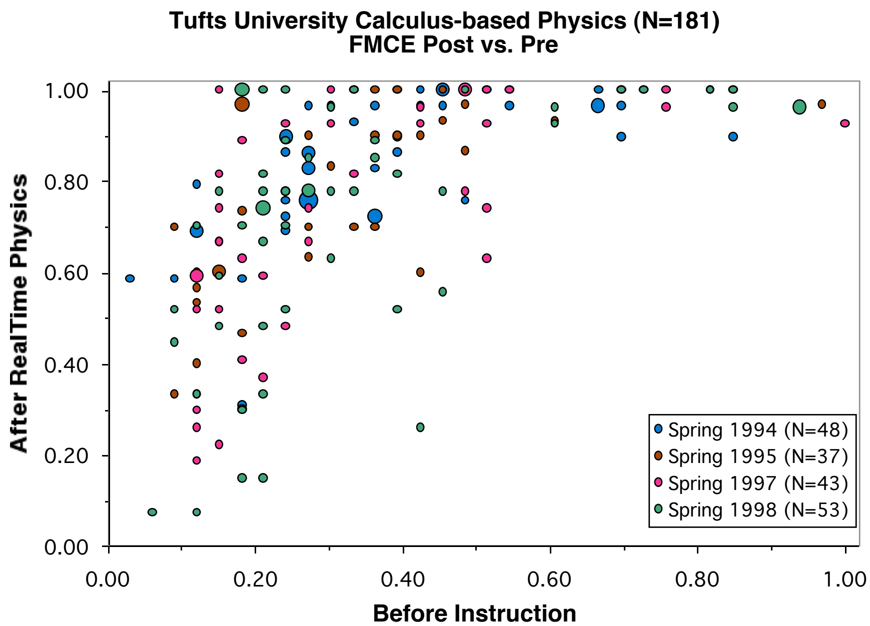

Fig. 1: Comparison or pre and post performance scores on the Force and Motion Conceptual Evaluation (FMCE) for 181 students in the course described in Section 3. Students who started low and finished low are in the lower left hand corner. Students who finish high are along the top edge of the figure.

4 – Research Methods

We observed students in the laboratory of the course described above. Three of the six lab stations were equipped with camcorders aimed at the students and remote mikes. Computer screens were also recorded. Forty student trios were observed closely in 4 years and 11 were useful for detailed study. Five groups have been observed in excruciating detail. Students were observed over the entire semester although not every lab was recorded for every trio.

4.1 Evaluation of student conceptual knowledge

Because we wish to correlate behavior with conceptual learning, we needed a reliable means to assess student conceptual knowledge. We know from our research that course grades are not a reliable means to assess student conceptual knowledge. We are using the *Force and Motion Conceptual Evaluation (FMCE)* [4] for pre and post measure of conceptual understanding of kinematics and Newton's Laws.

We have categorized students using their pre and post instruction scores on the *FMCE.* Figure 1 shows a scatter plot of the conceptual scores of 181 students in the course we are studying. The horizontal axis shows a measure of conceptual knowledge as students start the course. Students with little conceptual knowledge have low scores to the left. The vertical axis is a measure of conceptual knowledge at the end of the course. Students who do well are higher in the diagram. We are interested in three categories of students.

- A student who begins low (below 25%) and ends low is designated low-low or L/L. These students appear in the lower left-hand corner of Figure 1.
- A student who begins low and finishes high (78% or above) is low-high or L/H. These students appear in the upper-left hand corner.
- Medium-high or M/H students start between low and high and end up high. These students are in the upper-middle of Figure 1.

Notice that there is a "threshold" effect. Starting above "threshold" (about 25% on the pre evaluation) essentially guarantees a high finish when students experience *RealTime Physics*. Students scoring below 25% on the *FMCE* know very little kinematics and essentially no mechanics (force and motion) concepts. There are essentially no medium-medium students

We are particularly interested in comparing low-low and low-high students since they start at the same place and end up with very different results. One considerable research problem with an effective learning environment is that there are very few low-low students to study. In some years there are none.

4.2 Justification for using the Force and Motion Conceptual Evaluation (FMCE)

We have spent many years creating effective learning environments for introductory science (physics) courses (curricula, tools, pedagogical methods, group structures) and developing methods of conceptual evaluation to measure student learning and guide our progress. For large scale, frequent evaluation or reliable quantitative measures we have settled on conceptual multiple-choice assessment. (This is not the only assessment used in courses.) The *FMCE* is a reliable measure of concepts associated with one-dimensional kinematics (description of motion) and dynamics (force and motion concepts which are well characterized by Newton's Laws).

