EFFECTIVE LEARNING ENVIRONMENTS FOR COMPUTER SUPPORTED INSTRUCTION IN THE PHYSICS CLASSROOM AND LABORATORY

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This chapter was originally conceived as a general presentation of the uses of computer-based technology in physics education and, as should be obvious, the topic is much too big to be covered in a single chapter. We are imposing the requirement that, in order to be discussed here, the curricular methods and computer-based technological learning tools we review must have been shown to produce substantial gains in student conceptual understanding compared to traditional instruction when examined using the methodology of physics education research (PER). This requirement will limit the scope of our considerations but will direct our attention to valuable educational reforms. Why focus on conceptual learning (or qualitative understanding) in physics? A large body of research shows that physics students, even in classes for majors, have considerable difficulty with the fundamental understanding of physics that is characterized by conceptual thinking.

Initial applications of computers in science education focused on using technology to support the more rote and mechanical aspects of learning. Even now the vast majority of software designed for science education supports facts-and-formula science. There is a role for this sort of simulation, tutorial, or drill-and-practice exercise, and when well designed, such software will improve student learning of facts and formulas. However, such learning is not the focus of this chapter where we will examine those uses that enable active student construction of knowledge, not drill to aid memorization. The primary use of computer technology that we examine here is technology as a tool that the learner manipulates to learn about the physical world.

For specific curricula that are supported by computer tools and meet the above criteria, we will look at the evidence for learning, the characteristics of the computer-based tools, the curricula, and the learning environment in classrooms and teaching laboratories. This will be an effort to highlight important considerations for successful learning for students of diverse academic interests and preparation.

Since successful computer-supported learning environments follow the practices of good pedagogy, it should not be a surprise that most successful environments involve interactive engagement, peer interactions, or both. Although this is not a discussion for this chapter, we should also keep in mind that not all curricula that result in substantial conceptual learning make use of computer technology.

Because of the restrictions outlined above we will not consider computer-based technology that is largely used for communication, record keeping or in a recording function. Consequently, we will not examine the sometimes very important functions that computer software can play in such aspects of classroom management and teaching as assessment, presentation, student feedback, and student access to information over the internet about the course and for the course.

WHAT IS MEANT BY THE TERM A "RESEARCH-BASED" CURRICULUM?

A research-based curriculum uses the methods of physics education research to select and order the content. Student learning is evaluated using multiple methods and the curriculum is altered to improve learning. The curriculum pays attention to what students know at the time of instruction and starts instruction with what students know. There is most often a focus on conceptual understanding but not to the detriment of algorithmic or quantitative learning.

What is meant by an "activity-based" or "interactive engagement" curriculum?

The methods used and the learning environment actively engage students in learning the concepts on which the curriculum focuses. This always means that students are intended to be mentally involved, but often in activity-based physics courses they are also physically involved. Strong peer interaction is generally encouraged. Because we are discussing physics, it means that students are learning about the physical world often by direct interaction (experiment).

What is the evidence for improved conceptual learning in interactive engagement environments?

There is substantial evidence that environments that encourage interactive engagement or activity-based learning result in improved conceptual learning. Hake (1997) conducted a large-scale survey of introductory physics courses using pre and post instruction results from the Force Concept Inventory (FCI) (Hestenes, D. et al., 1992). He asked respondents to indicate whether the courses taught had made substantial use of interactive engagement methods, which he defined to be as "designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors." The results showed a significantly higher normalized gain on the FCI for courses that were described as using significant interactive engagement. Normalized gain measures the fractional or percentage increase of student understanding for those students who don't know a concept or concepts. (1) He reported normalized gain on the FCI of .23 (g= 0.23+/-0.04) for 2084 students in traditional courses that used little or no interactive engagement while 4458 students in courses that reported substantial use of interactive engagement had a normalized gain more than twice as large (g=0.48+/-0.14).

In a paper (Thornton *et al.*, 2007), comparing the *Force and Motion Conceptual Evaluation (FMCE)* (Thornton and Sokoloff, 1998) with the FCI, the average normalized gains on the FMCE for 926 students taking traditional courses was 15% (±3%) while 2621 students in research-based courses that made use of interactive engagement was 62%(±3%). The actual methods used in these courses were reviewed by the authors. Note that the difference between the gain for interactive engagement courses and traditional courses was even larger than that reported by Hake. Clearly the evidence for increased gains in conceptual understanding from interactive engagement, however it is defined, is substantial.

GUIDANCE FROM PHYSICS EDUCATION RESEARCH

Before we consider specific computer-supported curricula, let's look at advice from the physics education community on the construction of effective curricula. There is more widespread agreement on the ineffectiveness of traditional instruction than there is on the solutions to the problems of traditional instruction. For some time, substantial agreements among researchers in physics education on the ways that traditional instruction is not working have been masked by real and apparent disagreement over particular ways of defining physics learning and over disagreements about the appropriate pedagogical response. Such disagreement has too often meant that much work in research and pedagogy has gone on as a series of separate efforts, so that projects with the potential to have widespread impact on physics teaching and learning remain isolated. For some time, it's been understood that what is needed to change the state of physics education is agreement on a set of underlying principles about the teaching and learning of physics that will support the integration of the work of many different groups into a coherent educational response based on careful research and with the potential to influence the larger physics and science community. Work towards defining such principles can also offer some ideas about what in computer-supported instruction can contribute to students' conceptual learning.

At a meeting entitled "The New Mechanics" at Tufts University in 1992, a consensus began to emerge concerning the inadequacies of traditional instruction (Thornton, 1999). The physicists who attended the meeting and form the New Mechanics Advisory Group are all researchers in physics education and wished to establish general agreement on those methods of teaching physics that have been shown through research to enhance student learning. They came to agreement on some generalizations about student learning in physics that were originally drafted by Lillian McDermott. Each generalization is supported by research from different sources using different techniques. A list of these points of agreement about student learning in physics follows.

- Facility in solving standard quantitative problems is not an adequate criterion for functional understanding.
- A coherent conceptual framework is not typically an outcome of traditional instruction. Rote use of formulas is common.
- Certain conceptual difficulties are not overcome by traditional instruction.
- Growth in reasoning ability does not usually result from traditional instruction.
- Connections among concepts, formal representations (algebraic, diagrammatic, graphical), and the real world are often lacking after traditional instruction.
- Teaching by telling is an ineffective mode of instruction for most students.

