Why Teach Kinematics? An Examination of the Teaching of Kinematics and Force—I†

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The development of two new units for the *Powerful Ideas in Physical Science* (PIPS) Project of the American Association of Physics Teachers has motivated another look at the teaching of kinematics and force. The two new units and findings related to their efficacy is described in part I of this pair of papers. These and some of the other units of the PIPS Project are unique in that they advocate and model a *radical, student understanding-driven* approach to instruction as opposed to the more common *content* or *goal driven* approach. Several novel ways to view the results of using these new motion and force materials are introduced to demonstrate that shifts in pre to post instruction diagnostic results of the order of *two standard deviations* are routinely possible even under adverse teaching and learning conditions. These new means of viewing the results are made possible by a diagnostic (the Force and Motion Conceptual Evaluation by Thornton and Sokoloff) capable of indicating the degree of presence of multiple views. In part II a conjecture concerning the relationship between understanding the physicists' concept of acceleration and the development of new views of force is tested. The test involves extending the *radical, student understanding-driven* instruction approach used to develop the original units. From this experimental test of the conjecture shifts on the diagnostic of *2.5 standard deviations* are found with non-science majors, compared with the results of *0.6 standard deviations* shifts in traditional, *content-driven* instruction of physics and engineering majors. Furthermore, normalized gains of 0.60 are accomplished using *radical, student understanding-driven* instruction, even under difficult instructional conditions with non-science majors in large classes, while the typical normalized gain for physics and engineering majors, under traditional *content-driven* instruction appears to be only about 0.15.

I. INTRODUCTION

This work has its roots in work begun in the late 1970's.[1] It is a further iteration with a number of subsequent themes that have emerged and been woven in. This work truly owes much to pioneers who shall be mentioned below, most of whom in one way or another the author has had the privilege of directly consulting with during the course of this project and the development of this report on the work. One benefit of having the opportunity to "stand on the shoulders of giants" is that one can then get a view of what goes beyond what might be seen otherwise.

Grateful as the author is for the opportunity of standing on the shoulders of giants, there are challenges to be found in what follows. There are two stark findings concerning physics education that shall be referred to below several times. One is that the overwhelming majority of students leave physics instruction with the *same* understanding of the world as they had when they began that instruction. The other is that they learn that only certain special people *can* understand the phenomena.[2]

The present work comes from a view that neither of these findings should be the typical outcome of an *educational* experience. It is the result of an attempt at a version of physics instruction that is an *educative* experience and not the filtering, indoctrination experience most students are subjected to. The challenge taken up here is: how can we help *all* students deepen their understanding of the physical world, develop dispositions which support inquiry generally and enhance their skills at the processes necessary and develop confidence that they can make deeper sense of the physical world? At this point the readers might be tempted to say that they share these goals, but be warned. The evidence of the effect of physics teaching is that these goals are far from being reached.

If the reader really is interested in this challenge to *educate* all people as opposed to merely finding and training physicists and engineers, then the reader is invited to consider an alternative classroom practice as described in this work. It will not be easy to let go of the filtering/training/elitist frame of mind currently pervading most physics teaching, but it is possible to accomplish with some effort. Many potential surprises and rewards await those willing to make the effort.

In order to meet the challenge a primary distinction arises in that the work is about assisting people in making their own sense of the physical world and developing their abilities to do so. It is not about teaching physics in the traditional sense. This work is about *educating* people, not about training or *teaching* to a canon. Keeping this in mind might enable the reader to avoid potential misinterpretations of the work at many turns.

This distinction is much more easily stated than understood. It is not about dismissing the canonical knowledge or about rendering it unimportant. It is about re-thinking the role of such canonical knowledge in the *education* of people who are not *training* to be scientists or engineers (although it is also about educating this second group as well).

A. The problem of kinematics as descriptive mathematics

My experience in Physics Departments suggests that many who teach introductory physics do not consider kinematics particularly difficult or interesting. Kinematics, the study of motion, is seen as hardly more than just an exercise in mathematics. Kinematics problems are often seen by many instructors as mere exercises in matching the givens and unknowns to an appropriate equation from among a small, memorized set of fundamental and other specially-derived equations given to the students. Once the appropriate match has been made the solution is trivial. Kinematics is a descriptive part of physics as opposed to an explanatory activity in that it is the description of motion and not the explanation of motion. This description is thought of by instructors and textbook authors almost completely in terms of mathematics. As mere description, it is considered somewhat superficial. Hence, it is intended to serve as a "simple" introduction to physics containing the basic elements of measurement, mathematization, mathematical problem solving, and an elementary starting point for the course and the study of physics in general.

There are two fundamental problems with this formal mathematical view of kinematics in the context of the present work. But, first, there are the potential arguments over numeracy and the potential value of coming to appreciate the elegance of the application of formal mathematics to kinematics. The course involved has no mathematical prerequisites. This is typical of many such "conceptual physics" courses at most universities. Whether or not this should be and why such courses exist are neither the subject nor the message of the present work. The present work is not about advocacy or rejection of advancing the numeracy of society or of future teachers. It is more about the obfuscation of the conceptual understanding of kinematics by the insistence on the use of formal mathematics instead of attending to the issues of students' conceptual understanding of either the kinematics or the formal mathematics and about the consequent serious damage done to the students. The elegance of the application of formal mathematics to the description of motion, kinematics, is only truly understood by one who understands *both* the mathematics and the conceptual aspects of motion; a fact consistently missed both by instructors of kinematics and of the calculus. Neither the future teachers, some of whom are subjects in this work, nor their future students are in possession of either an understanding of formal mathematics or of a conceptual understanding of kinematics.

Let's choose to work on assisting the future teachers with an understanding of kinematics now so that they might be successful at helping their students with the same and then go on to add the formal mathematics to this understanding once they are in a position to appreciate it. As things are now insisting that we keep the formal mathematics in the instruction, we accomplish *neither* with most students and we effectively teach this same majority *they can do neither* in the process.

Finally, one should not confuse numeracy with formal mathematics. What is unconscionable with respect to the mathematics aspect of the issue is that we have long known how to teach mathematics for understanding, as opposed to rote memorization,[3,4] We are still learning more. Similarly insightful work in mathematics teaching is still being done,[5,6,7] yet in many ways the new practices developed remain atypical and rote memorization *still* dominates.

Coming back to the afore-mentioned two fundamental problems, the students involved in the present work do not "do" such mathematical problems as are typically the focus of attention in other physics courses nor do they need to be able to. They are not being trained as future physicists and engineers. An important sub-set of these students may eventually find themselves assigned to teach topics in kinematics and force to elementary or middle school students. What would such mathematics mean to those future elementary and middle school students when the mathematics does not mean what is intended to their teachers? Such a view of kinematics and kinematics instruction based on the mathematics is essentially useless for students who are not going to become scientists or engineers. On the other hand, those few who do decide to become scientists or engineers, having first carefully developed a conceptual understanding of kinematics beyond the typical person-on-the-street understanding would be in a much better position to take advantage of the sort of training we offer them at the beginning of their professional preparation. They might even be able to skip a spiral or two of the typical "spiral" curriculum to which we currently subject our trainees.

Not only is it the case that none the students in this study need the formal mathematics laden presentation of kinematics, but the same is true of the vast majority of all students who experience instruction on topics in physics. This point might be missed by the average university professor who is not cognizant of the large number of high school teachers who teach physics, the larger number of eighth or ninth grade physical science teachers, and the vast number of elementary school teachers, many of whom are expected to teach topics in physics. According to National Center for Educational Statistics and American Institute of Physics data, from the size of the cohorts in elementary school and typical class sizes there are very nearly 600 times more elementary school teachers who are expected to teach topics in physics to their students than there are college and university physics professors.

Running throughout the present work is the challenge: what are the conceptual aspects of physics that are the foundation for the mathematics? Specific examples of answers to this question in the case of kinematics and force are described in the sections below describing the initial ideas of the students and the new ideas students work out to explain the phenomena.

B. The Nature of Student Understanding: **Conceptions *or* knowledge-in-pieces*?***

Work on the nature of student understanding of physical phenomena has been on-going for more than twenty years.[8] During that time differentiated stances with respect to the nature of the knowledge have arisen. On the one hand there is the *knowledge-in-pieces* (kip) view. In this view the explanation is that students possess what are called phenomenological primitives (*p-prims*). A very basic example would be the Ohm's *p-prim.*[9] Ohm's *p-prim* describes the notion that the bigger the effect, the bigger the cause – the greater the current desired, the larger the voltage necessary. Ohm's *p-prim* applies to *any* effect and cause, but because it can be so easily exemplified in terms of electrical phenomena it is given a name associated with electrical phenomena.

These *p-prims* are described as being mobilized by students in various combinations that manifest themselves in the different ways students make predictions and give explanations of the phenomena. DiSessa regards individual *p-prims* as the building blocks of *all* understanding or explanations of the physical world. Teaching is sometimes seen in this view as a matter of getting the students to bring together the most appropriate combinations of *p-prims*. Some of these particular combinations are sufficiently robust that the combinations appear reliably in student thinking in particular settings. These particular combinations of *p-prims* have been called facets.[10]

On the other hand what might be thought of as particular combinations of *p-prims* occur so reliably and seem to be used so frequently by students that they can be seen as complex entities themselves, called *conceptions*.[11,12] Students can be thought of as having conceptions about the nature of force for example and its relationship to motion. These conceptions consist of beliefs about how force works and how it applies to observables. Such a *conception* is in evidence when a student answers multiple questions, makes predictions and acts in a way consistent with the conception in multiple situations as we shall see later in the present work.

It is not clear that these two views: *knowledge-in-pieces* (kip) and *conceptions* are fundamentally incommensurate. The kip view makes it possible to think in terms of resources students might marshal to result in a particular explanation. The *conceptions* view lends itself to thinking about how and why students might come to develop and adopt a new understanding of a phenomenon. Both views have served as the basis for work that has been very effective for student learning.[13,14] The present work could be understood and interpreted from either view. To avoid redundancy in what follows language consistent with the *conceptions* view will be used.

C. Approaches to Instruction: content-driven or student understanding-driven?

Although it might not be so obvious, another bifurcation exists in how the research in student conceptions of the phenomena is employed in the development of curricula. Since the present work deals in issues of materials development, it is important to acknowledge this bifurcation and to indicate where the present work stands with respect to this split. There may be others, but two particular approaches to instruction stand out.

In the following descriptions it is the intent to delineate the two approaches. One might argue that the two can be blended and indeed are blended in certain examples not explicitly treated in the present work,[15,16] but extreme caution should be exercised. It is not clear that the two approaches can successfully be blended in such a way as to have positive attributes of both actually survive. The reader is invited to withhold judgment until the distinction between the approaches is clear.

The more prevalent approach is one in which typically the instructional goal is claimed, assumed or *implied* to be to get the students to know a particular, pre-determined explanation of the phenomenon to be studied. This particular explanation might be justified by the fact that this "content" is the officially sanctioned explanation, a part of the official professional canon. It might be justified just because this "content" is what the students are supposed to know at the end of the course. It might be justified because it is the "truth" or it might be merely because this "content" is an explanation that people have thought of and found useful. Of primary significance is the fact that something the students do not understand generally dictates the progression of instruction. One might call this approach *content-driven.* In traditional instruction uninfluenced by research in student learning, this dominance of the ends over the means can be identified as a contributing factor to the negative outcomes of instruction.[17,18] Just exactly what the "ends" actually are is yet another "layer of the onion" to be peeled. In most discussions the "ends" of *content-driven* instruction seem nominally to be that the students are to somehow end up in possession of some content, but as will be demonstrated later in this work this tacit description of the "ends" of traditional, *content-driven* instruction can be strongly questioned.

The other approach starts "where the students are" and then directs their attention toward aspects of the phenomena that *they* might find challenge *their* existing ideas. This approach requires at the start at least two things of the instructor and curriculum designer: a working understanding of the students' view of the phenomena and knowledge of the behavior of the phenomena beyond the range of normal student experience. The primary distinction between this approach and the more prevalent *content-driven* approach is that this approach is driven at any point in time fundamentally by the nature of the students' understanding of the phenomena, *i.e.* by what they *already understand* and not by the need to present some content which at that point is usually not commensurate with their understanding.

The shift in attention from the drive to present particular content to responding to student understanding makes it possible not only for more students to reach powerful understandings of the phenomena, but also for more students to see themselves as *capable* of reaching reasonable new understandings. Because the process involves considering and exploring reasonable alternatives and rejecting some for various reasons, this approach tends to result in students not only reaching reasonable conclusions but also having decided why the "blind" alleys are "blind." One might call this approach, *student understanding-driven.* It focuses their attention their own understanding and on skills and habits which support generally the process of making new sense of the world, instead of the most prevalent outcomes of physics instruction: learning to play guess-the-answer games with the instructor[18] or becoming left behind and lost making the whole experience horrible.[17] The instruction experienced by the students in the present study was of the second type, *student-understanding driven*; from the instructor's point-of-view driven by the instructor's understanding of the students' understandings as the work progressed.

There is a terminology issue here in that there is not an established nomenclature for the distinctions being described. There are many "approaches to instruction" that have been described in the literature. In a sense the distinction here could be described as a distinction between *categories* of approaches to instruction. All approaches to instruction with the specific goal of "delivering" particular content are considered in the *content-driven* category of approaches. All approaches to instruction with the specific goal of starting with the students' existing understanding and facilitating what are sensible changes to the students, but without the constraint of delivering any specific content pre-determined independently of the students are considered in the *student understanding-driven* category of approaches.

