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ABSTRACT

The Comprehensive Unified Physics Learning Environment (CUPLE) is a project that brings together innovative uses of the computer for physics teaching into a single, multi-purpose learning environment. The status of college-level introductory physics teaching is reviewed. In these courses, physics instructors have been forced to be satisfied with only the best students achieving significant learning. Even those students often have to wait until later in their training to begin to learn many of the tools that are fundamental to the activities of the professional physicist. This paper discusses how educational computer technology might be used to change this situation. The CUPLE environment, as an example of a way to deliver the requisite computer tools, is also discussed. (Contains 25 references.) (ASK)

The CUPLE project: A hyper- and multi-media approach to restructuring physics education

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1. Introduction

The computer is an information processing tool with revolutionary capabilities. Because education is about the structure and transfer of information, the computer has important implications for colleges and universities. With the computer as an integral part of the student's learning environment, previously unimagined possibilities open up, both for the number and kinds of students we can reach, for what they can learn, and for how we can help them learn it.

The Comprehensive Unified Physics Learning Environment (CUPLE)[1] is a project that is bringing together innovative uses of the computer for physics teaching into a single multi-purpose learning environment. It integrates these with sets of powerful tools that can make the learning process much more active and enriching. It is a highly modularized environment whose structure could have significant implications for how the teaching of physics evolves.

In this paper we first review the status of college level introductory physics teaching. In these courses we have typically been forced to be satisfied with only the best of our students achieving significant learning. Even those students often have to wait until later in their training to begin to learn many of the tools that are fundamental to the activities of the professional physicist. We then discuss how educational computer technology might be used to change this situation. Fi-

[1] The CUPLE project is supported in part by grants from IBM and the Annenberg/CPB Project.

nally, we discuss the CUPLE environment as an example of a way to deliver the requisite computer tools.

How many of our students do we reach?

We teach physics in order to help the next generation of learners build their understanding of the basic ideas of physics. Our current techniques have been successful in continuing to produce new high quality research physicists, but it takes time. Physics majors learn the material through a spiral process that covers the same material a number of times at increasing levels of sophistication over six years of training. If the students don't "get it" the first time through, they can get it later.

However, fewer than 2% of the students who take introductory college physics will go on to be physicists and take the full spiral of physics courses. Most are taking physics as part of their training for other professions -- chemistry, engineering, biology, medicine. Some are taking it as part of a liberal education. Most will never take another course in physics.

There is mounting evidence that for most of the students taking introductory physics, the classes are massive failures. After introductory physics, the student's basic view of the world remains decidedly non-Newtonian. Although most students achieve some fluency with the vocabulary and can reproduce on exams the solutions of problems whose near analog they have seen before, when tests are devised to probe their understanding of the basic ideas, their grades fall precipitously. [6] [22] [23]

Many physics teachers are satisfied with this state of affairs (perhaps in the sense of making the best of an unsatisfactory situation). They feel that as long as physicists produce more physicists, they don't have to worry about the rest of their students. But economic and social changes associated with the development of technology and the information age result in increased pressure on the education system to deliver a larger fraction of technically literate graduates. We can no longer be satisfied if most of our students fail to get the point. In Section 2, we discuss in some detail the problems the bulk of students in introductory physics classes have and the skills we would like them to learn.

Where do we need to do better?

Educational and cognitive studies suggest that some of the problems in the introductory course arise from two causes:

1. We do not focus enough on what it is we want them to know how to do.

2. We do not pay sufficient attention to our student's underlying mental models: neither to the ones they come in with nor to the ones they go out with.

Firstly, our courses tend to focus too much on content and not enough on process. We do not want our students to just memorize a list of definitions and equations. We want them to build a robust mental model. We want them to structure their knowledge into a scientific framework that allows them to

- understand what evidence leads us to believe the elements in the structure,
- see the relation of the parts,
- use those relations in problem solving, and
- use the structure to solve problems they have not seen before.

Secondly, we often consider our students as *tabulae rasae* -- blank slates -- and assume we can "write knowledge" directly into their heads. We fail to realize that they come with "naive preconceptions" which can block them from understanding what we are trying to teach them. As a result, few of them rebuild their mental models to resemble the scientific, Newtonian structure we are trying to convey.

We discuss what educational and cognitive researchers have learned about the nature of mental models and how to change them in Section 3.

Can the computer help?