Each of these generalizations about student learning has strong implications for the changing of physics teaching. It will be difficult for scientists who look at the evidence and who accept these results to find justifications for continuing to teach in a traditional manner. But what is a teacher to do? Even physics education researchers have disagreements about the "best" way to proceed. While most believe that students must be intellectually engaged and actively involved in their learning and that traditional instruction is failing to provide a context in which a majority of students can learn, there is more debate about which methods of teaching and what learning contexts will help students learn most effectively. Can educational technology improve physics learning? Under what conditions does collaborative learning work well? What role should experimentation play in student learning?

While the New Mechanics Meeting did articulate agreements about current student learning, the time was too short to agree upon generalizations for suggested methods of physics teaching and because of limited resources, participants were only from the United States. To see how to start changing our teaching, it is useful to look at agreements about productive methods of physics teaching reached at an earlier, international meeting of physicists and physics education researchers on a more specific topic. A NATO Advanced Study Workshop entitled *STUDENT DEVELOPMENT OF PHYSICS CONCEPTS: THE ROLE OF EDUCATIONAL TECHNOLOGY* was organized by Robert Tinker and the author and held at the University of Pavia in Italy in1989. The participants included researchers from nine different countries. The NATO workshop was concerned with student conceptual learning and the pedagogical uses of interactive educational technologies in physics teaching and learning. One major focus was on the uses of technologies that allowed students to construct physics concepts successfully from their own experiences of the physical world. After examining the evidence, participants were in substantial agreement that students of all ages learn science better by actively participating in the investigation and the interpretation of physical phenomena; that listening to someone talk about scientific facts and results was not an effective means of developing concepts; and that well-designed pedagogical tools (generally computer-based) that allow students to gather, analyze, visualize, model and communicate data can aid students who are actively working to understand physics. In particular, there was evidence from a number of countries (Italy, Germany, UK, USA, USSR) that real-time Microcomputer-Based Laboratory tools in appropriate learning environments resulted in successful student learning of physics concepts. It was also agreed that to best develop their understanding, students need the freedom and ability to pursue interesting scientific investigations; the opportunity to interact with their fellow students; and the means to communicate their findings. (Unfortunately, most introductory courses have none of these features.)

The international NATO Workshop resulted in substantial agreement on ways physics teaching can be changed to improve student learning. These conclusions have subsequently stood the test of time and research. The New Mechanics meeting at Tufts, in addition to building agreement about student physics learning, began the work of refining curricular and instructional strategies that will help introductory physics students acquire a conceptual understanding in one specific area of the curriculum--Newton's Laws of Mechanics. The results of this meeting, including a revision of the dynamics sequence described by Arnold Arons in Chapter 2 of his book *A Guide to Introductory Physics Teaching*, have been incorporated into a number of curricular projects (Laws, 1997). We will examine these computer-supported curricula in sections following.

PEER INSTRUCTION

A widely used pedagogical method in the lecture classroom has been named *Peer Instruction* (Mazur, 1997). It makes use of peer interaction and can result in substantial conceptual gains (Crouch & Mazur, 2001). In this method, a multiple choice conceptual question is displayed with an overhead or computer projector and students are polled for their choice using flash cards or in some cases a radio frequency "clicker system" that records the results of the polling of students on the instructor's computer. After individual voting the students are asked to discuss their ideas with their neighbors and vote again. The correct answer is then supplied by the instructor. Because a computer is not necessary to this process (although it is convenient) and because the computer only functions as a display and recording device, this method does not meet our criteria for computer-assisted curricula.

Peer Instruction uses a number of the same steps employed by *Interactive Lecture Demonstrations* (*ILDs*). *ILDs* result in large conceptual gains when used in the physics classroom and the computer is most often an essential part of the process. We discuss *ILD*s below.

REAL-TIME DATA LOGGING AND DISPLAY

Real-time data logging tools (sometimes called Microcomputer-Based Laboratory or MBL tools in the United States) are now one of the most commonly used computer tools in physics teaching laboratory and classroom. In 1999, Euler and Müller reported at the ESERA-conference in Kiel that MBL is the only method of using computers in physics curricula that has a proven positive learning effect. Tools of the style we use now were first developed almost twenty years ago at the Technical Education Research Centers (TERC) as part of the Microcomputer-Based Laboratories for Middle Schools project using Apple II computers and at the Center for Science and Mathematics Teaching at Tufts University as part of Tools for Scientific Thinking Project. This project created data logging tools that were also suitable for high school and university students and made them available on Macs and PC's.

There are three large venders of real-time data logging tools. (2) Our purpose in this chapter is not to examine in detail the various features of these hardware and software packages but to identify the affordances of the tools that allow students to learn concepts when used in an appropriate research-based curriculum.

A single specific example might make our considerations more concrete. One particular dynamics experiment is done by students in a number of the laboratory curricula described below and is used also in an *Interactive Lecture Demonstration* sequence done in a lecture hall. Figure 1 shows the velocity, acceleration and force over time for the motion of a low friction cart. These quantities are displayed in *LoggerPro* in real time by using a force probe and motion detector to take measurements. A force probe mounted on the low-friction cart measures the force applied to the cart by a weight attached to a string hung over a pulley (a modified Atwood's machine). The cart is given a quick push opposite to the force exerted by the hanging weight, and it moves toward the motion detector, slows down and returns. The shaded portions of the graphs show the time interval when the cart was moving under the influence of a constant force after the push and before the catch.

What advantages can well-designed real-time data logging tools bring to appropriately structured, research-based curricula?

Real-time data logging tools can allow students to find answers directly from the physical world. Rather than appealing to the teacher or professor for the "correct answer" students can collect physical data and display it in a manner that can be remembered, manipulated, and thought about.

Real-time data logging tools can make the "abstract" concrete through immediate feedback. They allow the immediate linking of a concrete measurement of an actual physical system with the simultaneous production of the symbolic representation. This linking may make the "abstract" concrete. There is also good evidence that the real-time display is important. A delay of even 20 to 30 seconds greatly affects learning results in kinematics (Brassel, 1986). If students are to move on to formal scientific reasoning, they must be able to manipulate scientific symbol systems. One of the most important symbol systems is graphing, where the quantity that is graphed is changing over time. (In fact, a graph displaying a quantity over time is a narrative, a common means to share knowledge.) Graphs allow large amounts of data to be organized in a manner that can be remembered, manipulated, and thought about. Graphing is a key symbol system for scientific learning because it allows one to follow changes in physical phenomena as a function of time and to see the result of various interventions (Mokros and Tinker, 1987). McKenzie and Padilla (1984) state that graphs are an important tool in enabling students to predict relationships among variables and an important means to substantiate the relationships. They suggest there is a link between students' cognitive skills, particularly the ability to understand relationships, and their graphing skills. Howard Gardner asserts that understanding the use and interpretation of symbol systems such as graphs is a central developmental task, and "mastering of symbolic systems...might even be regarded as the principle mission of modern educational systems" (Gardner, 1983).