At first glance it might appear that this distinction is merely a process vs. content or means vs. ends issue. In order to understand the nature of the instruction intended it is important to realize that neither of these characterizations capture what is fundamentally important about the distinction being made. It is clear from more than two decades of research that students come to us with different understandings of the phenomena than are the basis of what we teach.[8] If change in student understanding is a goal and if a person can only change her or his own understanding, then it is the students' understandings that must be the object of manipulation and at the center of attention for both students and teachers. Hence, we have the logical necessity of a *student understanding-driven* approach. This is an attempt to get to the fundamental roots of coming to understand physical phenomena. For this reason the *student understanding-driven* approach being described can be called "*radical*." It is the result of a focus on the root of the process of students coming to new understandings.

1. Problems of the process vs. content characterization

With respect to the process/content issue, again what is advocated in the present work is different. In the process/content debates, content refers to the standard *content-driven* instruction, but the process orientation is also driven by externally defined goals. In the purely process orientation, the goals were the "processes of science," instead of content of science. The problem here is that student understanding is again ignored. Rather than beginning by engaging what is naturally there in most students and encouraging that to develop, externally defined skills and dispositions are impressed on the students in the hope that some will be found to have "the knack" and be identified as viable candidates for further training and because it is apparently believed that science is such a special form of thinking that no one would ever develop this form of thinking on their own.[19]

2. Problems of the means vs. ends characterization

In means/ends terms, the position being taken here is that the *content-driven* approaches seem to justify or allow any means to accomplish the ends. It is difficult to consider means and ends issues separately. Given the linear nature of the printed word an attempt here will be made to in effect peel another layer of the onion. In order to discuss the problem with the means one must first refer to the ends. As was stated earlier the ends here are taken as what the students should "learn." As we shall see, it is problematic to characterize the ends in this manner, but since the ends of instruction are typically taken uncritically to be that the students "learn" some particular content and justification for instructional decisions are made on this basis, we will start here.

The "means" part of the problem can be attributed to what is considered to be the nature or status of the ends, the "knowledge" the student are supposed to get. The more objective this knowledge is thought to be, the more absolutely it appears to corrupt the means deployed to "get that knowledge to the students." After all, if we present the closest thing we can to the "truth" and the students do not "get" it, then it must be they were not capable or properly prepared. The perceived objectivity of the "truth" is used to justify a fixed or rigid presentation and a belief in an elite who can "learn" physics justifies failure of the students to learn. This "absolves" both instructor and students of any responsibility for failure and maims the students by leaving them to believe they are inadequate because in many cases the perpetrator of the approach apparently actually believes in the inadequacy of the students.[20]

At this point it may be easy for the reader to launch into a philosophical argument about the nature of the knowledge, but the issue here is fundamentally pedagogical. Some insist that most physicists will acknowledge the tentative nature of "their professional knowledge" when explicitly pressed. One can imagine an extreme humility could be exercised about the nature of knowledge in a *content-driven* approach that might result in an experience for the students that is not so damaging. Nonetheless, such respect for the knowledge has long ceased to exist in textbooks and few if any *content-driven* approaches restrict themselves to means that minimize the damage normally done. It is this lack of humility with respect to the knowledge, usually justified by an appeal related to objectivity in some form, which appears to be what drives *content-driven* approaches to be insensitive to both student understanding and student self-image. Granted when professional selection and training is the purpose, student understanding and self-image are not necessarily the central issue, but when *education* is the point, student understanding and self-image are primary. As long as this insensitivity is allowed to come through, *no* "blend" of the two approaches can truly be said to benefit from the positive aspects of the *student understanding* driven approach and such blends can be said to suffer from the negative aspects of the traditional, *content-driven* approach.

Traditional approaches to instruction are *content-driven*. They do the most damage[17] and are the least likely to have any significant numbers of students actually coming to new understandings of the phenomena.[8] It appears that those examples of *content-driven* approaches in which means are restricted to ones that treat students and their ideas with respect might make claims of better track records of change in student understanding and appear to do them less damage otherwise.

4. *Content-driven* Instruction: an outcome-based deconstruction

Now let us peel the another layer of the onion. Much of the discussion of physics teaching has for many years operated under the assumption that physics instruction is *content-driven*. The tacit assumption seems to be that this means that we are attempting to somehow "get" the content to the students. This being the case it is surprising that there are many vocal critics of the physics education research community when it points out that most students do not "get" the physics instruction as it is currently offered at any level and there is open as well as covert resistance to advocated changes in physics instructional methods or approaches.[20,21,22] Given this apparent discrepancy, that students generally fail to understand physics instruction and many established physics instructors dismiss this data and suggestions about change in teaching methods, yet physics instruction is supposed to be about students "getting" specific content from the canon of physics, we need to re-examine our characterization of the situation. What is the data?

- Since the late 1970's the physics education research community has been uncovering and reporting the extent to which students leave their physics instruction with the *same* understanding of the phenomena they had before the instruction.[8]
- Most students leave this instruction having decided they cannot really understand physics and that they will have to rely on experts, really smart people, who know.[17]
- Physics teaching having been the same for many decades, even a century or more, we can imagine that these first two outcomes have been present for many decades, even a century or more.[23]

- For all that time until the late 1970's, a large number of very smart, very insightful, very sincere physics instructors have been on the job, but essentially NONE have noticed that almost no students change their understanding and most students diagnose themselves as not good at physics.[24]
- Vocal members of the physics teaching community dismiss the research results indicating students are not understanding.[25,26]
- Alternative approaches to physics instruction demonstrated to result in significant conceptual change are ignored and physics is still mostly taught as it was in the decades before 1980.

The tacit assumption that *content-driven* physics education is about the students "getting" specific portions of the canon of physics at any level fails. So why do we still call standard physics instruction *content-driven*? One clue might lie in the fact that all curriculum writers in physics are pressured to include the canon of physics in whole pieces or sections and they are strictly refereed to use a fairly narrow range of variations in presentation. What is very curious is that the canon of physics bears no particular relationship to anything we know about how students learn about physical phenomena.[27] The canon does not represent the way students think about or understand the phenomena or the ways in which they parse the world as they experience it. Yet, the canon seems to hold such a central importance in physics instruction. What if we take "*content-driven*" to mean that the instructors of physics are required to present complete portions of the canon in approved fashion? This would explain these pressures to use the canon.

Why is it that no attention is paid to the fact that so few actually understand at the end of instruction? It is often said that physics is hard and only certain people can really understand it. If this is the case, then those who can understand and have properly prepared will understand the canon when presented and thus deserve it. Those who cannot understand, prepared or not, will not understand it. So finally we have a possible reconstruction of what it might mean for standard physics instruction to be *content-driven*. It means that traditional, *content-driven* physics instruction is *the presentation of the canon in an approved fashion for the deserving*. This could be seen as an elitist extension of Bartlett's "Feynman" effect.[28] Such a description of standard physics instruction accounts for the data. With it we can understand why so many good, sincere physics instructors were essentially insensitive to the fact that so many students were not understanding and why the resistance demonstrated to the findings and the new approaches developed by the physics education research community. It was never really about getting "content" to all the students.

Not only are the actual results of traditional *content-driven* instruction inferior to those of an alternative, *student understanding-driven* instruction (as we shall see in the results in Part II of this pair of articles), but the goals of the two approaches were never even similar. In normal *content-driven* instruction the goal is for the instructor to present the canon in an approved fashion for the benefit of the deserving. In *student understanding-driven* instruction the goal is that all students personally construct new conceptions with respect to the phenomena.

It appears that two ideological factors support the notion of traditional *content-driven* physics teaching; *the presentation of the canon in the approved fashion for the deserving*. One is realism; the notion that we can actually judge our knowledge as to the extent to which it actually tells us the true nature of reality.[29] If we have this then we can justify our just telling it to the students. After all, who are the students to question this "truth"? Since it is "truth" or the closest we can come to it, then the students must either take it or leave it. The other ideological position is elitism: in this case, the notion that some people have significantly different abilities than others; that some students can just understand physics and others cannot. Hence, if one has made a proper presentation of the "truth" then those who do not "get" it apparently are either incapable or unprepared.

We see this clearly portrayed and reasonably presented recently by Ehrlich.[26] Explanations consistent with a well-entrenched ideology always sound reasonable; all the more so to those steeped in the ideology as are most physicists. This "invisible-as-the-air-we-breathe" effect is intensified in the case of an ideology claiming to be non-existent by taking the mask of objectivity. The issue is not about choosing between reasonable arguments or explanations, it is about discerning the features of underlying ideologies and choosing between ideologies. If one looks closely one can see that the selection of an elite is central to Ehrlich's goals while making sure the undeserving are weeded out. This might be in the view of some all very well and good if the only reason for physics teaching was to select and *train* physicists, but it leaves out the role of physics as a part of an *education* for everybody. In fact Ehrlich argues against certain things because it might open the doors for too many. Because the underlying ideology behind *content-driven* instruction is at best questionable in *education*, one would do well to consider just from whom we take advice about *education*. *Where can we find venues in which teacher candidates needed to educate with physics can learn physics and how to teach it?* It is unlikely this will happen in settings described by Ehrlich.

In his "non-attack" on the physics education research community, Ehrlich[26] manages to impugn the community's methods. As an alternative he offers anecdotes such as the one which opens the article and restatements of ideological platitudes: "I can still remember a time, however, when the conventional wisdom was that some students have what it takes to develop a mastery of a difficult subject such as physics, while others simply did not, even after expending considerable effort." This is elitism at its finest. The logical conclusion from this is that no one has any business even attempting to teach physics before students get to college. In particular no topics in physics should be taught by people such as elementary school teachers or middle school teachers, maybe even high school teachers who might not be among this elite few. *Should people with such elitist attitudes, who cannot tell the difference between weeding out the riff-raff and education, be the source of advice for those teaching or planning to teach at the pre-college level?*

On the other hand, *student understanding-driven* instruction described herein is supported by fundamentally different ideological factors. Knowledge, explanatory knowledge in particular, is treated with a great deal more humility than it typically is by realists because the view taken of the nature of knowledge is that of radical constructivism.[30] In this view we cannot know which of two explanations is closer to "truth," we can merely know which makes a more satisfactory fit to experience. The other supporting factor in *student understanding-driven* instruction is that students are viewed as more alike than different. This is neither to claim there are no differences nor that differences are completely immaterial. Instead it is the belief that all human beings can make sense of the world around them and have the basic capacities to advance that understanding, given the encouragement and opportunity. Given the superiority of the results below and in Part II, one can argue that the ideological underpinnings of radical constructivism combined with the egalitarian view of human capacities are a superior basis for *education* in physics than is realism combined with an elitist view.

II. THE POWERFUL IDEAS IN PHYSICAL SCIENCE PROJECT

This work grew out of an extension to the Powerful Ideas in Physical Science (PIPS) Project,[31] sponsored by the American Association of Physics Teachers and funded by the National Science Foundation.[32] The aim of the project is to put into the hands of college and university physics professors, resource materials to help them teach physics to elementary education teacher candidates and other non-science majors. The assistance is in the form of example instructional materials that are developed and thoroughly described in terms relating them to current research in physics learning. As such the materials are minds-on oriented. They utilize an approach that directs the attention of both student and instructor on *eliciting*, *comparing*, *revising* and *applying* the conceptions the students use to make sense of physical phenomena is at the center of all activities. The initial topics treated in the PIPS were: light and color, electric circuits, heat and energy and the nature of matter.

In response to requests from enthusiastic users, the original administrators of the project commissioned the development of two additional units, one on motion and one on force. It fell to the author to develop the new units. Much has already been done in the areas of student conceptions of motion and force. These two new units come out of that rich tradition. While all of the PIPS materials are fundamentally based on research in student learning of the topics involved, not all of the units employ the same approach, some are more *content or goal driven* and others are more *student understanding-driven.* The Motion and Force Units are *student understanding-driven.*

The primary sources of the motion unit are three-fold. Pioneering work illustrating the powerful form that research in physics learning can take was conducted by Trowbridge and McDermott and the early members of the Physics Education Research Group at the University of Washington studying student difficulties in learning about velocity and acceleration in one dimension. [1,33] Later Tinker introduced the notion of microcomputer-based laboratory (MBL) to the study of motion.[34] Thornton and Sokoloff carefully interwove the early work on student difficulties with MBL in their project, Tools for Scientific Thinking (TST).[35] With some modifications, the PIPS Motion Unit takes all of this and casts it in a form which directs students' and instructors' attentions on the conceptions the students use to make sense of motion by engaging them in making sense of "real-time" computer-generated graphs of motion.

The PIPS Force Unit comes from different sources. While it, too, incorporates MBL, it is based largely on the work of Minstrell.[36] A fundamental feature of Minstrell's approach is a focus on the students' conceptions and engaging the students in testing and revising their own conceptions. In fact, the PIPS approach of directing both the instructors' and the students' attentions on first *eliciting* the students' conceptions with predictions and then *comparing* those conceptions with the phenomena and then *revising* the conceptions along lines the students find appropriate to better fit or "explain" the phenomena is attributable in good part to Minstrell's influence.

Each of the six PIPS units acknowledges its sources. All of the units strongly benefit from work developed previously by their authors and others. The teaching of topics in physics stands to benefit strongly from the subject matter oriented studies of student conceptions conducted by the physics learning research community. As mentioned above, there is a thread running through them all. This thread is the orientation toward the students' conceptions of the phenomena. While most on the original development team would agree that it only makes sense that if one is trying to influence student understanding then student conceptions must be the center of attention, others would go on to acknowledge that this orientation is influenced by psychologists and philosophers such as Piaget and von Glasersfeld.[30] Piaget was introduced to the Physics community by Karplus, Lawson, and Fuller.[37] The late Arnold Arons, colleague and mentor to many cited in this work, the author included, placed great importance on Piaget's ideas and their value in teaching.[38] This orientation toward the importance of student conceptions is manifest in the cycle: *elicit, confront, resolve, apply,* prominently cited by the University of Washington Physics Education Research Group and the Children's Learning in Science Group at Leeds led by the late Rosalind Driver.