The immense growth and availability of computer technology in the past decade has put a number of new and powerful tools into the hands of educators. Some of these are highly appropriate for addressing some of the problems discussed above. In particular, a number of developments, both in hardware and in software, have powerful implications for the development of new tools for learning:

On the hardware side, the development of fast 32 bit microcomputers puts the power of a 1970s mainframe on a student's desk for a cost of less than $2000. This power permits quick access to lots of material and quick response times. The recent incorporation of multi-media tools -- sound and video -- increases the richness and the texture of the materials available. And CD storage permits making immense quantities of material easily available.[2]

On the software side, the development of graphical user interfaces (GUIs) has made the computer much easier to use. Multi-tasking software allows the user to run many programs at the same time in different windows on the GUI screen. Modern software development methods strongly encourage building highly modularized materials. This permits effective cumulation of software developments so that we don't have to continually reinvent the wheel.

These technologies have important consequences for the teaching of introductory physics.

1. Multi-tasking, multi-media, and the availability of powerful tools allow students to work more like professionals.

[2] A five inch CD can hold up to 650 Megabytes of data. This is equivalent to a stack of more than a thousand standard 5.25 " floppy disks -- a stack more than 12 feet high. This can hold more than a hundred thousand pages of typewritten text.

2. The integration of materials, particularly those using computer based laboratories can help students develop better mental models.

3. Modularization of computer materials leads to flexibility and opens the possibility for the system to evolve continuously.

The success of various projects in physics education that use the computer demonstrates these principles. We discuss their results in Section 4.

The CUPLE project

CUPLE is a project to bring together in a single unified computer environment some of the successful attempts to reach more introductory physics students and to train them more effectively and professionally. CUPLE is bringing together sophisticated tools for handling graphing, calculations, laboratories, and video with modularized text materials and a database of information. This unification opens up many exciting possibilities both for the student and the teacher. A prototype of the project has recently been completed and is described in Section 5.

The long-term evolution of the curriculum

One difficulty facing any attempt to change the physics curriculum is the fact that it has a large inertia. Over much of this century, the curriculum has changed very little, despite momentous changes in almost all relevant factors:

- the numbers and types of students taking the course,
- their background and the quality of their training,
- the content of physics itself, and
- the tools and approaches used by the professional.

In Section 6, we discuss the impact CUPLE can have on what can be learned in an introductory physics course and by whom.

In Section 7 we discuss the inertia opposing curriculum reform, consider some of the factors responsible for this inertia, and suggest how these could be profoundly influenced by an environment such as CUPLE.

2. Two Problems with Introductory College Physics

In this section we elaborate on two basic problems in teaching introductory physics: 1) most students fail to build a coherent, scientific mental model of the material presented, and 2) the processes taught in the introductory course represent only a pale shadow of the activity of the professional scientist.

2.1. Most students in an introductory physics course do not build a coherent mental model of the subject

When we teach introductory physics, we want our students to build a well-structured, scientific mental model for how the world works. They should not only know how to solve basic physics problems, they should also understand why these problems are solved in the way they are. They should understand why we believe the results we present and under what conditions they can be applied.

There is, however, mounting evidence that our courses are not being effective in changing most students' views of the world into more scientific ones. When we probe the mental model underlying the student's problem solving skills, we learn that many students use tricks, memorization, and key words to solve problems, and that their underlying concepts may be severely deficient.

Lillian McDermott [15], David Hestenes [6], Ronald Thornton [22], and others, have documented the lack of effectiveness of traditional approaches to introductory physics in changing students' underlying concepts. These studies have been done across a wide range of schools and student populations. In a particularly revealing study, Eric Mazur, at Harvard, has demonstrated that even Harvard physics students exhibit the same difficulties. [14] Alan van Heuvelen at Las Cruces, New Mexico, found only 5 of 100 students shifting from a pre-Newtonian to a Newtonian view of motion after a year-long calculus-based class. [23]

The situation may to deteriorate further as the crisis in education is producing students who are less well prepared than in the past. Fewer students are expressing an interest in science and math, and American students fare poorly against their analogous cohorts in Europe and Asia. [25] Furthermore, the demographics indicate that the student population is shifting. We must begin reaching a more diverse population of students than ever before.

2.2. Students in an introductory course often do not learn appropriate professional skills

The skills learned in a university environment are often not an appropriate preparation for the workplace environment in which our students will eventually find themselves. This problem is a general one in university training and has been highlighted by a group of cognitive scientists who encourage the replacement of traditional teaching by an "apprenticeship" type of activity. They note that in many fields, introductory students are not trained in activities that well represent what they will do as professionals. [5][11]

These observations are true in physics as well. This can be a particularly serious problem for physics majors, as it distorts their early view of the profession. Students may need significant remedial activities (sometimes as late as after their candidacy exams) when they may be getting their first real taste of research. Even worse, many students who might do very well as research physicists can lose interest if the material seems dry or poorly motivated. We may select against students who are excellent researchers, but who do not do well on timed exams where speed is a factor. For the non-majors, inappropriate training can make it especially difficult to understand the ideas behind physics.