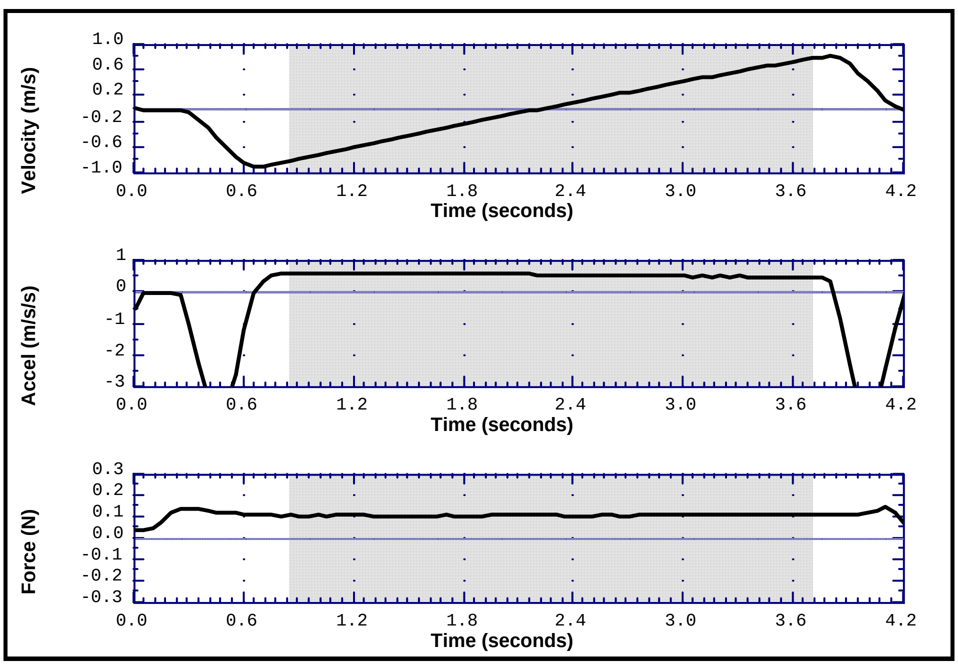

FIGURE 1. Low friction cart moving in front of a motion detector under the influence of a force. These are actual data from an *ILD* given at Tufts. Detailed description of the experimental setup t is described in the text.

Real-time data logging tools in the right curricular context may improve certain types of spatial ability. There has been some evidence that certain types of spatial ability are linked to success in learning physics. There is now evidence that using real-time data logging tools in research-based curricula can improve students' spatial ability. We will examine this evidence below in the context of specific curricula.

Real-time data logging tools can encourage learning from peers. The immediate presentation of data in a form that can be thought about and understood leads to discussions among lab groups or nearest neighbors in *Interactive Lecture Demonstrations* that result in learning. Peer interaction can be a very important learning mode in curricula based on real-time data logging tools.

Real-time data logging tools can encourage critical thinking skills by reducing the drudgery of data collection and manipulation. Although the student is still in control of data taking, many of the tedious aspects of measuring, storing, and displaying data are eliminated and the student is able to pay attention to understanding the science behind the data. Not only do students more often have the time and inclination to ask their own "what if" questions, but also, because the results of measurements are immediately available to the student, experimental techniques can be quickly modified to get data that clarify the concepts under investigation. Since data can be stored, manipulated, and analyzed, they can be easily used for hypothesis development and model building. That is, the availability of the data in forms that can be thought about and of modeling tools promotes student hypothesis development and the ease of collecting more data encourages hypothesis verification.

Real-time data logging tools are usable by the novice as well as the more advanced student. The tools dictate neither what is to be investigated nor the steps of an investigation. Carefully developed software make these laboratory tools easy to use even for the first time. Configuration files allow students to easily begin taking data with specific probes, graphs, and data collection speeds without prohibiting the ability to make changes. Most students feel in control of their own learning. Because these tools are general they can be used with many different curricula for a wide range of students from elementary school to the university. (see Thornton, 1987 for an earlier discussion of these points)

EXAMPLES OF COMPUTER-SUPPORTED CURRICULA, USING DATA-LOGGING, WITH LARGE LEARNING GAINS

In this section we will examine three related introductory physics curricula all of which incorporate the results of physics education research in their design and all of which show large student conceptual gains in different learning contexts and with different student populations. We will not look at these curricula in detail, but will examine the way that computers have been used and consider the general design principles of the learning environments.

Tools for Scientific Thinking (TST) (Thornton, 1989b) was the original curriculum of conceptual lab activities supported by real-time data logging tools. The tools were also used in Workshop Physics and *TST* was a basis with Workshop Physics for *RealTime Physics*.

Since *RealTime Physics (RTP)* (Sokoloff, Thornton, & Laws, 2004, 1998) is a more comprehensive conceptual laboratory curriculum, we will look at *RTP*, not *TST*, as an example of a conceptual laboratory curriculum in this chapter. *RTP* uses real-time data logging tools including features for modeling, promotes conceptual and quantitative learning through observations of the physical world, is research-based, and uses a student activity guide. Students work together often in groups of three.

Workshop Physics (Laws 2004, 1991) is calculus-based without formal lectures that meets in a collaborative, activity-based classroom for three 2-hour classes each week. It uses computer tools for data collection and modeling, is research-based, and uses a student activity guide. Students work together often in groups of two to four.