Regardless whether one takes a pragmatic or a philosophical stance on the issue of the nature of explanatory knowledge[39], it is firmly entrenched in PIPS for pedagogical reasons. It shows up in the cycle repeated in most PIPS activities. The cycle consists of four steps: "What's your idea?," "What are your group's ideas?," "Making observations," and "Making sense." The cycle is effective to the extent that the question that guides each activity captures issues relevant to the students and their thinking at the point they encounter it. To the extent that the question that guides an activity is about what the instructor or curriculum writer wants to introduce next instead of what is relevant to the students, the *content-driven* approach, the cycle is less effective by far. One must start with some idea of the students' ideas at the beginning of a course and constantly keep track of them as they evolve during instruction. This is the necessary starting point for the *student understanding-driven* approach to instruction used in these PIPS units.

A. Typical Initial Student Ideas About the Phenomena

Several decades of study of student conceptions[8] confirm that students come to us with already formed ideas about the world, be it conceptions or knowledge-in-pieces. They are not *tabulae rasae*. Regardless of what might be said of students today and their educational backgrounds, for every topic treated in a physics class students either already have well entrenched notions about the phenomena (conceptions) or a trusted toolbox of notions (kip) that can be opened at a moment's notice and brought to play on novel phenomena. These serve as a starting point for every PIPS activity.

1. Pre-existing student view of kinematics: undifferentiated motion

Since the late 1970's physicists interested in understanding the nature of student difficulties in physics courses have been reporting in various ways on the apparent nature of students' conceptions of motion on entry into our courses. [1,30] If one observes everyday language usage, spoken and in print, one finds that the terms, motion, speed, velocity, and acceleration, are almost indistinguishable. They are used interchangeably, certainly when an object's velocity is increasing. The term, acceleration, applies only to increasing velocity situations. Deceleration is reserved for decreasing velocity situations. Students generally employ only one direction in their thinking about motions: the direction of the motion. Acceleration for them is always "with" (same direction as) the motion. This is because for the students acceleration is hardly different than velocity and it is not, to the extent it may differ, a vector quantity for them. Conceptually their street-version acceleration is *not* a sub-set of the physicists' acceleration.

We know that another way of thinking about kinematics exists. The typical person-on-the-street views do not match the scientists' notions with respect to motion. One of the most striking questions raised by this state of affairs is why the difference. A very great fraction of our society graduates from high school. To graduate from high school in most states, one must take a physical science course in the eighth or ninth grades. In this course the topics include motion and forces. Generally, too, these topics are supposed to be treated somewhere in elementary school. Yet, all studies of student conceptions describe students arriving at high school and college physics courses with person-on-the-street views of motion and little or no evidence of any alternative view entailed in the instruction they *all* had previously. With respect to kinematics it is as if the instruction had no effect at all. If the goal of instruction was content elements including scientists' kinematics concepts, then it is an abject failure in this respect. As we shall see the present work will suggest that this failure is neither due to lack of ability in the students nor to the lack of a sincere effort on the part of their teachers. Instead the failure can be traced to the instruction and the failure of the system of preparing teachers to produce anything but teachers who are unprepared to deliver anything but the prevailing *status quo*.

2. Pre-existing student view of force

a. Energy vs. pushes or pulls

If one asks the students to come up with some simple words or basic ideas which they feel express their ideas about force in the case of forces acting on objects which might or might not move our experience is that the discussion generally comes down to two possibilities: energy or pushes and pulls. With some continued discussion the consensus generally shifts in favor of force as pushes and pulls and away from force as energy. Generally it appears from the class discussion in which this happens that the rationale for this is that people agree that energy is needed for force, but that energy some how is more than force. This happens without any attempt to explicitly define energy.

It is important that the significant fraction who do first think of energy have the opportunity to make this distinction. This negotiation for meaning is an opportunity for many in this group of students to avoid assuming they do not understand. If instead we never brought up the issue of force as energy and just stated that we are going to consider force as pushes and pulls, then a significant fraction would be left to conclude for themselves they do not really "get" physics because apparently the energy aspect of force was so obviously wrong that it was not even treated in class. The discussion also leaves an open hook that can be returned to for launching another unit on energy itself.

b. Relating forces as pushes and pulls to motion

For the students force as pushes or pulls is related to motion or the lack thereof. Their initial views can be summarized in a series of statements capturing the essential features. Force causes motion and as such the force that causes the motion is always in the direction of motion. In particular a constant force results in a constant motion or velocity. For twice the constant velocity one needs twice the force. If we were to generate force-time graphs like we generate velocity-time graphs and acceleration-time graphs, then the force-time graphs would look like the velocity-time graphs during the motion.

In the case of multiple forces, usually one force "wins." Although forces opposite the "winning" one may be considered to detract somewhat from the full effect of the "winning force," but the notion that the "winning force" overcomes the others is still prime. This force determines the motion and the rest are essentially ignored. This force is generally thought to come from the largest or most vigorous object. The other forces become relatively unimportant. The notion of net force is not really used.

Normally inanimate objects do not have the capacity to "exert" force unless they are embued with this capacity by some other agency. For example a table does not spontaneously exert a force upon a book lying on it. The table for some students is just "in the way." But, the book exerts a force downward on the table because gravity is acting on the book.[40]

During the elicitation phases of the Force Unit we ask them about explanations in terms force for an object remaining at rest, for an object maintaining a constant velocity, and for an object constantly increasing its velocity along a straight line. To explain a book remaining at rest on a table[40] we find that students who feel the gravity force down on the book is greater suggest this is so because gravity holds the book against the table. Those who claim a force up on the book from the table do so because the table force keeps the book from falling. Others suggest no force comes from the table because the table as an inanimate object cannot "exert" a force. The table is just in the way. The "one force wins or overcomes" feature is clear in these explanations. In the case of the constant velocity and constantly increasing velocity cases, if there are opposing forces then the force in the direction of motion had to be larger and constantly so in the case of the constant velocity. It has to be in the direction of motion and constantly increasing in size with respect to any opposing forces in the case of constantly increasing velocity.

c. Interaction aspect of force

It is probably impossible to hold an extended discussion of the nature of force and motion without dealing at least to some extent with the interactive aspect of force. If a cart is pulled upon by a string, the cart pulls back on the string. It can be argued that this feature of force is separable by typical adults from their notions about the relationship between force and motion. The present work focuses on students' views of the relationship between force and motion and not particularly on the interactive aspects of force.

B. The PIPS Motion and Force Units: an overview

The emphasis on the students' conceptions suggests features of the activities and what aspects of the phenomena need to be looked at, in what order. In practice it is not an over-generalization that students come to us thinking about motion without attending much to the process of changing motion. As such it should be no surprise that a practical generalization concerning student views of force is that it causes motion; in other words, that a constant force results in a constant velocity. Since it is possible in several ways to direct students' attentions to examples reproducible in the lab in which a constant force results in a velocity with a constantly changing magnitude, then it is possible that students might be challenged if they realize this outcome contradicts their existing view of force. But, it is unlikely to be recognized as much of a challenge to their ideas of force, if the processes of constantly increasing or decreasing velocity do not have sufficiently high status in student thinking to clearly distinguish them from constant velocity.[41] Hence, it appears an important role of kinematics instruction should be to get the students to compare their existing notions of acceleration and deceleration with a representation that emphasizes this distinction so that they might raise the status of this distinction in their own thinking.

The students' conceptions and the changes they might undergo could be diagrammed as in Figure 1.[42] While additional detail might be given to more fully describe the conceptions indicated in the columns of the diagram, it serves to indicate the major features of change that can be observed in students working their way through the PIPS Motion and Force Units. Starting on the left, students come to us without having explicitly thought about the connection between force and motion. Roughly for them there is motion and no motion.[43] If there is motion then there is force and if there is no motion there is not necessarily force. As a result of the Motion Unit, they begin to distinguish motion from changing motion. In other words the process of changing motion elevates in status and they begin to add to the possible meanings of the word, acceleration, the idea of the process of changing velocity in general. But, they still associate force with motion, now velocity. A constant effective force results in a constant velocity. This situation is represented by the second column from the left in the diagram. The PIPS Force Unit attempts to induce the students to challenge their existing view of force. Perhaps the most difficult change in conception is represented in the difference between the second and third columns from the left in the diagram. The third column from the left describes the typical minimum level of new view developed by the class that the force "goes as" the acceleration. The fourth column represents a further refinement of the conception in the third column. The three changes in conceptions have been called, *differentiation, reconceptualization, and class extension.*[12]

1. The PIPS Motion Unit

All PIPS Units are organized into investigations that are composed of activities. Each investigation dwells on a major issue in the unit. The activities in each investigation are tied together by some common theme or thread. Some of the activities are laboratory activities involving equipment and specific observations of aspects of the phenomena. Other activities are invitations to explore the consequences of ideas developed so far and as such do not necessarily involve laboratory equipment. Some of these latter can be viewed as homework activities.

The PIPS Motion Unit consists of four investigations. The first involves position-time graphs exclusively. The second involves velocity-time graphs and combines them with position-time graphs toward the end. The third investigation involves acceleration-time graphs in the company of velocity-time graphs and position-time graphs. MBL apparatus makes it possible for students to study graphs of their own body motions in these first three investigations. The fourth investigation is a continued study of acceleration-time graphs in the company of both position-time graphs and velocity-time graphs, but the motion studied is that of low friction carts moving on inclined ramps capable of producing uniform acceleration, using the MBL motion detectors.

The focus is on the students' conceptions of what they are experiencing. They have experienced motion their whole lives, but have not needed to notice certain features of motion. It is our effort to introduce the MBL generated graphs as a renewed look at motion. The more closely they connect the graphs with their own motion and the more closely they inspect the graphs, the more likely they are to notice features of motions they have not before taken into account.

In this spirit at the beginning of each of the first three investigations the students are invited to explore a "new" kind of graph. At the beginning of the first activity of the first investigation position-time graphs are displayed with generic "x-y" labeling. Students are invited to generate their own descriptions for what is being displayed on each axis.[44] With discussion they decide on things like: the distance from the detector for the vertical axis and time from the start for the horizontal axis. Once the class has decided on a consensus view then the graphs are displayed with standard labels, in this case, position and time. The point is made in class that until or unless something happens to change our minds apparently then we can take "position" to mean "distance from the detector" and "time" to mean "the time from the start". Similarly, the velocity-time graph is introduced with generic labels, "x(2) and y(2)". The students work out that again the horizontal axis is time, but that the vertical axis this time is “how fast you’re going” and the positive and negative are “which way you’re going, positive away from the detector and negative is toward the detector.”

In the first two investigations, the introduction to the new kind of graph in each case is followed by applications of the class-developed notions for the nature of the graphs. They are asked to decide what the graph would look like if they made a particular, prescribed motion and then to test their conjectures. They are asked how they would have to move to make a given particular graph and then to test their conjectures. Once the velocity-time graph is developed they are asked what shape velocity-time graph would be made by the same motion as made a given position-time graph and vice versa.

Because there is so little attention paid in everyday life to the process of speeding up, going to some trouble to engage them in the process makes a difference. At the very beginning of the third investigation we introduce the students to features of a single step: an initial stand still, a continual speeding up, a continual slowing down, a terminal stand still. In the context of this motion we introduce the acceleration-time graph, but again we give the vertical axis a generic label, “y(3).” The students are engaged in describing what apparently is being displayed on this axis. The students decide that you have to be changing speed to be off the zero of the vertical axis and whenever you are not changing your speed you are on the zero. When they see the conventional label for the vertical axis, “acceleration,” because of the particular motion (a movement away from the detector) they are studying they find it convenient to decide that speeding up (acceleration) must be positive and slowing down (deceleration) negative. This is problematized when in a subsequent activity they are asked to predict the graphs for a similar motion, which is a single step now *toward* the detector instead of away. It is pointed out here that the surprising behavior of the acceleration-time graph is because of a difference in meaning for the term, acceleration.

The fourth investigation involves the study of constant accelerations using low-friction carts on ramps. Fan carts on horizontal tracks could be substituted. First, the complete motion: standing still, release and constant acceleration, catch to a full stop, standing still of a cart on a slightly inclined ramp or a fan cart on a horizontal track at low power is studied. Then the same for a cart on a more steeply inclined ramp or a fan cart on a horizontal track at higher power is studied. Finally the motion of the cart given a shove up the inclined ramp or against the action of the fan on the cart on a horizontal ramp is considered.

The author worked for a number of years in collaboration with Thornton and Sokoloff using their Tools for Scientific Thinking (TST) Project materials. Anyone familiar with those materials will recognize many of the activities in the Motion Unit of PIPS. The Motion activities in PIPS differ in three respects. First, only kinematical issues are considered in the PIPS Motion unit, no references to force are made explicitly. Second, the TST materials do not engage the students in deciding what the graphs are showing before giving the conventional labels. Third, the TST materials do not explicitly reveal the cycle: “What do you think?,” “What does your group think?,” “Making observations.,” and “Making sense.,” used throughout the PIPS materials.