Some characteristics of the differences in approach between the way the beginning student is taught and the way the professional physicist works are listed in Table 1..

Many of these differences flow from the common strategy of presenting introductory physics in the model of mathematics. Mathematics is an abstract science in which one can define one's own axioms and conditions. Consequently, her results can be both exact and precise. Physics, on the other hand, is an experimental science. Nothing in physics is "true" in the sense of mathematics. Physics is not an "exact science" constrained only by internal, self-defined relations. It's a science constrained by our observations of the real world and one in which we believe we know the accuracy of our approximations.

Students:	Professionals:
Solve narrow, pre-defined problems of no personal interest.	Solve broad, open-ended and often self-discovered problems.
Work with laws presented by experts. Do not "discover" them on their own or learn why we believe them. Do not see them as hypotheses for testing.	Work with models to be tested and modified. Know "laws" are constructs.
Use analytic tools to get "exact" answers to inexact models.	Use analytic and numerical tools to get approximate answers to inexact models.
Rarely use a computer.	Use computers often.

Table 1: Comparison of students' activities with those of a professional physicist.[3]

The primary reason for the distortion in the introductory course is the fact that, for most circumstances, obtaining approximate results without numerical methods requires a high level of mathematical sophistication not possessed by most students (even physics majors) at the introductory level.[4] The presence of the computer allows a fundamental change in this situation.

What skills do we expect physics students to acquire? An analysis will help us understand better what it is that is and is not taught in a traditional introductory physics course.

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[3] Adapted from Brown, Collins, and Duguid, ref. [5]

[4] For example, solving for the corrections due to a small air resistance force on a projectile would require substantial experience with differential equations, a skill not usually possessed by the introductory student. This subject is often considered by physics majors at the junior level and there the problem is simplified (a linear or viscous force law is used rather than the more correct quadratic drag force) to permit the use of analytic methods. However, with the computer and a simple numerical solution using the Euler and half-step methods, the problem (with the correct force law) can be easily solved by the introductory student.

An outline of the general process skills required is given in Table 2. We define two basic skills: having a scientific framework and number awareness. By *a scientific framework* we mean that the student must understand the "story-line" of science -- that science means observation, hypothesis, analysis, and testing against observation. By number awareness, we mean that the student must understand the idea that aspects of the real world may be quantified by measurement and that the results of analysis have implications for observation in the real world. These two are a *sine qua non* of doing physics. It is often assumed by the introductory physics teacher (incorrectly!) that the first is present. The second is stressed in most introductory courses.

To these two basic skills, we try to add a set of theoretical or modelling skills. The first of these are analytic skills: students should be able to write equations from word problems, to solve a variety of equations, and to interpret their results in terms of the physical world. Some aspects of this skill are stressed in the traditional introductory course. Other theoretical skills needed by physicists tend to be shortchanged in an introductory course, even one restricted to majors. These include estimation, approximation, and numerical skills.

These three skills are essential in learning how to model physical systems and understand the implications of models built by other. Since physics is not an exact science, the "art" in the science is knowing what physical laws to apply under what circumstances and what additional complicating factors can be safely neglected. We call this "getting the physics right". It involves being able to estimate the size of an effect, and to calculate corrections by understanding approximations. Today, it often involves putting physical insight into and getting it out of a complex numerical calculation. Yet these skills -- critical for the professional physicist and essential for the engineer -- are almost completely ignored in traditional introductory courses.

Since physics is a science whose results are continually tested and evaluated against the real world, a physicist needs experimental skills as well as theoretical ones. Majors are often trained in error analysis, mechanical skills, and given experience with a variety of devices. A fourth component, empathy for the apparatus, is something which one hopes that students develop as a concomitant part of their experimental experience. Yet this skill is primary to their understanding of what even basic physics means and how the equations we write down relate to the behavior of the real world.

1. Basic skills A scientific framework Number awareness
2. Theoretical skills Analytic skills Estimation and natural scales Approximation skills Numerical skills
3. Experimental skills Error analysis Mechanical skills Device experience Empathy for the apparatus
4. General skills Intuition Large-problem skills Communication skills

Table 2: Skill analysis for physics students.