Interactive Lecture Demonstrations (ILDS) are used in the physics lecture classroom where the teacher performs actual experiments in front of the class. The students learn conceptually and quantitatively by interactive engagement through physical observations

1. The instructor describes the demonstration and does it for the class without measurements displayed.
2. The students are asked to record their individual predictions on a Prediction Sheet, which will be collected at the end of the session, and which can be identified by each student's name written at the top. (The students are assured that these predictions will not be graded, although some course credit is usually awarded for attendance and participation at these *ILD* sessions.)
3. The students engage in small group discussions with their one or two nearest neighbors.
4. The instructor elicits common student predictions from the whole class.
5. The students record their final predictions on the Prediction Sheet.
6. The instructor carries out the demonstration with measurements (usually graphs collected with real-time data logging tools) displayed on a suitable display (multiple monitors, LCD, or computer projector).
7. A few students describe the results and discuss them in the context of the demonstration. Students may fill out a Results Sheet, identical to the Prediction Sheet, which they may take with them for further study.
8. Students (or the instructor) discuss analogous physical situation(s) with different "surface" features. (That is, different physical situation(s) based on the same concept(s).)

Table 1: The Eight Step Interactive Lecture Demonstration Procedure

and peer collaboration. Students make individual predictions, discuss them with their neighbors, and predict again. Most often, real-time data logging tools are used for data collection, analysis & modeling. The “correct” answer is determined by experiment. *ILDs* are sequences of carefully chosen short demonstrations intended to help students learn fundamental concepts. Each short demonstration follows the eight-step protocol shown in Table 1.

Table 2: Passive vs. Active Learning Environments

Passive Learning Environment	Active Learning Environment
Instructor and textbook are the authorities--sources of all knowledge.	Students construct their knowledge from experimental observations. Observations of the physical world are the authority.
Students' beliefs are rarely overtly challenged.	Uses a learning cycle in which students are challenged to compare predictions (based on their beliefs) to observations of real experiments.
Students may never even recognize differences between their beliefs and what they are told in class.	Changes students' beliefs when students see differences between their observations and their beliefs.
Instructor's role is as an authority.	Instructor's role is as guide in the learning process.
Collaboration with peers often discouraged.	Collaboration and shared learning with peers is encouraged.
Lectures most often present the “facts” of physics with little reference to experiment.	Results from real experiments are observed in understandable ways--often in real-time with the support of data logging tools.
Laboratory work, if any, is used to confirm theories "learned" in lecture.	Laboratory work is primarily used to learn basic concepts.

All of the curricula discussed here are part of *The Physics Suite* available from Wiley. (3)

At first glance it would seem these curricula would not have much in common since RTP is laboratory curriculum designed to replace traditional cookbook laboratories, Workshop Physics restructures the whole course, and *ILDs* replace traditional lectures. However, from a pedagogical view, they are all very similar in spite of their use in very different contexts. All employ real-time data logging tools in an activity-based environment, all examine the physical world for answers, all use peer interaction, all are research-based, and all result in substantial conceptual learning gains.

Table 3: Design principles for the *RTP* laboratory guides.

***RealTime Physics* Design Principles**

Each laboratory guide includes activities that:

- are sequenced to provide students with a coherent observational basis for understanding a single topic area in one semester or quarter of laboratory sessions;
- provide activities that invite students to construct physical models based on observations and experiments;
- help students modify their common conceptions about physical phenomena that make it difficult for them to understand powerful general principles of physics;
- work well when performed in collaborative groups of 2 or 4 students;
- incorporate MBL tools so that students can test predictions by collecting and graphing data in real time;
- incorporate a learning cycle consisting of prediction, observation, comparison, analysis, and quantitative experimentation;
- provide opportunities for class discussion of student ideas and findings; and
- integrate homework assignments designed to reinforce critical concepts and skills.

We discussed in general what was meant by an active learning environment as opposed to a passive or more traditional learning environment in a previous section. Table 2 (adapted from Thornton & Sokoloff 2006) elaborates these differences. The *RealTime Physics* design principles provide some more detail about the pedagogical structure of the curriculum (adapted from Sokoloff, Laws, and Thornton, 2007). In most cases these design principles apply equally well to *Workshop Physics* and *ILDs*.

We will examine some of the learning gains using the learning of mechanics concepts as the example. We are again using the *FMCE* which has been shown to accurately measure student understandings of force and motion when compared to interviews or written answer questions (Thornton & Sokoloff, 1998). We have seen average normalized gains from traditional instruction in previous sections. The point of these specific examples is that the computer-supported, activity-based pedagogy works for different student audiences and settings even when implemented for the first time. The gains shown for traditional instruction in black in Figure 2 are consistent with those results. One surprise might be the gains for Renssalear Polytechnic Institute's (RPI) Studio Physics. The course structure was modeled on Workshop Physics but adapted for larger classes. The classes were activity-based, the students worked at computers in the Studio Physics Classroom, but the curriculum was not research-based so the results were close to traditional instruction (only about 20%). When Karen Cummings introduced research curricula such as *ILDs* in 1999, the normalized gain on the *FMCE* became approximately 60%. (Cummings et al., 1999)