Although not formally a part of the PIPS Motion Unit, in the course under study in this work, the homework, paper-and-pencil, materials from TST were used. The TST homework sets were divided up into four sets of questions appropriate to the PIPS Motion Investigations. These materials were used in class as discussion issues. The questions frequently revealed the presence of aspects of the students’ conceptions that do not match the behavior of the graphs. Students were asked to fill out the materials with their own answers and bring them back to class. In class they were gone over by the class as a whole. Issues of why or why not each of the possible answers were discussed and if necessary an actual demonstration would be performed with the apparatus in the lecture hall and computer projection of the resulting graphs. They were given credit for "doing the homework," but it was not graded *per se*. Students were responsible for deciding what the best answer was in each case and why, based on their experience in lab and class discussion and for making their own record of it.

Evidence which will appear later in the present paper suggests that if one were to try to carefully determine differences in efficacy between the TST and the PIPS motion materials one might find some small differences in student performance on the diagnostic used. Even though the TST materials were not actually developed for the purpose they are put to here, clearly the successes of PIPS we show below are due to the foundation provided by the TST Project.

2. The PIPS Force Unit

The first three investigations in the PIPS Force Unit are devoted specifically to the conceptual development described in the transition across the center of Figure 1. They are a large-scale version of the cycle employed in all of the PIPS materials. Investigation 1 is completely devoted to a thorough elicitation of the students' ideas about force and its relation to motion with the class arriving by consensus on a particular view they all share. Investigation 2 invites the students to test the elicited ideas in a specific example. This example could be a cart in a modified Atwood's machine, set up so that the cart is pulled along a horizontal track by a falling mass or it could be a cart pulled along a horizontal track by another cart with a fan drive mounted on it. This investigation contains "Making observations" and "Making sense" stages for a large-scale cycle begun in Investigation 1. Investigation 3 invites students to continue testing their ideas on high friction and constant velocity situations.

Force Investigation 4 invites the students to consider falling objects, the role of inertia, and whether force in the vertical direction is essentially equivalent to force in the horizontal direction. In the process of the investigation students also experience the consequence of attempting to apply a constant force to an object; namely that one has to accelerate too in order to continue to apply the constant force. This is the origin of the title to this activity, "Feel the Force." This investigation has roots in the Physical Science Study Committee (PSSC)[45] activities first devised in the late 1950's.

The fifth and final investigation in the PIPS Force Unit addresses the issue of the mutual interactivity of forces. A series of situations is considered in which in the everyday view the force on one object by another is not generally equal to the force exerted by the other object back on the first. An example might be one in which a large truck is pushing a very small car along with an ever increasing velocity. The observation that in every case the two forces of interaction are the same makes possible the development of yet another notion concerning the nature of force.

This description of the strategies and details of the process in the two units is necessarily brief. Additional insight can be gained consulting the PIPS materials and the extensive instructor notes and from two other publications containing descriptions of the process.[12,46]

C. Typical Student Ideas Concerning Motion And Force At The End Of Instruction

During each unit the instructor attempts to train the students' attentions on their ideas concerning the phenomena. In the large class setting of this study, this was accomplished by having the class agree by consensus on what they thought made sense at various points along the way. In this particular course in each unit the goal set for the class was to develop a document summarizing the findings and conclusions during the unit. Computer projection and word processing software was available in the lecture-hall to support whole class development and editing of the document. This document would serve as the authority for judging responses to test questions. Exams are not measures of who knows externally approved answers, but of who appears to understand this consensus view developed by the community of scientists consisting of the members of the course. The students came to call their initial views in each case, "the old view," and the final view developed during a unit, "the new view."

The reader may find this course policy surprising. After all what happens if the students come up with a non-Physicist view? Is this not a problem? This would be a problem if both the advertised purpose was to teach some particular approved view and the students were not capable of improving the sense they make of the phenomena. As it turns out, the course does not advertise to "teach" some particular approved view and the students are capable of improving the sense they make of the phenomena. The reader is reminded that the purpose of this course is *educative* and not training. The goal is for students to deepen the sense they make of the phenomena, to develop their skills at sense making and to realize they can make deeper sense of the phenomena. In the 15 years over which this approach was developed involving more than 2000 students, the "new view" the class came to could always be successfully defended on the basis of the data directly available to the class to any physicist who would care to listen. In fact in geometric optics the class routinely comes to a model that it would have to teach to the physicist because it goes beyond the normal training of the typical physicist.

1. Typical Class Consensus View on Motion and Motion Graphs at the End of the Motion Unit

Table 1 illustrates the contents of a typical class consensus document on motion and motion graphs during the study. All students were allowed to question or challenge any item in the document as it was being developed. The instructor attempted to problematize any term he thought might not really be understood by everyone in the course. Hence, as nearly as possible every student was in a position to be able to give essentially the same interpretation of each statement in the document. A comparison between Table 1 and the initial student view on motion suggests evidence of the conceptual change or shift indicated in the transition between the first two columns on the left of Figure 1.

The students were given as free reign as possible in the development of the document, but they were attempting to develop their own interpretation of the graphs of their motion and that of the carts generated by the MBL equipment. The MBL apparatus and software is designed to produce graphs that are consistent with the established meanings for terms such as position, velocity and acceleration. It is no surprise then that this consensus document is easily understood by any physicist or engineer.

It is interesting that Table 1, the consensus document, contains no diagrams. This was typical even though every semester the instructor repeatedly offers that diagrams could be added. Students seem to do perfectly well with the document in this form, but to most scientists it seems it could be more efficiently expressed with a few diagrams.

More significant to this study by far is what the document in Table 1 implies about the physics "education" the students have experienced so far. Nearly all of these students had a physical science course in the eighth grade or possibly ninth grade if they were from out of state. A tiny percentage of the order of 5% may have had high school physics. Possibly a few more have taken courses such as Calculus for Business, maybe 10%. The junior high physical science course includes instruction on motion and force. Nonetheless, we have the difference between Table 1 and the description of the initial student views. It can be added that those who did admit to having had high school physics did not stand out as having had views significantly different than their peers at the beginning of the course, in fact no one in the study group did.[47,48]

What does this imply about the effect of the instruction these students have experienced before this course? As suggested before, it is an abject failure, but now we can say more. These students actually developed the ideas in Table 1 themselves. There is neither lecture nor text to tell them. They are capable of constructing and understanding these ideas. Either the previous instruction was developmentally inappropriate or just inappropriate. We have evidence that there is an appropriate alternative instruction in the present work. In another study[49] we have evidence that it is not developmentally inappropriate. Hence, it appears likely students in the present study *could* exit eighth or ninth grades generally having constructed these understandings of motion as displayed in Table 1 for themselves. They did not, leaving us with the conclusion that their previous instruction was profoundly ineffective on this issue.

Second, on a more positive note, the contents of the class consensus do indicate an understanding of terms we know that physics and engineering students have difficulties with.[1,8,31] Many in the sciences are inclined to imagine that non-science students, mostly without calculus or even much algebra for that matter, could not master such ideas let alone develop such ideas for themselves. One could claim that the approach used demonstrates the possibility that people are much more alike than they are different. Yet most typical science instruction seems to be "teaching" people that only certain people are capable of developing and mastering such ideas.

2. Typical Class Consensus View on Force and Its Relationship to Motion at the End of the Force Unit

Table 2 contains a typical consensus document on force. There is clear indication here in Table 2 that students have crossed the centerline conceptually in Figure 1. As before the students had free reign as to how to structure this document and what to include in it, but their efforts were constrained in that they were attempting to describe shared experience.

The students were engaged in trying to describe forces as pushes or pulls to explain motion both from their previous life experience and new experiences available to them in the laboratory and large class demonstration. Being there to witness many classes over the semesters since 1981 when Minstrell first shared the approach with the author[50] do this same thing, it comes as no surprise that this "new view" the students develop looks familiar to physicists and engineers. That normal, intelligent adult human beings are more alike than they are different becomes an even more likely conclusion.

Another feature should be pointed out here in relation to the two approaches described in the introduction. This work is an example in which the instruction is *student understanding-driven*. The students are not given a series of building block experiences or concepts and asked to guess from these some particular goal structure or content. They are invited to make explicit their ideas and then to compare these ideas with some actual apparatus whose motion and the forces on which ca be studied in greater detail than in normal everyday life. The students decide if and what is flawed about their notions and how to patch or reconstruct something that they then could check against experience again. It generally is not accomplished in one step. It takes several iterations, but in the end they can tell you why they prefer the final consensus ("It works. We tested it.") and why several other possibilities are not better. This is an automatic outcome of such an approach. It is not generally an outcome of a *goal or content-driven* approach. The final consensus view from the *student understanding-driven* approach in this case is what is tacitly taken as the goal in the *goal or content-driven* approach, although we see now that the actual goal of *content-driven* physics instruction is to appropriately present knowledge in its canonical form for those few who deserve it. To assist the students in understanding this different approach an extensive course philosophy document was prepared and made available to them.[51]

III. EMPIRICAL EVIDENCE THAT AN UNDERSTANDING OF ACCELERATION MAKES POSSIBLE A NEW UNDERSTANDING OF FORCE

A. The Setting

It was recognized early on by the PIPS development team that such materials are taught at the college level under a variety of circumstances. In some settings there are multiple instructors for class sizes of 30 for which one can move between lab activity and discussion at will in multiple semester courses. In other settings the class size may be as much as 150 or more and class meetings are rigidly divided between what is typically called “lecture” and “lab” in a single semester course.

The present work was in a setting similar to the latter. The class size was from 100 – 120 students. They met with the instructor for two blocks of 75 minutes in a large lecture hall equipped with computer projection and demonstration apparatus. In addition they met with the same (yes, the same) instructor in 5 sections of 24 for about two hours at a time each week.[52]

All of the students were non-science majors. There are contingents of pre-service elementary education and bilingual education majors each semester in the course. The course is part of the university’s Core Program; hence many students from various non-science majors take the course. Most science majors have the science portion of the Core requirement satisfied by other courses. The presence of science majors is a rare exception in the case of candidates preparing to teach which incidentally did not occur during the semesters under study.

B. Diagnosing Understanding

How does one know what another understands? How does one know when that understanding changes? All one has is the behavior of the other as evidence. Based on our observations of the behavior of others we make rational reconstructions of the notions of others about the phenomena. Probably the best most convincing type of data comes from individual demonstration interviews. These typically take 30 to 60 minutes to conduct per student and many hours of subsequent analysis. Typically with numbers of students around one hundred individual interviews are not practical even if a large team of interviewers were available. To deal with this problem of numbers multiple-choice diagnostics have been developed in conjunction with individual interview feedback and written feedback in an iterative process to yield convincing data.

The diagnostic questions used in the present study were mainly from the Force and Motion Conceptual Evaluation (FMCE) developed by Thornton and Sokoloff.[53] The first 21 questions all probe a student’s ideas concerning the relationship between forces on an object and the motion of the object. A subset of 17 of these questions was used in various ways to indicate the nature of the students’ ideas about force. Another subset of 8 questions from the FMCE probes nature of the students' understanding of acceleration. Finally, another subset of 5 questions probes student thinking on velocity and velocity graphs.

Still, the questions initiating this section remain unaddressed. How do we take the choices made on these multiple-choice diagnostics and make decisions about what we think the students' ideas are? If the students find choices that genuinely make sense to them in the context of the questions, the choices will be consistent with the notion or conception the student has concerning the phenomenon. For example, if the student is using the conception described as the pre-existing student view of force, then in cases where the object's motion is along a straight line and the magnitude of its velocity is constantly increasing the student will associate with this a force of constantly increasing magnitude in the same direction as the motion of the object. We observe this pattern regardless whether the motion is described and the force is asked for or the force is described and the motion is asked for and whether the setting is in terms of graphs of the force and motion or the setting is independent of such graphs. If a student answers several different questions consistently with this scheme, then it is reasonable to imagine that the student might be using the pre-existing view, also sometimes called the person-on-the-street view at least with respect to increasing velocity situations. With the aid of Table 2 and the description of initial student views on force described earlier in this article, one can generate additional patterns of response for additional questions. This is the set of responses consistent with the "old" view," the view most came to the course with.

Table 3 illustrates a typical set of data for a class at the beginning of a semester. Table 3 is a frequency table of the choices made by students responding to the 1st 21 questions of the FMCE. The core of this table is a frequency table giving the number of students picking particular choices for each question. The top row indicates the characteristics of the velocity in each question: (I) increasing, (C) constant, (D) decreasing, (Z) zero, and (R) rest. On the left, the letters correspond to the choices a student might make. At the bottom are indications of the choices consistent with the new view and those consistent with the old view plus the percentages choosing each. The question numbers match the question numbers in the original article by Thornton and Sokoloff on the FMCE.[52] A scan of the percentages reveals that at this point in the semester there is little prevalence of the new view while the old view reigns supreme. The new view is the one they generate during the semester to match the observations they make. It should be pointed out again that a small number of such a class typically may have had high school physics, 5% or less, but that nearly all have had a junior high course in physical science which contained instruction on motion and force. Yet, there is *no evidence* that such a course has had *any effect* on how they see forces in the world.

C. Diagnostic Data as Evidence of Change in Ideas of Force

Table 4 illustrates a set of data for the same students in the same class at the end of the semester. The table has the same structure as Table 3. It is clear though that noticeably fewer students are answering consistently with the old view and many more are answering consistently with the new view. Clearly, there is evidence of a shift away from the old view and toward the new view in the distributions of these answers.

D. Thornton's Conceptual Dynamics

Thornton[54] has analyzed the responses of several thousand students and is able to distinguish features of changes in ideas of force which correspond to the facets described by Minstrell.[10] It appears that students parse the range of possibilities of motion into four categories when they are trying to explain motion in terms of force: rest, constant velocity, increasing velocity, and decreasing velocity. The FMCE does not dwell much on the ‘at rest’ condition, but it does attend to the other categories. Thornton sees evidence of a developmental sequence of student positions and transitional states with respect to force in each of the motion categories in the patterns of choices students make on certain of the questions in the diagnostic.