What are some of the advantages of the *FMCE* conceptual multiple-choice assessment? It has been given to many thousands of students over the world. It is quickly and easily administered to large numbers of students. Student responses can be reliably and unambiguously evaluated even by the inexperienced. The results can be used to guide instruction.

Student views can be evaluated from the pattern of answers and changes over time can be seen. In addition, the frequency of student views in a general population can be easily measured. When combined with open response or observation, the *FMCE* can help the teacher/researcher explicate the students' responses.

Finally the *FMCE* is well validated. Student answers correlate well (above 90%) with written short answers in which students explain the reason for their choices and with interviews. Almost all students pick choices that we can associate with a relatively small number of student views in the context of the question (or questions). For questions involving graphs, testing with smaller student samples shows that those who can pick the correct graph under these circumstances are almost equally successful at drawing the graph correctly without being presented with choices.

4.3 Advantages of the RealTime Physics learning laboratory for studying conceptual learning behavior)

Learning behavior is much more explicit than in a traditional learning environment. Students are actively working, discussing ideas within the group, and recording their responses to probing conceptual questions in the workbooks. Because we are able to videotape, over an entire semester, student groups engaged in activities and discussion (and, in some cases, recording the computer display as well) we are able to study the evidence of their learning processes in detail.

It is an advantage that most students learn. Students who don't learn using a combination of traditional and research-based materials may have special characteristics. In a traditional environment where only 10 to 15% change their conceptual ideas[5], most students don't learn and it is difficult to distinguish learning behaviors.

4.4 Selection of students to observe and methodology

For the years 1997-98 we have identified nine trios that have the characteristics that make a detailed analysis especially useful. For these trios we have both a pre and post *FMCE* conceptual evaluation and we have videotaped at least five of ten two-hour Lab sessions spread over the semester In addition, each member of the trio has been present for at least eight of the ten Lab sessions.

In studying student learning we use a multidisciplinary methodology. Student conceptual development is determined by the judgment of physicists using the methods of physics education research. Behavioral categories are decided empirically and by learning-theory.

We are studying both individual learning behavior and the behavior of the group as a whole. For this reason, we use different methods of qualitative data analysis, one to study individual learning behavior and others to examine group behavior.

4.4.1 Individual behaviors

We wish to characterize the learning behavior of individual students observed over a long time (one semester) so that we can associate particular behaviors with conceptual learning and understand the pattern of conceptual development. One basic issue is how a continuous string of student behavioral data can be segmented and categorized so that we can understand more about the learning process. Our analysis has some similarities to that proposed by Chi[6], but it involves fewer steps with somewhat different labels.

4.4.2 Group behavior

A microanalysis of interactions among participants in the MBL environments was performed in order to examine effect of students' interactions with one another and with instructors on learning.

This kind of analysis is based on a variety of theories of language and social interaction, including discourse analysis (Gee[7]), conversational analysis (Goodwin & Heritage[8]), and Vygotskian approaches to learning (Wertsch[9]).

In our case, since we are interested in implications for participants' learning, we look at how interactional patterns might contribute to students' learning or failure to learn.

4.4.3 Whole-group analysis

We use a second method of analysis that treats the trio as a system. It examines how each of the students interacts with each of the others in the group, and with the occasionally present teaching assistant.

In this analysis we are able to see how the willingness or relative ability of the students to explore and understand the physics concepts is expressed in their interpersonal interactions. The results of this study will not be presented in this paper.

5 – Comparing Research Results to Common Knowledge

I will use our research results to examine the accuracy of four different instances of common knowledge about learners held by teachers.

Common Knowledge about Learners

- Successful learners ask more questions than unsuccessful learners.
- Successful learners do not propose "incorrect" or inconsistent explanations as unsuccessful learners do. (By definition as one professor said.)
- Successful learners are more likely to use and link multiple representations.
- Successful learners are more involved in learning activities than unsuccessful learners.

As you examine the following results remember that generalizations are not always true but are generally true and that student behavior is a strong function of context. Nothing leads us to believe that the following results are a function only of this particular context

We will examine each of the teacher common knowledge statements above in order.

5.1 Student questions

While common knowledge predicts that successful learners ask more questions than unsuccessful learners, our research results are "uncommon knowledge." Students who don't learn ask more questions than students who do learn. However, it is more useful to distinguish two classes of questions.

A closed question is one that can be answered by a single word or phrase and does not invite exploration. "What is the sign of the acceleration?" is in most cases a closed question. Similarly, a closed statement -- such as " It happened because this is how physics laws work" -- does not invite any further discussion or analysis.