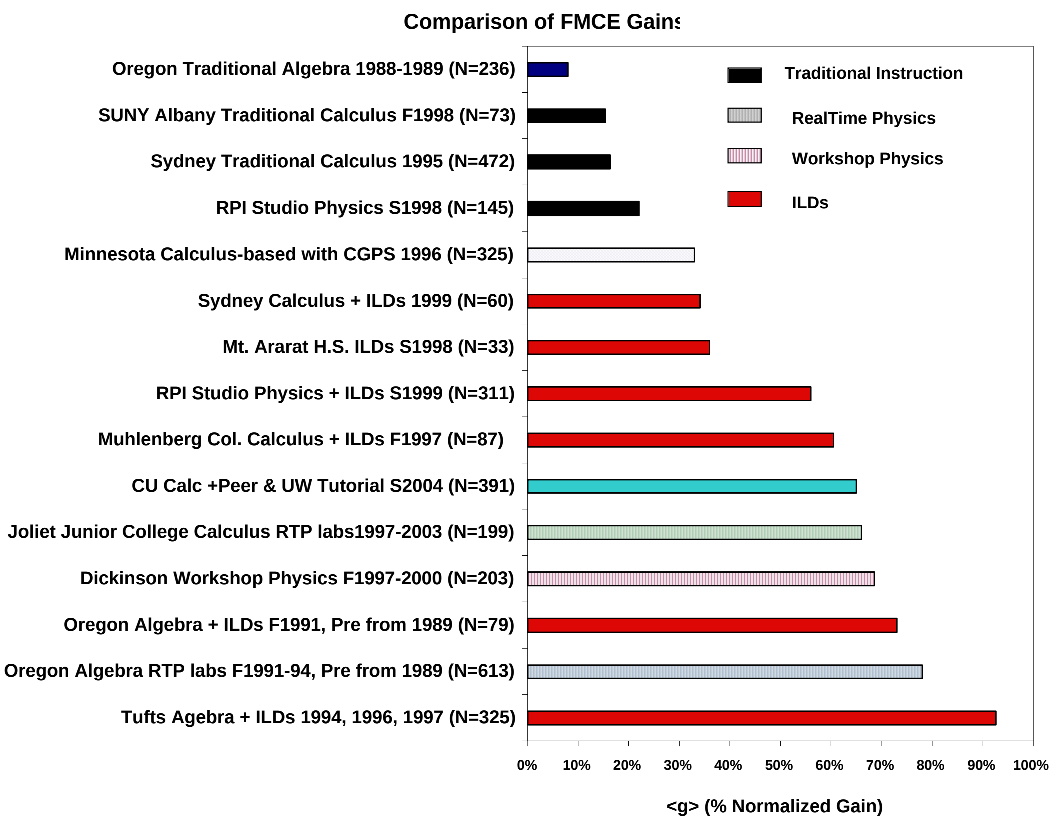

Figure 2. Normalized gains of the FMCE for specific implementations of computer-supported courses compared to normalized gains for traditional instruction.

Workshop Physics at Dickinson has an approximately 70% normalized gain over a number of years. Saul and Redish (1998) found in an evaluation of a dissemination project for Workshop Physics that the secondary adopters averaged 65% normalized gain. *RealTime Physics* implemented in the University of Oregon algebra-based physics class averaged normalized gains of 78%. When used in a community college (Joliet Junior College) in a calculus-based course the gain over five years was approximately 70%. *RTP* at Tufts in the calculus-based course averaged approximately 83% over three years.

ILDs at Tufts University averaged 94% normalized gain in the algebra-based course over three years with multiple instructors and 76% at the University of Oregon. The first implementation at Muhlenberg College (a private college in Pennsylvania) resulted in gains of 65% that have improved with future implementations. The first implementation by a high school teacher at Mt Ararat H. S. in Maine resulted in a normalized gain of 40%, at least 3 to 4 times the gain in traditional instruction.

These previous, rather remarkable gains for the *RTP*, *ILD*, and *Workshop Physics* curricula are for those curricula used in English with no major modifications -- although not all instruction was with students in the United States. It is not only with English speaking students that these materials and pedagogy are effective. Bernhard adapted the *RealTime Physics* approach to the Swedish educational setting with instructional materials written in Swedish (Bernhard, 2003). His results for both engineers and pre-service teachers taking a course in mechanics show large conceptual gains (normalized gains on the *FMCE* of over 50% and the FCI of approximately 45%). In fact, using the method developed in Conceptual Dynamics (Thornton, 1997 &1995) the pre-service teachers show a higher fraction of "physicist views" (i.e. Newtonian view) in all areas compared to the engineers in the modified class. This is to be compared to a normalized gain from traditional instruction for the engineers of approximately 16%. It is encouraging that these changes of language and very different populations in different educational systems do not destroy the learning.

EVIDENCE FOR RETENTION OF CONCEPTUAL LEARNING

It is clear from the above results that activity-based computer-supported curricula result in substantial conceptual learning gains in many different contexts. There is also evidence that students retain this learning. (Thornton and Sokoloff, 1998) Student retention of the Newtonian conceptual view seems to be very good for students who have completed the *Tools for Scientific Thinking* or *RealTime Physics Mechanics* labs. Whenever questions from the *FMCE* were asked again up to six weeks after instruction in dynamics had ended, the percentage of students answering in a Newtonian way increased rather then decreased, as is often the case when conceptual knowledge is considered. We attribute this increase to assimilation of the concepts. For example, Oregon *RTP* students were asked a scrambled version of some dynamics questions from the *FMCE* on the final exam approximately 5 weeks after all instruction in dynamics had ended. There was an average increase of 6% on these questions that more than 80% of students had already answered correctly. The research data from both Oregon and Tufts also show that the *ILD*-enhanced learning is persistent. For six (Oregon) and seven (Tufts) weeks after dynamics instruction, students also show an approximately 6% increase in their already substantial understanding.

Even though the fact that students' performance on conceptual questions is still improving many weeks later argues for a substantial change in the students' conceptual framework in dynamics, conceptual understanding measured years later would be even more convincing. Fortunately Jonte Bernhard has done such a study (Bernhard, 2001). As discussed in the last section Bernhard adapted the *RealTime Physics* approach to the Swedish educational setting with instructional materials written in Swedish. Using these materials he found that pre-service teachers and engineers in beginning physics class had similar large conceptual gains compared to standard instruction. Five semesters or 2.5 years later, with no additional instruction in mechanics, Bernard found that the pre-service teachers show a good conceptual understanding of mechanics similar to results achieved by them soon after instruction and by engineers in the reformed physics class soon after instruction. The results would seem to indicate a permanent change in their conceptual framework.

The importance of curricular context and learning when real-time data logging is used

From the number and variety of instances where using real-time data logging led to increased student understanding, an educator might be tempted to think that just adding real-time data logging to a traditional setting with no substantial curricular changes will result in dramatic learning increases. In fact, the use of real-time data logging in the traditional laboratory, which is largely concerned with equation verification, can improve the laboratory in the sense that students can make more accurate measurements, more quickly recognize experimental procedural errors, take data more quickly, use the analysis tools to evaluate the data, and make use of other affordances outlined in a previous section. However, such laboratories rarely result in increased conceptual understanding. In fact, even though students sometimes work together in these laboratories, there is much less of the valuable peer interaction that leads to increased conceptual understanding since the students are not focused on this task and are more concerned, in discussion, with getting it "right" since that is how the laboratories are focused.

Bernhard did a careful study comparing real-time data logging conceptual labs with real-time data logging formula verification labs using multiple instructors and two different groups of students. (Bernhard, 2003) The study determined there were no significant teacher effects but variations in student learning, discussed below, were a result of the pedagogical method used. The two different student groups were engineering students and future teachers of Swedish grades 4-9.

As discussed in the last section Bernhard adapted the *RealTime Physics* approach to the Swedish educational setting with instructional materials written in Swedish and translated the *FMCE* and the *FCI* into Swedish so he could evaluate learning. It is these labs that were called "conceptual labs." The design principles by Bernard listed below are entirely consistent with those for *RealTime Physics* listed above.

> " – … MBL was used as conceptual labs and among other things the labs emphasized concepts and connections between different concepts and the active engagement of students.