Table 5 gives the basis for the analysis. It contains the questions used to make the determination in each motion category and the choices used to determine the position in each category. Thornton’s paper[53] describes the process and the positions in each category in more detail. Each position is identified by a pattern of choices to specific questions. A position could be thought of as a view of the nature of the relationship between force and the type of motion under consideration. Briefly, following Table 5, it works like this: There are two positions observed to be taken concerning the relationship of force to increasing velocity. Both of these positions are diagnosed using FMCE questions 1, 4, and 16. Question 19 is taken as a backup indicator. Choices A, G, C, and D respectively are indicative of position (1) on increasing velocity and choices B, F, A, B respectively are indicative of position (2) on increasing velocity. With respect to student thinking about the relationship between force and constant velocity phenomenologically there appear to be three positions. Questions 2 and 14 are used to diagnose these positions with questions 5 and 17 as backup indicators. Choices indicative of each position are found in Table 5. Finally in the case of decreasing velocity and its relationship to force 5 positions are found. Questions 3 and 7 are used with question 18 as a backup indicator. The choices indicating each of these positions on force with respect to velocity under the various conditions are found in Table 5.

It is important to note that the positions in Thornton’s conceptual dynamics sequences were worked out phenomenologically from the raw data as apparent student “models” identifiable in patterns of choices made by thousands of students. The “old” view of force as described above and as identified by the choices made by the students before experiencing the PIPS instruction matches the first positions in the increasing velocity and constant velocity category and the first two positions in the decreasing velocity category of the conceptual dynamics analysis. The “new” view of force as identified by the PIPS students both in Table 2 their end-of-unit consensus document and in their answers on the FMCE questions at the end of the PIPS instruction appears to match the final positions in the conceptual dynamics analysis.

Significantly, Thornton’s data is largely from high school physics classes and from algebra-trig and calculus levels of introductory physics at the college level, but not from students who would not typically take any of these courses. The students in the present study were not as likely to have had high school physics, although a few did, and none were going on to take the algebra-trig or calculus level of introductory physics. Yet their starting and ending conceptual states appear much the same as those seen by Thornton and Sokoloff. Instruction previous to the present appears to have had little effect on how they answer these questions. None in the present study who had high school physics will be seen to stand out as having a different background in the pre-instruction data anywhere in this study.

Using Thornton’s conceptual dynamics on several semesters of students yields the results in Table 6. Students in Spring, 1996 experienced TST kinematics activities and instruction on force based on Minstrell’s approach. Students in Fall, 1998 serve as a kind of control. Their instruction included the activities from the first draft of the PIPS Motion unit only. They did not study force that semester. Note that when they are not engaged over their ideas concerning force, their ideas do not appear to change. Students in the semesters, Spring, 1999 and Fall, 1999, experienced both the PIPS Motion and Force Unit activities. The Spring, 1999 students are the ones whose responses are in Tables 3 & 4.

All of the data in Table 6 is in terms of percentage of the number of students in that semester. The exception is the first column labeled "N" which is the total number of students from whom we have matched pair data pre and post instruction for the given semester. Columns labeled "1," "2," etc. are the percentage of students in each of Thornton's conceptual dynamics positions. The columns labeled "OR" and usually followed by a pair of numbers give the percentages of students who appear to be in a transition state between the positions whose numbers are given after the "OR". These are considered evidence of transitional phases by Thornton.

It is important to note that while Thornton's data suggests a kind of developmental progress through the positions, it is not absolutely clear that each student would ever necessarily be seen in each of the intermediate and the relevant OR positions along the way from position "1" to the final position. What is clear from Thornton is that there is evidence of a "direction" of change. A student who answers consistently with a position "1" before instruction can be expected to be found answering consistently with "OR1,2" or later at the end of instruction. A student answering consistently with a position "2" is unlikely to be found answering consistently with position "1" or "OR1,2" but more likely to be found answering consistently with "OR2,3" or later at the end of instruction. Students in the present study seemed to show more of these mixed "OR" positions than in Thornton's original study.

It is clear that when students are engaged over their ideas of force as they are in the *student understanding-driven* PIPS materials, the result is a change in how they appear to think about force as indicated in their answers on the diagnostic questions. The Spring, 1996 students seem to do about the same as the students from both semesters in 1999. This suggests that the pre-PIPS instruction, TST kinematics activities and activities based on Minstrell's approach to the relationship between force and motion, has almost the same effect as does the PIPS instruction. This is not too surprising given the same instructor was involved and that the PIPS instruction is based on the earlier work.

E. Scatter Graph Display of Change in Ideas of Force

The presence of a set of choices that match the new view and another set of choices that match the old view makes possible two scores, a new view score and an old view score, simultaneously each time a student fills out choices on the diagnostic.[55] The scores are calculated in the manner described in endnote 54 and can have a maximum value of 15. The diagnostic items used are the same as the ones used by Thornton on which to base his conceptual dynamics. With two scores we have an ordered pair. With such pairs we can make scatter graphs. Figure 2a represents in new view on force vs. old view on force scatter graph format the raw data summarized in Tables 3 and 4 (Spring, 1999). Each point on this graph represents a pair of scores (old view, new view) for a student answering the FMCE. For example, a point at the location 9 on the horizontal axis and 2 on the vertical axis corresponds to the pair of scores (9 old view, 2 new view). In simple terms 9 of the student's choices matched the old view key and 2 matched the new view key. More than one student might have the same score. In order to get a better sense of the distribution, the average position of the pre and post instruction diagnostic scores are indicated by the arrows. Figure 2b contains the same display of results from the second semester of students taught in the same fashion (Fall, 1999). The results are very similar.

This new view on force vs. old view on force scatter graph of two distributions, pre and post instruction responses to the diagnostic questions, shows several apparent effects of this instruction. First, we note that the pre-instruction distribution is strong on old view and very weak on new view of force. One might feel this is no surprise since the instruction had not started yet, but it should be pointed out again that *motion and force was in the curriculum of nearly every one of these students in the eighth or ninth grade* and probably at least once sometime earlier in their schooling. Second, the effect of the present instruction appears to have focused the student thinking on the old and new views. The post-instruction distribution is more or less distributed along and beneath the upper-left to lower-right diagonal. Third, while a fair number of students are in the upper-left corner where one might like them to be at the end of instruction, there are also a number of students distributed all the way back down the diagonal to the lower-right even at the end of instruction with a class-generated consensus document in their possession.

One wonders why it is that with a consensus document with "everything you need to know" summarized on one page and in the hands of every student, some students still did not bring themselves to pick choices consistent with the ideas represented on the document. Clearly, it is not a matter of merely being told. A reasonable supposition concerning the students who do not move out of the lower right of the graph is that they are still trying to "take" the course like a normal science course in spite of the instructor's efforts to get them to try something different.

Any good instructor is bound to wonder what makes the difference between those students who moved far up the diagonal to a strong "new" view score minimizing their "old" view score and those students who moved only half way up the diagonal or those students who stayed down in the lower right corner. An investigation of what appear to be major determining factors is the subject of part II of this pair of papers.

F. Scatter Graph Display of Normalized Change in Individual Views of Force

When discussing another diagnostic, the Force Concept Inventory (FCI),[56] one uses what is called normalized gain. Hake[57] introduced this notion to the field in his rather thorough large-scale meta-analysis of pre and post testing using the FCI in a range of instructional settings. Hake indicates that (unknown to him in 1998) Hovland evidently first suggested use of the normalized gain.[58] In his work Hake develops certain guidelines and benchmarks in terms of particular values of normalized gain in FCI scores. It should be noted that normalized gain derived from the FMCE are sufficiently different that the same numerical values should not be used to judge results on both diagnostics without additional analysis.[59] This is all the more so the case when considering comparing normalized gain from FCI total scores with normalized gain from a selected subset of FMCE items all on one conceptual issue.

For any two measures of the same thing over time one can calculate a normalized gain as the actual change divided by the maximum possible change. Of course, the maximum possible change only exists for measures having some finite limit, hence it is not normally possible to calculate normalized change for just any quantity which might change over time.

In the present work we have the opportunity to look at two scores (new view and old view) as opposed to just the one normally considered in the FCI. Clearly if one begins to abandon features of the old view in favor of features of the new view, then as the old view score diminishes the new view score increases, but it is important to note that for the students in this study it is almost never the case that the new view score plus the old view score equals fifteen (the max possible). All of the items in the diagnostic have more than two choices available.

This leaves room for the possibility of intermediate views between the “old” and the “new” views as developed by the class and as seen by Thornton in his analysis. Hence, the two scores are somewhat independent. If they were not independent then all of the points in Figure 2 would be on the diagonal. A glance at the graph reveals they are not. It is possible then that there is some value in considering the change in the two scores as separate entities.

Typically we have gain in new view score, but the old view score tends to diminish. Hake has shown us how to calculate the normalized gain in the new view score.

$$\text{normalized gain new view} = [\text{new(post)} - \text{new(pre)}]/[\text{max} - \text{new(pre)}]$$

In this case, the maximum possible score is 15. Following Hake we will use <g> to represent the normalized gain in new view. As long as there is a gain in new view score then the values of the normalized gain range from zero to one.

How would we calculate a normalized loss in old view? There are several options, but the following was chosen in order to best illustrate the results.

$$\text{normalized loss old view} = [\text{old(post)} - \text{old(pre)}]/[\text{old(pre)} - \text{min}]$$

In this case the minimum score is zero. We will use <L> to represent the normalized loss in old view (upper case “L” to avoid confusion with the digit “1”). As long as there is a loss in old view score the value of the normalized loss in old view ranges from zero to minus one. It should be noticed that normalized losses and gains are not simple linear quantities and have decidedly “strange” behaviors if the score changes in a direction opposite to normal.

With these quantities established we can calculate <g> and <L> for each student in a given semester. Because we again have an ordered pair for each student we can produce a scatter plot which illustrates the same data as in Figure 2, but which looks very different. Figures 3a & b contain plots of <g> vs. <L> for the same two semesters presented in Table 6 and Figure 2. Arrows point to the average positions in the distributions.

G. Effect Size

Recently there has been a move to standardize the measure used to indicate results in studies of human behavior. Many journals on these issues have as a policy that results be reported in terms of effect size, sometimes called Cohen’s *d*.[60] Simply, effect size is an indication of the difference between two measures in terms of the equivalent number of standard deviations of the measures. Specifically it is calculated in pre and post measures as the difference between the post and pre measures divided by something called the pooled standard deviation. The pooled standard deviation is the square root of the average of the squares of the standard deviations of the two measures. Both effect size and normalized gain/loss are easy to calculate. There are things that normalized gain/loss tells us which effect size does not, in particular normalized gain/loss tells us fractional change students have made moving from answering consistently with one view to being able to use another view to answer the items.

The class average new view and old view scores can be calculated, as can the standard deviations in these measures for both pre-instruction and post-instruction. With this information effect size can be calculated. Table 7 gives the effect sizes of the changes in new and old view of force scores for the two semesters reported on so far (Spring and Fall, 1999) plus a previous semester (Spring, 1996) in which the same sort of instruction was used but the materials were from the TST kinematics activities followed by Minstrell-inspired force activities; i.e., precursors to the PIPS Units.

It is clear that whole class effect sizes of nearly *2 standard deviations* are routinely possible even under the fairly difficult instructional circumstances in this study. The reader is reminded that the class size is 100 – 120 with full-class meetings in a lecture hall and 5 or 6 sections of 2 hour lab sessions all taught by the same instructor with no assistance.

Effect sizes of the order of *two standard deviations* are major. They surpass by far mere statistical significance. An effect size of *2 standard deviations* means that mean of the post-instruction measure is at the 98th percentile of the pre-instruction measure. In the 1980's Benjamin Bloom, Dean of the College of Education at the University of Chicago lamented that the best educational innovation then known, the mastery approach championed by Bloom, was capable of about one standard deviation in performance improvement and that it took one-on-one tutoring to reliably generate two standard deviations.[61] Here we have evidence of a *student understanding-driven* approach to instruction necessarily *informed by research in physics learning* apparently resulting in routine effect sizes around *2 standard deviations*. Given other evidence from research in physics education of similar effect sizes for instruction informed by research in physics learning,[52] it should be abundantly clear that research in physics education stands to make substantial contributions not only to the teaching of physics topics, but to teaching in general.

H. Demands Placed on the Diagnostic

It should be pointed out that without a diagnostic that provides students choices that make sense to them, it is not possible to discern the patterns of choices representing differing views. Without this feature the richness of the four preceding ways of rendering the diagnostic data would not be possible. Indeed some of them would not be possible, rich or not. This is a challenge to developers of diagnostics that seems to have been met by Thornton and Sokoloff in the FMCE.

IV. CONCLUSIONS CONCERNING THE EFFECT OF THE PIPS INSTRUCTION ON MOTION AND FORCE

Clear evidence that the *student understanding-driven* instruction on the topics of motion and force from the PIPS Project result in significant change in apparent understanding of both acceleration and force. Furthermore, the results presented were generated under nearly the most difficult conditions under which this course is taught anywhere. Possibly worse would be to teach it without laboratory sessions.