An open question or statement cannot be answered by a single word or phrase and does invite exploration For example, "How can a collision result in changed motion since the forces between the two objects are equal and opposite?"

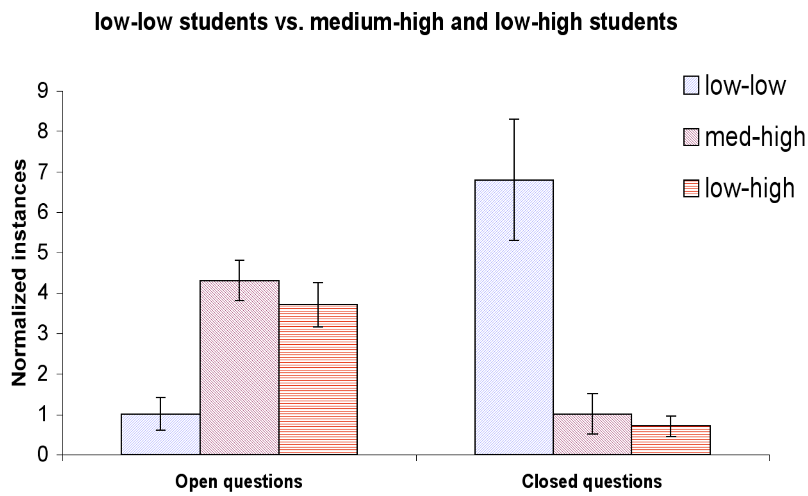

Fig. 2: Comparison of the relative number of open and closed questions asked by students assigned to three different groups by their pre and post performance scores on the Force and Motion Conceptual Evaluation (FMCE).

The nature of the question distinguishes students who learn and those who don't. "Closed" questions are asked primarily by students who don't learn and "open" questions are asked more often by students who do learn. Figure 1 shows the research results for students in all nine groups that we intensively studied. It is clear that students who did not learn (low-low) asked many more closed questions and almost no open questions. Students in the two groups that learned (low-high, medium-high) ask primarily open questions and there is little difference between students who started low or medium and ended high.

Rather than comparing students across groups and in different laboratory sessions as we did above, we can in this instance compare the number of open or closed questions asked directly since four of the groups we studied in detail included a low-low student and a medium-high student

We took the ratio of instances of closed or open questions asked by a low-low student to those asked by a medium-high student in the same group during the same time period and averaged over the four groups.

The average ratio would be 1.0 if the behaviors were similar. We find that low finishers ask 0.23 (about one quarter) as many open questions as the high finishers. (p=0.0001) and high finishers ask 0.05 (or 1/20) as many closed questions as low finishers. (p<10-7) In these ratios we are comparing students doing the same activities since they are in the same group and the difference between students who learn concepts and those who do not is even more significant.

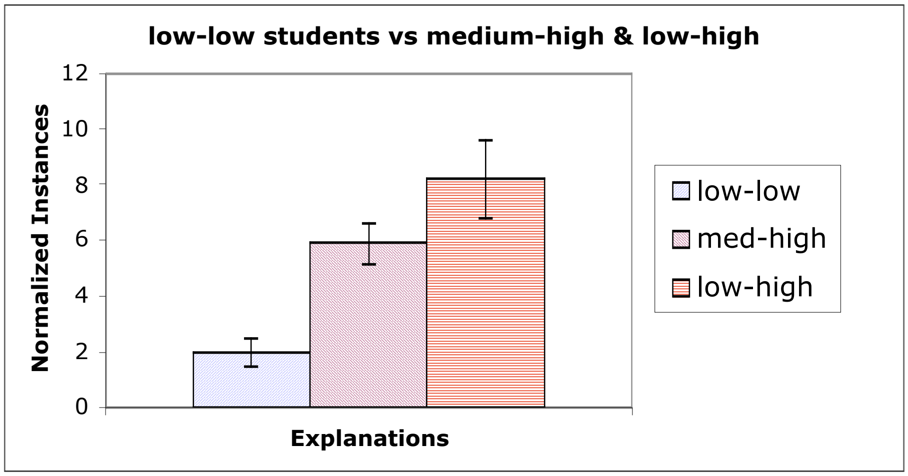

Fig. 3: Comparison of the relative number of explanations based on cause or principle given by students assigned to three different groups by their pre and post performance scores on the Force and Motion Conceptual Evaluation (FMCE).