– Co-operation among students was encouraged.

– Students' preconceptions were addressed by using a POE-cycle (Predict – Observe – Explain). In implementing this cycle the rapid display of the results by the computer in graphical form is thought of being of crucial value.

– Each lab-group of 2-3 students was asked to submit a written report from each lab. This reinforces and strengthens student understanding, since they have to describe the lab in their own words.

– The instructions for the labs in both Case I and II were written in Swedish by the author.

– MBL was used both as a technological tool (measurement, processing and display of experimental data) and as a cognitive tool (sense making)" (p.315).

The only major difference was the requirement that the Swedish students submit a group written report from the lab. *RTP* students taking the English version were not required to submit a group written report for each lab but were required to do conceptual homework after the lab. This homework also reinforced what they have learned.

The engineers and future teachers who took these conceptual labs showed substantial conceptual gains (the gains in both groups were similar) on the *FMCE*, many times better than those measured by earlier testing in the traditional mechanics course.

A professor who valued traditional labs created a second set of laboratories that were principally traditional equation-verification labs using real-time data logging equipment that covered the same kinematics and dynamics content as the conceptual labs. Students who took these labs had less than half the normalized gain of those taking the conceptual labs.

The results were more striking for labs concerned with Newton's Third Law. Future teachers taking the conceptual lab showed a normalized gain on questions concerned with contact forces and with collisions of 80%. Students taking the equation-verification labs which used exactly the same MBL hardware and software had a slightly negative gain on questions about third law contact forces and a gain of only 23% on those concerned with collisions. Further analysis by the author shows "that the equation verification approach has been especially disadvantageous for female and poorly prepared students" (p. 317). This study clearly establishes that the curriculum in which the tools are embedded makes a difference.

Sassi (2001) found a similar dependence on the curricular context for the success of real-time data logging.

VISUAL EXPERIMENTS: THE PEDAGOGICAL METHODS WILL WORK WITHOUT REAL-TIME DATA LOGGING.

The learning environment described for *RTP*, *Workshop Physics*, and *ILDs* can in some cases result in effective learning even without the use of real-time data logging. As an example, consider the optics *ILD* Image Formation with Lenses where direct observation of the effect of lenses is appropriate. (Similar exercises are used in *RTP* optics.) Figure 3 below is taken from Sokoloff and Thornton 2007.

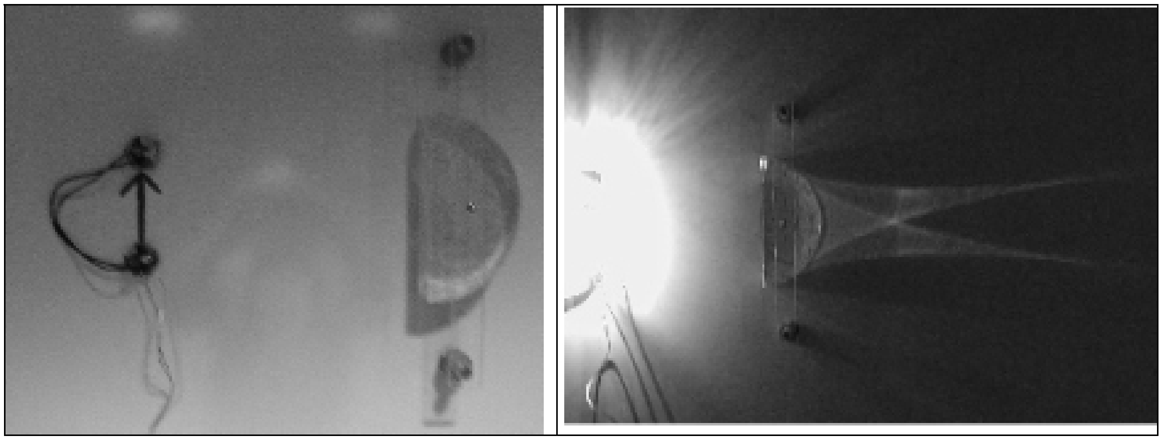

Fig. 3 Apparatus for the Image Formation with Lenses ILD sequence, including a large acrylic, cylindrical lens and two flashlight bulbs. The right figure shows how the images of the two bulbs are formed when the bulbs are illuminated.

After viewing the image formation in demonstration (1), students examine what happens when (2) the top half of the lens is blocked by a card, (3) the top half of the object is blocked by a card, (4) the lens is removed, (5) the object is moved further away from the lens, (6) the object is moved closer to the lens, and (7) the object is moved closer to the lens than the focal point. Because students can see all of the light (an infinite number of rays) from each bulb incident on the lens, they can better understand the function of the lens in producing the image, and observe that blocking half the lens has a very different effect (producing a whole but dimmer image) than blocking half the object.

Students in the algebra-trigonometry-based general physics course at the University of Oregon had only a 20% normalized learning gain on our *Light and Optics Conceptual Evaluation* after all traditional instruction on image formation. With just one additional lecture consisting of the *ILD* sequence described above, their normalized learning gain was 80%.

VISUALIZATION AND INTERACTIVE TUTORIALS: THE PEDAGOGICAL METHODS WILL WORK WITHOUT REAL-TIME DATA LOGGING.

The *ILD* protocol will work with other computer technologies than real-time data logging. Strictly speaking the previous example was not computer-assisted. This example definitely is, and we have evidence for learning. The *Mathematical Modeling Conceptual Evaluation II* (MMCE II) (4) was designed to measure students' conceptual understanding of vectors. (*MMCE I* measured students' understanding of mathematical functions in the context of modeling.) Traditional physics courses are largely ineffective in improving student understanding of vectors. Student understanding of vectors as measured using part of the MMCEII showed less than a six percent improvement before and after standard instruction in the Tufts introductory physics class. Less than half of the students understood vector concepts.