Thornton has reported that under traditional instruction, calculus level introductory physics students have been seen to only achieve at the 20% rate on the same and similar questions to those in the FMCE.[35] The PIPS students did obviously much better than this. In the PIPS *student understanding-driven* instruction we have another example of what could be called an "interactive engagement" (IE) method of instruction because of the constant focus in the approach on getting students to interact with each other and the experiences with the phenomena over their own conceptions. It appears to meet Hake's operational criteria for IE methods.[56] It also appears to result in superior learning by the students as did many but not all of the IE examples in Hake's meta-analysis. It may interest the reader to consider his discussion of those examples of IE which did not result in as high a performance.[62]

A small amount of data presented here enables a partial comparison with another research informed set of materials, Tools for Scientific Thinking. The comparison is only indirect in that only the kinematics activities from TST were used and the primary data is on student notions about force. In addition the PIPS materials are based on the TST kinematics activities. Hence, it is not too surprising that there is little difference seen in the diagnostic results. It may be the chief differences between the different research-based materials are the circumstances in which they are intended and not particularly differences on the diagnostic results.

These results of nearly *two standard deviations* apparently only dreamed of in the 80's go beyond demonstrating the value and efficacy of the PIPS instruction. It is clear that a substantial portion of the students go far beyond *2 standard deviations*. They obligate us to re-think long held beliefs in the physics community about students in various categories and long held beliefs about instruction. Non-science majors can with their own native resources develop, what are for them, new and powerful ideas about the phenomena, very similar to ideas scientists had in the past. These students can do it in fair numbers under adverse conditions, if they are engaged in comparing their own ideas with the phenomena.

To be sure the 8th and 9th grade physical science teachers of these students are conscientious, sincere, and hard working teachers, teaching what they understand and in the best way they know how. To be just as sure it is extremely likely that they are using *content-driven* approaches and given the shift toward the rigid application and assessment of standards they are likely to become even more *content-driven*. Sadly, in spite of their best intentions what they were doing before appears to have had no effect on student conceptions of the phenomena in the first place and becoming more *content-driven* can be expected to exacerbate the negative effects on student self-images. Clearly there are many rewards for our students, society and ourselves if we have the courage to ignore the self-imposed external dictates of canonical knowledge *content-driven* approach and instead focus on *radical, student understanding-driven* approaches to *educate* students rather than *train* them.

One might respond that this is a little unfair to the 8th and 9th grade physical science teachers and indeed it might be. After all, by the time the students are in college it is three or four years since that physical science instruction. Let us make a direct comparison between the traditional *content-driven* approach and students experiencing a radical, *student understanding-driven* approach each by comparing pre and post diagnostic results in the same semester as the instruction, but this time let us shift the balance of the comparison in the other direction. We will be able to compare science and engineering majors experiencing the traditional *content-driven* instruction with non-science majors in the radical, *student understanding-driven* instruction in Part II of this pair of papers.

Figure Captions:

Fig. 1. A sequence of conceptions concerning motion and force encountered in students as they construct new explanations of motion and force and its relationship to motion. The Powerful Ideas in Physical Science Units on Motion and Force are example instructional materials that induce these changes. The left-hand column describes their ideas when they arrive in an introductory course at the high school and college level even after they have had one or more instructional experiences on motion and force. The left-middle column is a possible state of understanding students develop as a result of kinematics instruction. The shift between these two conceptual states focuses on a kind of conceptual differentiation between motion and how motion changes. The right-middle column describes the features of a conceptual state students are seen to develop as they first reconceptualize force from a construct to explain velocity to a construct that explains how velocity changes. The right-hand column describes a further development of the new conception of force in which motion is re-parsed in a manner more consistent with the new construct force. This involves the inclusion of constant velocity and rest together into a single class of motion.

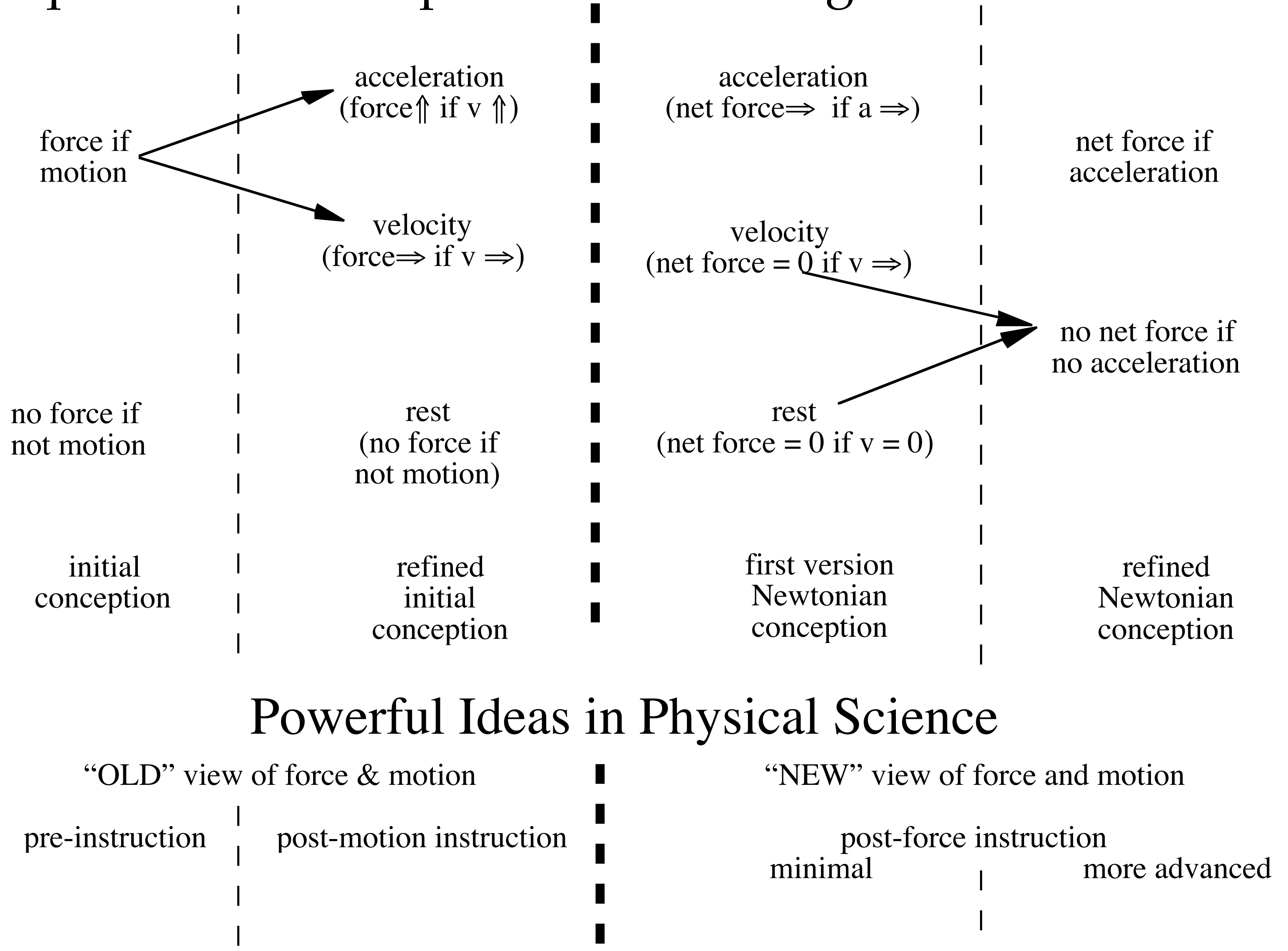
Fig. 2a. This scatter graph of student “old view of force, new view of force” score pairs both at the beginning of the instruction (black diamonds) and after the end of the instruction (open squares). This data was collected in the Spring of 1999 and includes 97 students in both the pre and post distributions. Because more than one student’s score may be at any given point the arrows point to the average position of the two distributions. The lower right arrow points to the pre-instruction average position and the upper left arrow points to the post-instruction average.

Fig. 2b. This scatter graph of student “old view of force, new view of force” score pairs both at the beginning of the instruction (black diamonds) and after the end of the instruction (open squares). This data was collected in the Fall of 1999 and includes 93 students in both the pre and post distributions. Because more than one student’s score may be at any given point the arrows point to the average position of the two distributions. The lower right arrow points to the pre-instruction average position and the upper left arrow points to the post-instruction average.

Fig. 3a. This normalized gain versus normalized loss plot illustrates this view of the student performance from Spring, 1999. Any point in this plot could represent more than one students of which there are 97. The arrow points to the average position in the distribution. Note that the positive normalized losses represent gains in old view of force on the part of some students.

Fig. 3b. This normalized gain versus normalized loss plot illustrates this view of the student performance from Fall, 1999. Any point in this plot could represent more than one students of which there are 93. The arrow points to the average position in the distribution. Note that the positive normalized losses represent gains in old view of force on the part of some students.

Sequence of Conceptions Concerning Motion and Force



force if motion

no force if not motion

initial conception

acceleration (force⇑ if v ⇑)

velocity (force⇒ if v ⇒)

rest (no force if not motion)

refined initial conception

acceleration (net force⇒ if a ⇒)

velocity (net force = 0 if v ⇒)

rest (net force = 0 if v = 0)