5.2 Student explanations based on cause or principle

It is teacher common knowledge that successful learners do not propose "incorrect" or inconsistent explanations as unsuccessful learners do. (By definition as one professor said) Our research shows uncommon knowledge since students who do not learn rarely suggest an explanation based on cause or principle, right or "wrong." Students who learn do propose "wrong" and inconsistent explanations. (There is most often an evolution to the physics explanation.) [10]

As we did with open and closed questions we can take the ratio of instances of explanations by a low-low student to those asked by a medium-high student in the same group during the same time period and averaged over four groups.

The average ratio would be 1.0 if the behaviors were similar. We find that low finishers give 0.33 as (about one third) as many explanations as the high finishers. (p=0.0018)
In these ratios we are again comparing students doing the same activities since they are in the same group and the difference between students who learn concepts and those who do not are even more significant.

5.3 Student use or linking of multiple representations

Common knowledge among teachers is that successful learners are more likely to use and link multiple representations. This common knowledge is supported by our research results and shows that common knowledge is not always wrong.

Figure 4 compares the use of multiple representations for students who finish low to that of the students in the two groups who finish high. Representations that may be linked include spoken and written language, mathematical formulas, graphical presentations, and the physical phenomenon itself. The *RealTime Physics* learning environment the students are working in is designed to encourage the use of multiple representations and the great difference between the low-low and low-high students is a significant indicator of learning success.

As we have done for previous learning behaviors for each of four groups, we can take the ratio of instances of the use or linking of multiple representations by a low-low student to the use or linking by a medium-high in the same group during the same time period. The average ratio would be 1.0 if the behaviors were similar but unsuccessful learners are less likely to use and link multiple representations by a factor of 0.17 than successful learners. (p<10-7)

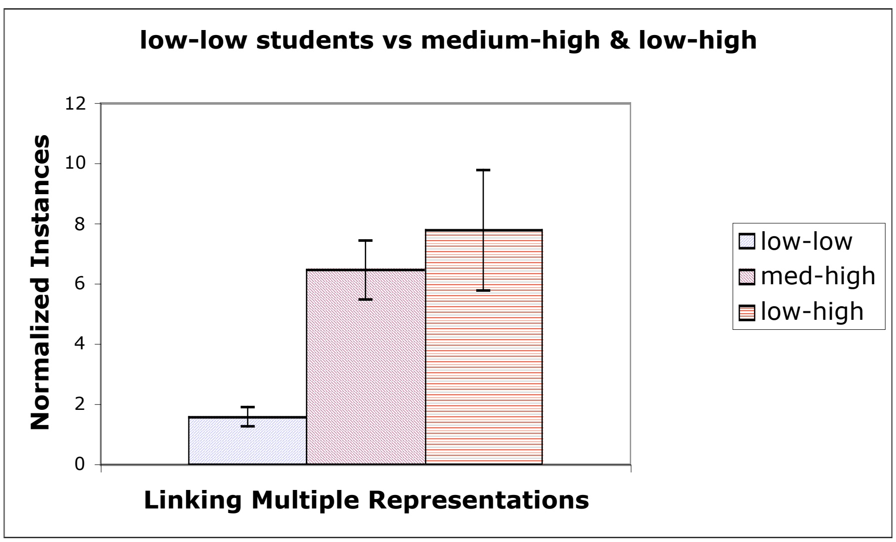

Fig. 4: Comparison of the relative number of times students in each of three groups use or link multiple representations. They are assigned to the three different groups by their pre and post performance scores on the Force and Motion Conceptual Evaluation (FMCE).

5.4 Student attention

Common knowledge is that successful learners are more involved in learning activities than unsuccessful learners. Our observations show that students who do not learn the conceptual material we have been discussing are most often as involved as those who learn it. Being actively involved is not enough in this case. It is most likely true that students who are not at all involved will not learn. However, when we have shown our video observations to teachers it is clear that teachers sometimes mistake quietness for non-involvement.

6 – A Developmental Model of Conceptual Learning

Our data suggest a learning process characteristic of conceptual learning (at least in a guided discovery laboratory). We believe that we are often observing conceptual learning as it occurs. As a student learns a new concept or changes an existing one, the student appears to progress through four behavioral phases.

Phase 1

As is intended by the guided curricular learning materials, the student's initial response when asked to explore a new conceptual area is typically situation-specific with emphasis on descriptive sensory data. For instance, students may give a description of motion in terms of the movement of their own body or some other object or show just an obviously increased level of attention.