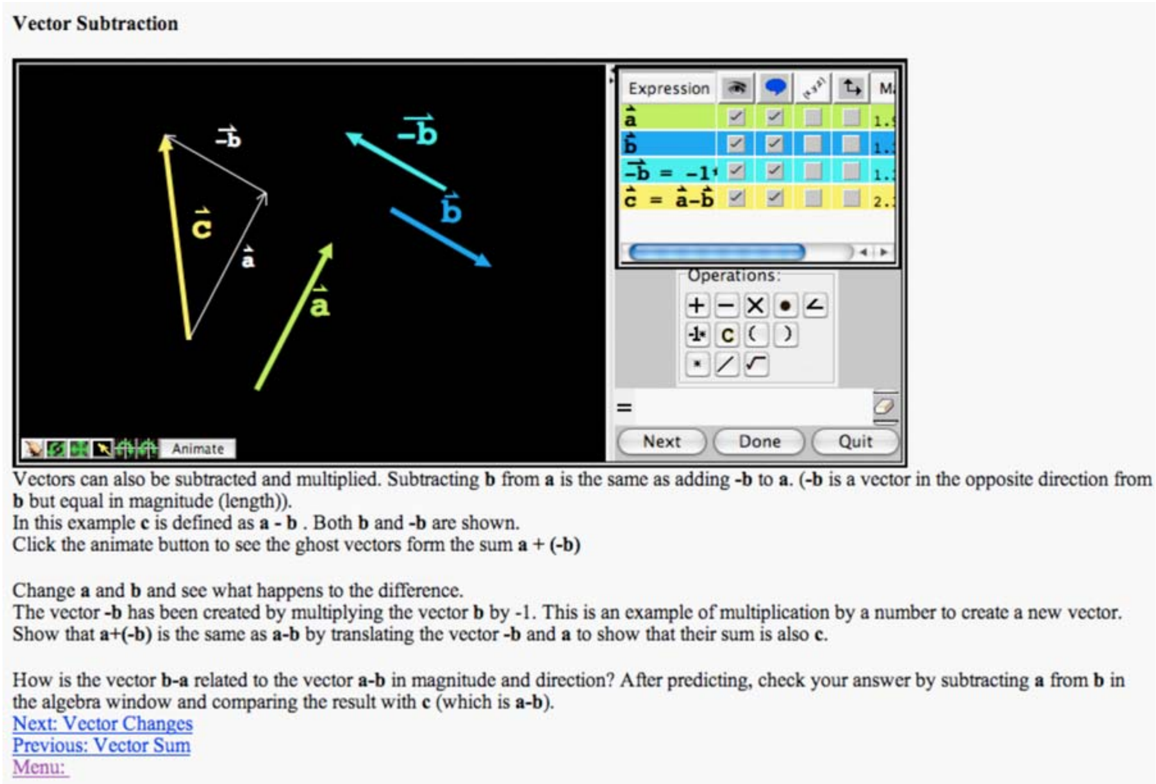

Fig. 4 The vector subtraction activity in the Vector Interactive Tutorial with the Visualizer® showing in the window

However, student understanding of vectors before instruction gave us false hope. In this same class students' conceptual knowledge of Newton's Laws started at 10-15% and traditional instruction had little effect, yet our activity-based curricula resulted in 90% post-test scores (see previous section). Therefore, we thought starting near 40% for vector knowledge would make further gains easier than our previous conceptual gains. We were wrong.

We used a vector *Interactive Lecture Demo* in class (about 30 minutes) and we assigned a web-delivered vector dynamic tutorial (4) as homework. Both use the *Visualizer®* The *Visualizer®* can display physical data or the output of models in 3-D vector form, including time evolution and trajectories. It understands vector operations and can display 3D vectors graphically and algebraically. Users can change vectors dynamically, observer viewpoint, and coordinate systems. Figure 4 shows and an example of the web-delivered interactive tutorial with the *Visualizer®* showing in the window. Students can manipulate the vectors in the window. As a result of using the vector *Interactive Lecture Demo* and the web-delivered vector dynamic tutorial as homework, we achieved the results shown in Figure 5 where 60% of students who did not know the vector concepts learned them. The results are certainly acceptable, but still not what we would wish. Modifications have improved results and things are getting better as shown by the other normalized gains in Figure 5 for very different groups of students. It is clear that computer visualizations or simulations can work reasonably well in the curricular contexts we have been discussing.

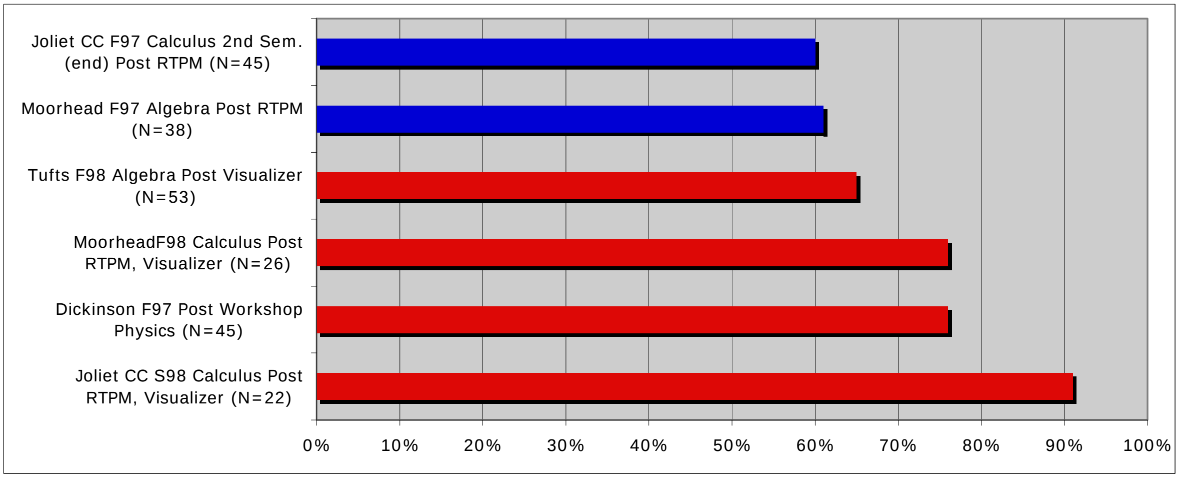

Fig. 5 Normalized gains using part of the MMCEII to evaluate knowledge about vectors. Students experienced various instruction as noted. Students taking RTP mechanics and Workshop Physics make substantial gains in vector knowledge unlike standard instruction.