first version Newtonian conception

net force if acceleration

no net force if no acceleration

refined Newtonian conception

Powerful Ideas in Physical Science

"OLD" view of force & motion

pre-instruction

post-motion instruction

"NEW" view of force and motion

post-force instruction

minimal

more advanced

Figure 1 Part I

Figure 2a Part I

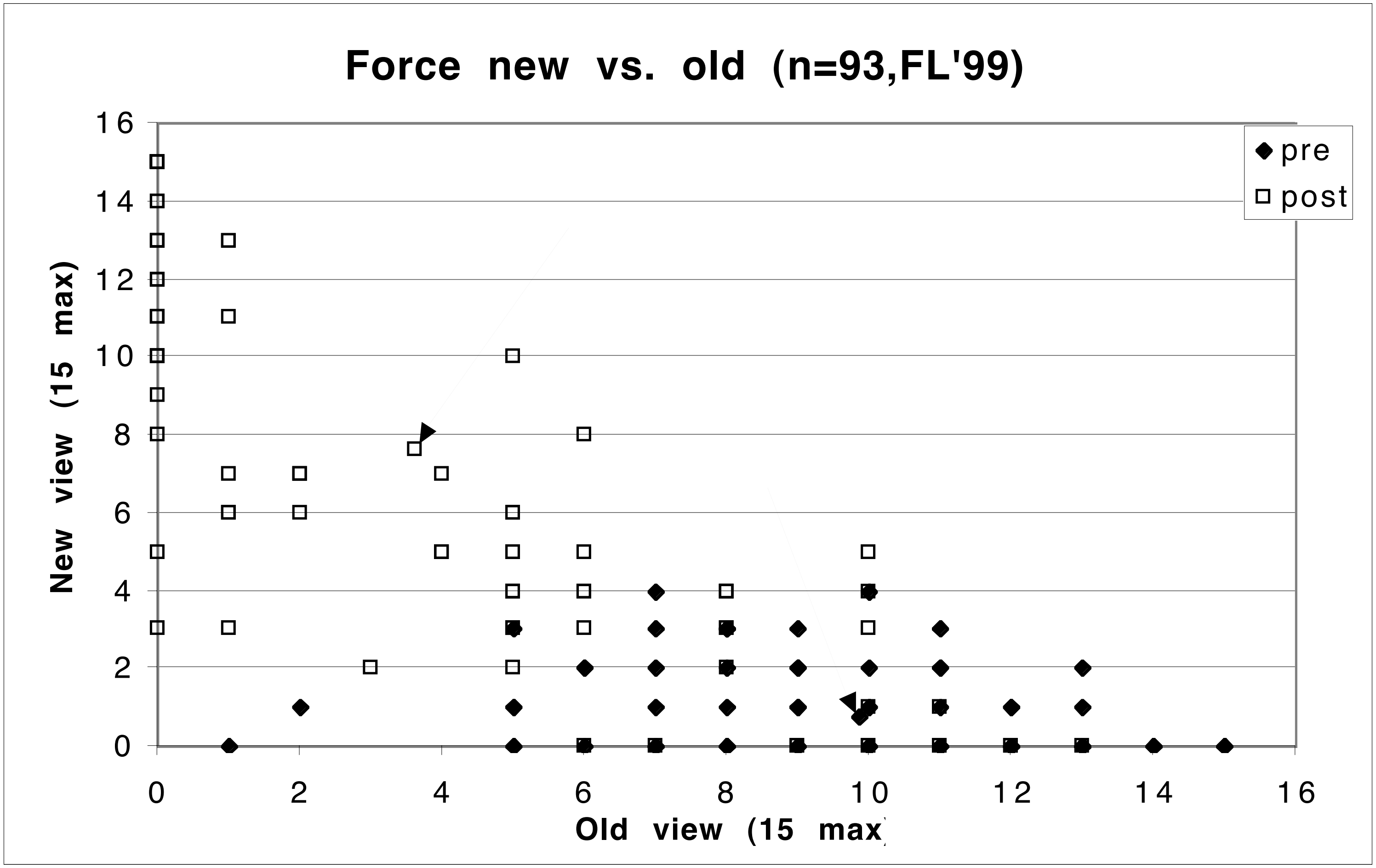


Figure 2b Part I

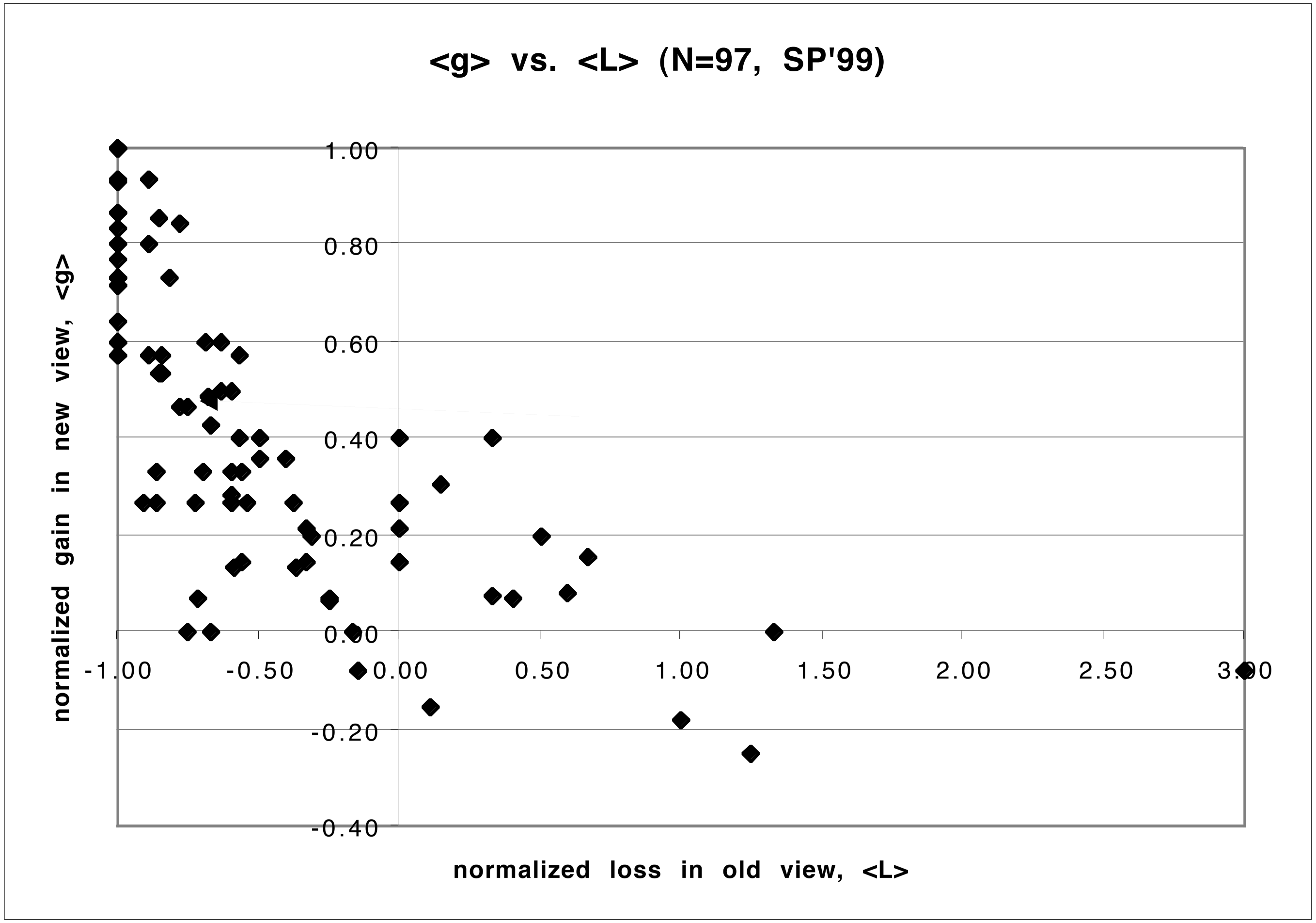


Figure 3a Part I

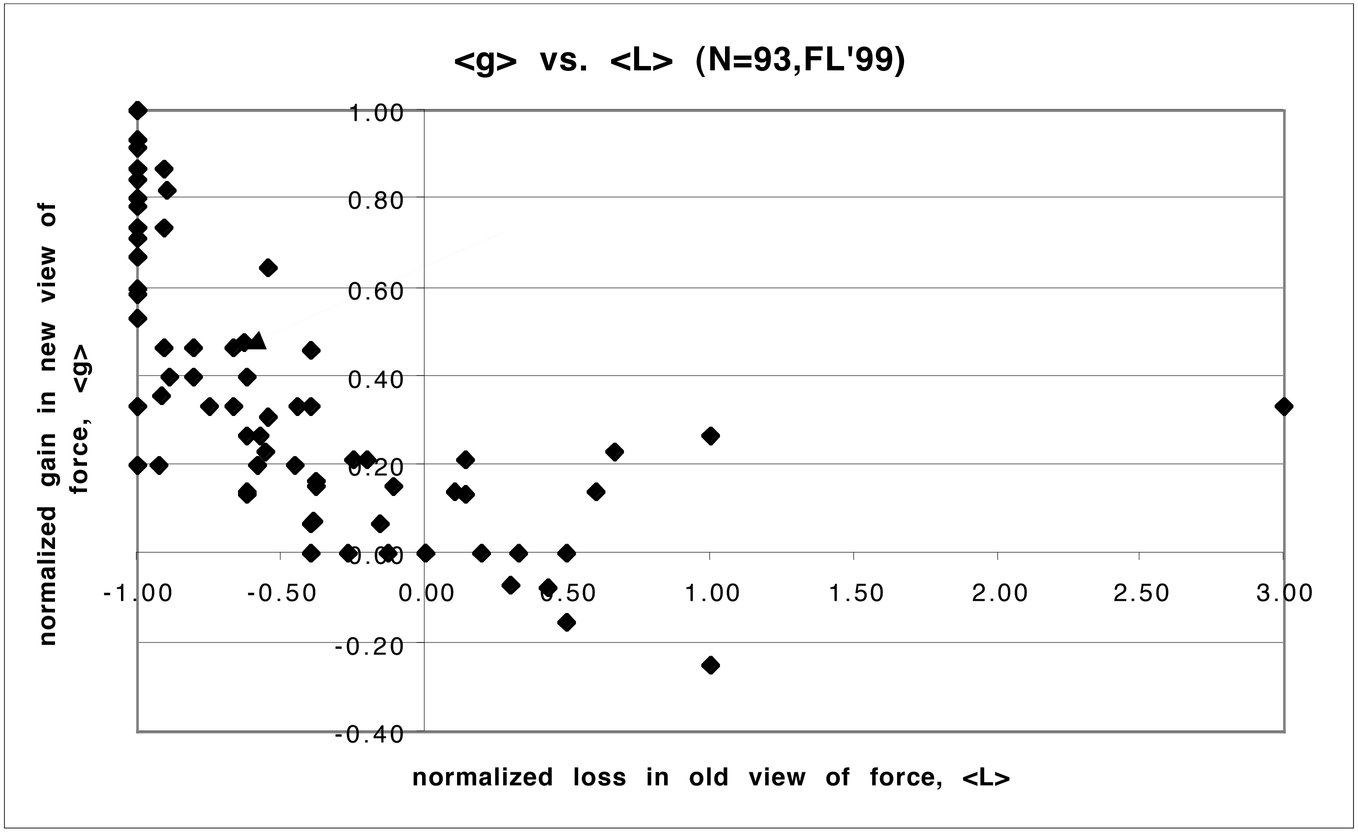


Figure 3b Part I

Table 1: The Consensus Document of One Class Concerning Motion and the Motion Graphs

Position:

The position graph measures how far (distance) an object is in front of (away from) the detector during a period of time

A horizontal line means the object is not moving

Line moving up (sloped up, positive slope) means the object is moving away from the detector.

Line moving down (sloped down, negative slope) means the object is moving toward the detector.

The steeper the slope the faster the object is moving.

Straight lines indicate constant velocity and curves indicate changing velocity

The zero on the graph represents the location of the detector

In general we are working with just the positive positions

Velocity:

Velocity measures how fast the object is going; its speed

Velocity measures the rate at which the position of an object is changing during a period of time

Velocity graphs are about motion. They measure speed and tell direction, but not position.

Positive section = the object is moving away from the detector

When the graph crosses zero it indicates a change in direction of the object

Negative section = the object is moving toward the detector

When the line is horizontal the object is not changing its speed

Zero on this graph means the object is not moving

Steepness measures the rate the velocity is changing

If the rate at which the velocity is changing changes, then the line will curve

The farther from zero the faster the object is going

A line sloping toward zero is slowing down and sloping away from zero is speeding up

Acceleration:

Acceleration is the rate of change of the speed or velocity

Acceleration is about CHANGE in velocity and not about just velocity

Acceleration doesn’t care about what the velocity is only how it changes

When acceleration is at zero the velocity is not changing

The farther from zero the greater the rate of change of the velocity, the greater the acceleration

A constant rate of change of velocity (a straight line on a velocity graph) is a constant acceleration (a horizontal line on the acceleration graph)

Slope scheme: negative slope on velocity means negative acceleration, positive slope on the velocity graph means positive acceleration, zero slope on the velocity graph means zero acceleration

Signed number scheme:

- speeding up (+) moving away the detector (+) and slowing down (–) moving toward the detector (–) give positive (+) acceleration
- speeding up (+) moving toward the detector (–) and slowing down (–) moving away from the detector (+) give negative (–) acceleration

Direction scheme: when the object is slowing down the direction of the acceleration is the opposite of the direction of the velocity, when the object is speeding up the direction of the acceleration is the same as the direction of the velocity, acceleration directed away from the detector is positive (+) and acceleration directed toward the detector is negative (–)

Table 2: The Consensus Document of One Class Concerning Force

Motion Example	Net Force Description
At rest	Zero (equal opposing forces on the stationary object or no forces at all)
Constant velocity	Zero (equal opposing forces on the moving object or no forces at all)
Constant acceleration (constantly speeding up)	Constant (Force in the direction of motion a constant amount greater than forces in the opposing direction.) Net force in the same direction as the motion
Constant acceleration (constantly slowing down)	Constant (Force against the direction of motion a constant amount greater than forces with the motion.) Net force in the opposite direction to the motion

Shape of the force graph appears to be the same as the shape of the acceleration graph DURING the motion.

The force graph appears to show us the “string” force <u>only</u> during the run of the cart.

Table 3: Spring 99 Pre-Instruction Frequency Table

velocity	I	C	D	I	C	D	D	D	Z	I	D	Z	I	C	R	I	C	D	I	ID	C
question	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
new view	B	D	F	F	D	B	B	A	A	A	A	A	A	E	E	A	E	B	B	G	E
A	77	0	2	4	3	13	7	1	3	11	2	5	13	76	3	10	5	1	1	1	11
B	13	84	0	0	68	4	14	1	3	70	3	1	71	3	3	2	59	2	8	0	3
C	3	2	53	1	1	44	7	3	1	12	2	0	7	10	1	64	8	13	8	1	4
D	0	5	16	1	12	9	14	1	75	3	2	78	0	1	1	8	9	8	51	0	0
E	0	0	8	4	2	7	45	7	7	1	11	7	0	5	85	0	2	4	1	1	7
F	1	4	10	6	8	3	4	31	6	0	24	2	0	0	0	0	1	9	1	73	25
G	2	2	5	81	2	9	3	53	0	0	53	4	4	0	1	5	4	11	9	4	16
H	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	5	7	42	6	8	19
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
J	0	0	2	0	0	8	3	0	2	0	0	0	2	0	3	3	1	6	10	8	12
new%	14	5	10	6	13	4	14	1	3	11	2	5	13	5	88	10	2	2	8	4	7
old view	A	B	C	G	B	G	D	G	D	B	G	D	B	A	E	C	B	H	D	F	A
	E		D	C		C	E										D	C			
old%	80	87	72	85	71	55	61	55	77	72	55	80	73	79	88	66	71	57	54	76	11
sum %	94	92	82	91	83	59	75	56	80	84	57	86	87	84	88	76	73	59	62	80	19

Table 3 Part I

Table 4: Spring 99 Post-Instruction Frequency Table

velocity	I	C	D	I	C	D	D	D	Z	I	D	Z	I	C	R	I	C	D	I	ID	C
question	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
new view	B	D	F	F	D	B	B	A	A	A	A	A	A	E	E	A	E	B	B	G	E
A	39	0	1	2	2	3	14	38	41	53	41	43	58	18	1	81	3	26	12	10	23
B	56	34	3	0	28	19	41	7	5	35	6	5	26	2	1	2	12	54	74	1	12
C	1	4	27	1	0	21	4	1	1	2	2	0	3	5	0	9	0	0	2	1	3
D	0	50	4	1	54	5	5	1	37	0	0	35	0	2	0	0	10	0	7	0	2
E	1	0	3	1	1	6	25	13	6	2	18	7	4	65	93	3	68	1	1	1	36
F	0	2	38	51	7	27	7	11	1	2	7	0	4	0	0	0	1	1	0	22	7
G	0	0	20	41	2	14	1	26	1	3	23	1	2	1	0	1	0	7	1	20	0
H	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	5	0	1	6
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
J	0	7	1	0	3	2	0	0	5	0	0	6	0	0	2	1	3	3	0	41	8
new%	58	52	39	53	56	20	42	39	42	55	42	44	60	67	96	84	70	56	76	21	37
old view	A	B	C	G	B	G	D	G	D	B	G	D	B	A	E	C	B	H	D	F	A
	E		D	C		C	E										D	C			
old%	41	35	32	43	29	36	31	27	38	36	24	36	27	19	96	9	23	5	7	23	24
sum %	99	87	71	96	85	56	73	66	80	91	66	80	87	86	96	93	93	61	84	43	61

Table 4 Part I

Table 5: Thornton's Conceptual Dynamics

Velocity increasing (1)				Velocity constant (1)				Velocity decreasing (1)		
1	4	16	19	2	14	5	17	3	7	18
A	G	C	D	B	A	B	B	D	D	B
Velocity increasing (2)				Velocity constant (2)				Velocity decreasing (2)		
1	4	16	19	2	14	5	17	3	7	18
B	F	A	B	C	H	C	J	C	E	H
				Velocity constant (3)				Velocity decreasing (3)		
				2	14	5	17	3	7	18
				D	E	D	E	E	C	J
								Velocity decreasing (4)		
								3	7	18
								G	A	C
								Velocity decreasing (5)		
								3	7	18
								F	B	B