Phase 2

As the topic continues to be investigated, attributions of cause become more common; that is, causes are attributed to motions. The descriptions may, or may not, involve the use of traditional physics terms but an effort is made to account for the motion. For instance, "You can't just stop immediately because…"

Phase 3

As conceptual development continues, statements using the formal terms of physics become more common--e.g. "For the acceleration graph to look like that the net force has to be positive and constant." This phase not only involves the use of scientific language but indicates the student's ability to state relationships between two or more variables more or less as a physicist would do. But even now the relationship may initially not be the one that physicists believe to be true.

Phase 4

Additional conceptual development is evidenced by the use of a single concept to explain phenomena that, perhaps, had previously seemed to require different concepts (extending the domain of validity) or by the use of two or more concepts to explain a single, complicated phenomenon. In the specific context studied, we see evidence that Newtonian concepts have become comfortable tools of explanation. Significant metacognitive behavior may also be evident at this phase.

There are a number of general observations about the conceptual learning phases. Students repeat this sequence as they learn new concepts. Not all behavior is necessarily observable. Students who are Low Starters/Low Finishers rarely display behavior above Phase 1. Students who progress to Phase 3 can learn concepts well and score highly on the *FMCE* without any significant Phase 4 behavior. Students who display even a single example of unambiguous Phase 4 behavior are always High Finishers.

7 – Conclusions

We have found that the behavior of the students who learn concepts differs from those who do not and that specific learning behaviors correlate with conceptual learning. Not all of this behavior is consistent with that expected by teachers when students learn. Students who are not learning conceptually may ask more questions than students who are. If the nature of the question is considered, then students who learn ask many more open questions which elicit discussion than do students who don't learn, while students who don't learn ask many more closed questions (sometimes called "fill in the blank" questions) than do students who learn.

As might be expected, students who learn offer many more explanations. The unexpected part is that students who learn often offer incorrect or inconsistent explanations (from the physics point of view in this case) that eventually evolve into widely accepted views. Students who don't learn do not commonly offer incorrect explanations but offer no explanations at all.

Students who use and link multiple representations do learn, as is predicted by teachers' common knowledge. They are about five times more likely to use and link multiple representations than students who do not learn conceptually. This large difference exists in an environment that effectively emphasizes multiple representations.

Many teachers believe that a lack of student involvement is a primary reason for students not learning. While it is true that a student who is not involved may not learn, it is not true that involvement assures learning. All of the students we studied who did not learn conceptually (these are a small minority) were actively involved. They also had significant academic success but still did not learn physics concepts either in the traditional part of the course or the laboratory.

We see evidence for a conceptual development process that can reasonably be divided into four phases. This is not developmental in the sence that when a learner reaches the fourth phase she begins there for all future learning. However, students who do not learn conceptually rarely exhibit behavior above phase 1.

REFERENCES

[1] SOKOLOFF, D., THORNTON, R. K., AND LAWS, P., *RealTime: Mechanics.* John Wiley & Sons, 1998, New York.

[2] THORNTON R. K., AND SOKOLOFF D., RealTime Physics: Active Learning Laboratories, *Proceedings of the International Conference on Undergraduate Physics Education*, (American Institute of Physics, 1997)

[3] LabPro interface and probes and LoggerPro software available from Vernier Software and Technology, 13979 SW Millikan Way, Beaverton,OR. 97005.

[4] THORNTON R. K., AND SOKOLOFF D., Assessing Student Learning of Newton's Laws: The Force and Motion Conceptual Evaluation of Active Learning Laboratory and Lecture Curricula, Am. J. Phys, 66, pp. 338-352 (1998)

[5] THORNTON R. K., Why Don't Physics Students Understand Physics? Building a Consensus, Fostering Change, chapter in *The Thirteenth Labor, Improving Science Education*, E.J. Chaisson, TC Kim Eds., (Amsterdam, Gordon and Breach Publishers, 1999), pp. 163-173.

[6] CHI, M. T. H. (1997) Quantifying Qualitative Analyses of Verbal Data: A Practical Guide. The Journal of the Learning Sciences, 6(3) (1997), p. 271-315, Lawrence Erlbaum Associates, Inc.

[7] GEE, J.P., An introduction to Discourse analysis: Theory and method. London: (Routledge, 1999)

[8] GOODWIN, C. AND HERITAGE, J., Conversation analysis. Annual Review of Anthropology, **19** (1990) 283-307.

[9] WERTSCH, J.V., *Voices of the mind: A sociocultural approach to mediated action*. (Cambridge, MA, Harvard, 1991)

[10] THORNTON R. K., Conceptual Dynamics: Evolving Student Views of Force and Motion, chapter in *Thinking Physics for Teaching*, C. Tarsitani, C. Bernardini, and M. Vincentini, Eds., (London, Plenum Publishing, 1996).