EVIDENCE FOR INCREASED SPATIAL ABILITY FOR STUDENTS INTERACTING WITH REAL-TIME DATA LOGGING (MBL)

We examined how students' levels of spatial visualization ability interact with learning physics in a microcomputer-based laboratory (MBL) environment (Kozhevnikov and Thornton, 2006). Undergraduate students who had taken an introductory physics course supported by MBL tools were pre- and post-tested at the beginning and at the end of the semester on spatial visualization ability and their conceptual understanding of mechanics. It was no surprise that the results showed that spatial visualization was a reliable predictor for students' performance on physics conceptual evaluation tests (*FMCE*) before MBL instruction. In one of the spatial visualization tests—a paper-folding test—students view an illustration of a piece of paper being folded and then having a hole punched through it. Students then attempt to pick the correct unfolded configuration (Ekstrom *et al.*, 1976). Spatial visualization ability tests like the paper-folding test have been shown to be reliable predictors of student achievement in a wide range of technical and engineering subjects (e.g., McGee, 1979) and there are also reports that physicists have uniformly high spatial but not necessarily high verbal ability indicating that the spatial, but not the verbal, component of intelligence is especially important for solving physics problems. Also, educational studies have found that science students (physics majors in particular) possess more highly developed spatial ability skills than do non-science students (Lord and Nicely, 1997). Since problem solving in physics often involves visualizing complex spatial processes and mentally manipulating graphs and diagrams, it is not surprising that low spatial ability students have been shown to experience difficulties in learning physics. In particular students experience difficulty while solving problems that require visualizing abstract physics concepts and/or interpreting graphs (Kozhevnikov *et al.*, 2002; Pallrand and Seeber, 1984), and that is what we found before instruction.

Even though students who initially had low spatial visualization also did not do well with conceptual knowledge, this study shows that there is no correlation between spatial visualization and conceptual knowledge after physics instruction that employs MBL (real-time data logging). The relationship has been altered as a result of MBL instruction, and students' levels of spatial visualization have increased significantly. Studies show that attempts to directly train spatial ability in general have not been successful, although there is some evidence that taking geometry or science courses or integrating computer graphics with such courses can result in some gains on tests of spatial ability. The problem with these studies is that they did not consider that the overall gains could be the result of increases in the speed of spatial tasks and not due to a reduction of errors (Kozhevnikov and Thornton, 2006, p. 113). In the Kozhevnikov and Thornton study students significantly increased their accuracy and score on spatial visualization tasks, as measured by the Paper Folding Test, after taking Workshop Physics at Dickinson College and participating in a full set (4-50 min periods) of kinematics and dynamics *ILDs* at Tufts University. Control groups did not show such increases.

We also wished to establish whether subjects with prior physics background would improve their spatial ability when exposed to MBL curricula. A group of 28 middle and high school science teachers who participated in different types of MBL activities during a two-week hands-on workshop on Activity-based Physics also showed a significant increase in spatial visualization ability. The activities included *RealTime Physics* lab activities in groups (9.5 hours), *ILDs* (4 hours), and open lab work (4 hours). The teachers showed significant improvements in total score and accuracy on two different spatial visualization measures, the Paper Folding Test already described and the Mental Rotation test.

We believe that the variety of visual–spatial graphical representations to which students were exposed during the course of MBL instruction as well as the possibility to interact directly with and explore hypotheses about these representations assisted students in developing their skills to deal with abstract spatial material. Moreover, the data show that such changes could not be attributed to speed-accuracy trade-off or test–retest effects. Because MBL activities improved spatial visualization skills even for those who already have a science background, it seems that the experience with visual graphical representations rather than learning physics concepts per se caused the change in spatial visualization skills. These studies pose an important topic for future research: what is the underlying reason for this improvement of spatial skills when MBL is used in these contexts?

CONCLUSIONS

At the beginning of this chapter we promised the reader, that after examining computer-enhanced curricula where students showed substantial gains in conceptual understanding, we should be able to identify the characteristics of computer-supported learning environments that can be used successfully in widely varying contexts with students of diverse academic interests and preparation.

Computer-enhanced or not, we learned that activity-based curricula are, so far, the only curricula for which there is evidence that students make substantial gains in understanding conceptually. It also appears that peer interaction may be an important component of successful curricula.

When students learn conceptually as indicated by results of conceptual evaluations (such at the *FMCE* or the *FCI*), it appears that this learning is retained by students. We examined in detail results from curricula such as *RTP* and *ILDs* that use real-time data logging (or MBL) that conceptual learning is retained. The most compelling evidence came from Bernhard's work where he translated *RTP* labs into Swedish with modification appropriate to the Swedish educational environment and found that Swedish future teachers still retained this conceptual understand 2.5 years after they had taken an introductory physics course. We would be remiss if we did not point out that students who learned conceptually using active engagement methods as a result of the research-based *Tutorials in Introductory Physics* (McDermott, 1998), with no computer enhancement, at Montana State showed only a very small decline after being evaluated after one through three years following their instruction (Francis, et al., 1998). These data support the statement that if students show conceptual learning as a result of conceptual evaluations (at least the *FMCE* or the FCI) then the conceptual knowledge is retained.

The example of real-time data logging or MBL shows that computer-enhanced instruction is particularly valuable when used in the context of a research-based, activity-based course that makes use of peer interactions. Tools such as real-time data logging tools can do the following:

- allow students to find answers directly from the physical world,
- make the "abstract" concrete through immediate feedback,
- in the right curricular context may improve certain types of spatial ability,
- encourage learning from peers, and
- encourage critical thinking skills by reducing the drudgery of data collection and manipulation.

Keep in mind that even with all of these advantages, real-time data logging introduced into a traditional environment results in more conceptual learning than the traditional environment but much less learning than an activity-based, research-based environment supporting peer learning. Such environments will not only support real-time data logging but also other kinds of computer tools such simulations that can be manipulated by students and can result in conceptual learning.

A final summary of points to guide curriculum development for effective conceptual learning are:

- Begin with what students understand.
- Begin with the specific and move to the general
- Keep students actively involved.
- Use peer collaboration.
- Emphasize conceptual understanding.
- Link abstractions to the concrete.
- Let the physical world be the authority.
- Make appropriate use of technology.

FOOTNOTES

1. Normalized learning gain is defined as the percentage (or fraction) of the possible improvement that was actually achieved by the students from pre to post-test, i.e.,

<g> = (Post - Pre)/(Perfect Score - Pre) x 100%.

2. Computer interfaces, probes and are available from Vernier Software and Technology (www.vernier.com), PASCO Scientific (www.pasco.com), and COACH (www.cma.science.uva.n1/english/Software/Coach6/Coach6.html).

3. John Wiley and Sons (www.wiley.com)

4. The Mathematical Modeling Conceptual Evaluation (MMCE) I & II are available from the Center for Science and Mathematics Teaching, Tufts University. (csmt@tufts.edu)

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