Table 6: Conceptual Dynamics Analysis of Several Semesters

		V incr (percentage				V const (percentage)							V decr (percentage)								mixed		
	N	I	OR1,2	2	NI	1	OR1,2	2	OR2,3	OR1,3	3	NC	1	OR1,2	2	OR2,3	3	OR3,4	4	OR4,5	OR	5	ND
SP'96																							
pre	82	88	12	0	100	78	4	1	1	10	2	96	10	5	41	2	10	0	7	1	2	17	96
post	82	13	27	60	100	17	4	2	2	20	44	89	4	1	20	0	1	1	15	5	2	51	100
FL'98																							
pre	74	81	11	1	93	81	3	1	0	8	1	95	14	7	42	0	4	1	12	0	4	12	96
post	74	76	16	3	95	78	1	0	1	11	1	93	9	3	39	4	7	1	3	1	11	15	93
SP'99																							
pre	97	75	18	2	95	78	3	0	0	10	2	94	10	6	44	1	4	2	4	2	3	9	87
post	97	8	40	48	97	12	5	0	2	22	47	89	1	5	20	3	1	2	12	9	4	36	94
FL'99																							
pre	93	81	15	0	96	83	3	0	0	8	0	94	4	2	55	0	5	1	9	1	9	8	94
post	93	16	31	46	94	27	0	2	8	23	41	100	0	2	19	0	2	1	10	3	8	49	95

Table 7: Effect sizes
(pre to post instruction)
Views of Force

	N	new	old	
SP'96	82	1.7	-1.7	TST + Minstrell approach
SP'99	97	2.0	-1.9	Standard PIPS Instruction
FL'99	93	1.8	-1.8	Standard PIPS Instruction

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[39] M. Jammer *Concepts of Force*. (Dover,1999) (originally Harvard University Press, 1957.) 2 - 4 “As a result of modern research in physics, the ambition and hope, still cherished by most authorities of the last century, that physical science could offer a photographic picture and true image of reality had to be abandoned. Science, as understood today, has a more restricted

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objective: its two major assignments are the description of certain phenomena in the world of experience and the establishment of general principles for their prediction and what might be called their "explanation." "Explanation" here means essentially their subsumption under these principles. For the efficient achievement of these two objectives science employs a conceptual apparatus, that is, a system of concepts and theories that represent or symbolize the data of sense experience, as pressures, colors, tones, odors, and their possible interrelations. This conceptual apparatus consists of two parts: (1) a system of concepts, definitions, axioms, and theorems, forming a hypothetico-deductive system, as exemplified in mathematics by Euclidean geometry; (2) a set of relations linking certain concepts of the hypothetico-deductive system with certain data of sensory experience. With the aid of these relations, which may be called "rules of interpretation" or " epistemic correlations," an association is set up, for instance, between a black patch on a photographic plate (a sensory impression) and a spectral line of a certain wavelength (a conceptual element or construct of the hypothetico-deductive system), or between the click of an amplifier coupled to a Geiger counter and the passage of an electron. The necessity for physical science of possessing both parts as constituents results from its status as a theoretical system of propositions about empirical phenomena. A hypothetico-deductive system without rules of interpretation degenerates into a speculative calculus incapable of being tested or verified; a system of epistemic correlations without a theoretical superstructure of a deductive system remains a sterile record of observational facts, devoid of any predictive or explanatory power.

"The adoption of rules of interpretation introduces, to some extent, an arbitrariness in the construction of the system as a whole by allowing for certain predilections in the choice of concepts to be employed. In other words, arbitrary modifications in the formation of the conceptual counterparts to given sensory impressions can be compensated by appropriate changes in the epistemic correlations without necessarily destroying the correspondence with physical reality. In consequence of this arbitrariness, scientific concepts "are free creations of the human mind and are not, however it may seem, uniquely determined by the external world." (Einstein and Infeld, *The Evolution of Physics*, 1938)

"When science attempts to construct a logically consistent system of thought corresponding to the chaotic diversity of sense experience, the selection of concepts as fundamental is not unambiguously determined by their suitability to form a basis for the derivation of observable facts."

[40] J. Minstrell, "Explaining the 'at rest' condition," *The Physics Teacher* **20**, 10-14 (1982)

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[42] Based on Figure 2 in reference 12.

[43] In this as in most respects scientists and students have much in common in their thinking as they try to make sense of the world. Scientists in the past had ideas very much like those displayed by students today. We see this in a comment from Galileo: "Now I say that whenever I think of any material or corporeal substance, I immediately feel the need to think of it as … being in motion or at rest…" Quoted in M. Jammer, *Concepts of Mass in Classical and Modern Physics* (Dover Publications, Inc., Mineola, NY, 1997), p. 51 from *Discoveries and Opinions of Galileo* translated by S. Drake (Doubleday, New York, 1957), p. 274.

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[44] The author was first introduced to the idea of engaging students in trying to make sense of unlabeled graphs by a colleague, Wm. S. Smith, at Boise State University some time in the late 1980's.

[45] Physical Science Study Committee, *Physics* (D. C. Heath and Company, Boston, 1960). For a study on the history and role of PSSC Physics in science education see, J. L. Rudolph. *Scientists in the Classroom: The Cold War Reconstruction of American Science Education*. (Palgrave, New York, 2002).

[46] D. I. Dykstra, "Teaching Introductory Physics to College Students" Chapter 12 in *Constructivism: Theory, Perspectives and Practice*, C. T. Fosnot (ed) (Teachers College Press, New York, 1996)

[47] One example stands out as striking. One student after the end of the semester complained to the instructor about his grade in an e-mail exchange. When asked to explain, the student pointed out that he had taken Honors Physics in high school and that he should not have had to pay attention to the ideas of his fellow students (the discussion and editing of the consensus document and the final document). He apparently felt that his answers on the diagnostics and the exams were "more correct" than those of his peers. Sadly, in this case, this individual's diagnostic scores from beginning to end of the course were essentially unchanged. In raw score format (based on all 21 of the questions used from the FMCE) his old view score on force at the beginning of the semester was 13 out of 21 and his new view score on force at the beginning of the semester was 2. At the end of the semester his old view and new view scores were 15 and 3, respectively, each out of 21. The student was invited to take all of his course materials and consult with his high school Honors Physics teacher, after that he and his teacher were welcome to consult with the instructor in this study. No response since. This is not the first example of arrogance apparently learned in high school physics.

[48] Another less extreme example, but possibly more common is the following: "For the last six years, my brain has been mathematically programmed with sequences, theories, postulates, equations and other various tools to assist in the problem-solving area of learning. These tools are all very basic and to-the-point. They require memorization and an understanding of how each can apply to specific problems. I've dealt with story problems, mathematical sequences, graphs, maximums, minimums, limits, derivatives, anti-derivatives, and so many calculus problems that the entire left side of my brain is "pumped-up." Therefore, signing up for an Intro to Physics class seemed somewhat of a joke and would be considered as mentally challenging as Under Water Basket Weaving 101. I assumed that I would already know most of the material and the format to which we would attack these mathematical problems, but that when we got to forces and other related subjects, I may be challenged enough to keep me interested. … Within the first five minutes of class, I found that it would be much different. We would not be using any math. I asked myself, "How can we NOT use math for one of the most mathematically based subjects in the world?! Why NO math?! I know math!" With this confusion, I quickly felt betrayed by the class being titled Physics. Along with that betrayal also came a sense of arrogance, assuming the class would be full of people who had the mathematical experience that I pride myself on. "This class was going to be a joke…." That was the overall view that I had of the class, and continued to have about the class until we really started doing things in lab. … When describing the relations between graphs I would use "derivative," "maximum," "minimum," and "slope" and found that nobody understood what I was saying… I didn't have the simple vocabulary to explain my

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understanding. Because of this, I started to really question my overall understanding of the subject in the first place. … Until now I had always been surrounded by peers that were on the "same page" as me and it always seemed very simple to converse about these topics as if it was just plain logic to the "average Joe." …I came into this class somewhat arrogant, expecting it to be a "walk in the park." I now realize that it may still be "a walk in the park" because that is what it supposed to be: simple for anyone to understand. But, this "walk" is much different than any walk I have had before." — excerpt from an essay written by a student for the modified PIPS instruction course between the motion unit and force units, Spring, 2001.

[49] D. I. Dykstra, Jr & D. R. Sweet "Conceptual Development About Motion and Force in Elementary/Middle School Students", in preparation, 2002.

[50] J. Minstrell, private communication, January, 1981.

[51] D.I Dykstra, Jr. "PHYS 100: Foundations of Physical Science: Course Philosophy and It's Implications"; online at http://www.boisestate.edu/physics/dykstra/psphil.html.

[52] Technical detail: in the lab experiences ultrasonic motion detectors, force probes, interfaces and software from Vernier (http://www.vernier.com/) were used with Macintosh computers. Carts on ramps and in modified Atwood's machine configuration were used instead of the fan cart option. There is evidence to believe that transducers, interfaces, and software from other vendors, and on other computers, can yield the same results described in the present study. The same is believed to be true of the fan cart option.

[53] R. K. Thornton & D. R. Sokoloff, "Assessing student learning of Newton's laws: The Force and Motion Conceptual Evaluation and the Evaluation of Active Learning Laboratory and Lecture Curricula," *Am. J. Phys.* **66**(4) 338 – 352 (1998).

[54] R. K. Thornton, "Conceptual Dynamics: Following changing Student Views of Force and Motion," In *The Changing role of Physics Departments in Modern Universities: Proceedings of ICUPE*, E. F. Redish & J. S. Rigden (eds) (American Institute of Physics, College Park, MD, 1997) Abstract online at http://ase.tufts.edu/csmt/html/abstracts/icupe_cd.html.

[55] A subset of 17 questions out of the first 21 from the FMCE were used to calculate a score that could range from 0 to 15 for any given student performance. Questions 1, 2, 3, 4, 5, 7, 14, 16, 17, 18, 19, were matched one for one against the new view or old view key to generate 11 out of the possible 15 points. These particular questions were chosen because they were determined to be the clearest indicators of the students' notions and are the core used by Thornton in his conceptual dynamics analysis[51] of thousands of student responses to the FMCE. In his paper Thornton suggests that if questions 8 – 13 are to be used then they should be considered as coherent sets (8 – 10) and (11 – 13) and given credit only if all three student choices are consistent but not at the rate of one point per question. In the present work 2 points were given for either set of 3 if all three choices for the set were consistent with the view being scored.

[56] D. Hestenes, M. Wells, & G. Swackhammer, "Force concept inventory," *Phys. Teach.* **30**(3), 141 – 158 (1992). Updated version: Halloun, I., R.R. Hake, E.P Mosca, D. Hestenes. Force Concept Inventory (Revised, 1995; password protected at http://modeling.la.asu.edu/R&E/Research.html

[57] R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," *Am. J. Phys.* **66**(1) 64 – 74 (1998). Available on-line at http://www.physics.indiana.edu/~sdi/

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[58] C. I. Hovland, A. A. Lumsdaine, and F. D. Sheffield, “A baseline for measurement of percentage change,” in *Experiments on Mass Communication,* C. I. Hovland, A. A. Lumsdaine, and F. D. Sheffield (eds) (John Wiley and Sons, NY, first published in 1949). Reprinted as pages 77 – 82 in *The Language of Social Research: a reader in the methodology of social research,* P. F. Lazarsfeld & M. Rosenberg (eds) (Free Press, New York, 1955).

[59] K. Cummings, J. Marx, R. Thornton, and D. Kuhl “Evaluating innovation in studio physics,” *Phys. Educ. Res. Suppl., Am. J. Phys.* **67**(7), S38 – S44 (1999). A more specific analysis is forthcoming in a paper as yet in draft titled: “Comparing the Force and Motion Conceptual Evaluation and the Force Concept Inventory” by the same four authors. Draft shared as private communication from Ronald Thornton, October 2001.

[60] J. Cohen, *Statistical power analysis for the behavioral sciences* (2nd ed.). (Lawrence Earlbaum Associates, Hillsdale, NJ, 1988).

[61] B. S. Bloom, “The 2 Sigma Problem: The Search for Methods of Group Instruction as Effective as One-to-One Tutoring,” *Educational Researcher* **13**(4), 4 – 16 (1984): “Using the standard deviation (sigma) of the control (conventional) class, it was typically found that the average student under tutoring was about two standard deviations above the average of the control class. . . The tutoring process demonstrates that MOST of the students do have the potential to reach this high level of learning. I believe an important task of research and instruction is to seek ways of accomplishing this under more practical and realistic conditions than the one-to-one tutoring, which is too costly for most societies to bear on a large scale. This is the ‘2 sigma’ problem.”

[62] R.R. Hake, "Interactive-engagement methods in introductory mechanics courses, submitted to *Physics Ed. Res. Supplement* to *Am. J. Phys.*; online at <http://www.physics.indiana.edu/~sdi/>. This unpublished companion paper to Hake (ref 39) contains average pretest and posttest scores, standard deviations, instructional methods, materials used, institutions, and instructors for each of the survey courses in Hake (ref 39) are tabulated and referenced. In addition, the paper also gives case histories for the seven Interactive Engagement (IE) courses whose effectiveness, as gauged by pre- to posttest gains, was close to those of traditional courses, advice for implementing IE methods, and suggestions for further research.