Finally, there are a number of general skills that all professionals must develop. They must build an intuition for their field -- the ability to understand which tools apply in which circumstances and to have the complex network of internal checks that let them look at a wrong answer and have it not "feel" right. They must learn large-problem skills; the ability to take a significant problem and break it down into component, solvable parts in an appropriate manner while keeping track of the overall goal. Finally, they must build communication skills. In physics, as in any field, it does not suffice to do brilliant work in a notebook or in your head. Physics, as is any field, is a social agreement of what it is we know. To interact with the community one needs to be able to present one's results both in oral and written form in a clear and compelling fashion. This cluster of general skills is largely neglected in our professional training of physicists until they begin research in the second or third year of graduate school!

3. Can educational research help?

To understand the implications of the problems that students have building appropriate mental models of the physical world, and to see what might produce effective solutions, we turn to some of the basic results of cognitive science as applied to learning theory. We briefly summarize a few of these results.

3.1. The problem of mental models

Students do not come to us as *tabulae rasae*. They have both knowledge of the world and patterns of expectation for how they should learn. These patterns are often referred to as mental models[5] (or schemas). Observations that have been made about mental models include:

1. Each individual must build his or her own mental models. They cannot be "transferred" from teacher to student.
2. Mental models can contain contradictory elements.
3. It is reasonably easy to learn something that fits in well with your existing mental model.
4. It is very difficult to change a well established mental model.
5. Individuals develop a variety of preferred approaches or learning styles.

Item 1 is the fundamental element in the modern constructivist credo. Listening to a lecture or reading a book is not an effective way of learning if one does it passively. Item 2 implies that as teachers we can be fooled about how much our students know if we are not careful in probing their mental models. They can learn to do problems without realizing the implications of their answers. Item 3 can be summarized with the observation that much of our reasoning is done by analogy. Item 4 says that it can be very difficult to learn something you don't almost know already. This can be an especially severe problem if "what you know ain't so". Item 5 reminds us that anecdotal evidence from a small number of students (those who think like their teacher) is not necessarily generalizable to all students. It also helps to raise our consciousness to the kinds of wrong paths our students can follow.

In line with these general observations, experimental evidence in specific cases now shows convincingly that most students in introductory physics courses do not develop good physical mental models, even when they know how to solve traditional problems reasonably well. [2] [6] [21] [23] Why does this happen? Some specific findings regarding physics learning are:

- Introductory physics students come in with naive preconceptions about the world that don't get changed in the course.
- Students have trouble understanding what's important and how a part relates to the whole.

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[5] We use the term "mental model" here to stand for the set of propositions, rules, and ideas that an individual has about a particular phenomenon. This is the sense discussed by Donald Norman and others in their articles in the collection *Mental Models* [17]. The term has been used by others in the cognitive literature to have other more specialized meanings.

- Students have difficulty with the multiple-representation structure of physics.
- The thinking and learning styles of most students differ from that of most physicists (a highly selected and trained group.)

Having lived in the physical world all their lives, our students necessarily come to us with preconceptions about it. We use the phrase "naive preconceptions" rather than the more commonly found "misconceptions" to stress that the ideas and models the students bring to a physics course are often adequate and sufficiently accurate for normal life in the everyday world. They are, however, not productive as a base for scientific generalizations and do not extrapolate correctly to situations less commonly encountered (where they can be dangerous).[6] These views can lead students to build a shell around what they learn in physics class and only apply it to their physics homework and exams. Success in that venue does not necessarily imply that they have integrated these views into their everyday conceptions of nature. Their naive preconceptions can even cause them to reinterpret what we tell them incorrectly, in order to make the results agree with their existing mental model. [1]

If we want to overcome these scientifically unproductive mental models, we have to change our students' ways of thinking. Changing someone's mental model requires that the proposed change have these characteristics:

- It should be understandable.
- It should be plausible.
- There should be a strong conflict with the existing model.
- The new model should be seen as useful.

The judgment that a new model satisfies these conditions must be made by the students themselves. It rarely suffices to tell them, for example, that their view of the world contradicts an experiment shown as a demonstration in class. They must understand what is happening in the experiment, make their own clear prediction, and see clearly that it is controverted. Active engagement is crucial.

3.2. The problem of learning process

"Doing physics" is not the same as "knowing physics". Many students satisfactorily learn to memorize and replay definitions and equations, but cannot use or put these together in any but trivial ways. Learning to do physics means learning to run the machinery, not just be able to name the moving parts. And physics, like most sciences, is a tightly linked and overlapping structure. Most problems are highly overdetermined: they can be viewed and solved in many different ways. One of the characteristics of physics that convinces us that it is "right" is the fact that all these dif-

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[6] An individual whose intuition about motion is based on walking may get into trouble when driving on a highway at high speeds. Inadequate understanding of the concepts of linear and angular momentum can lead to tailgating (which produces "chain reaction" collisions on highways) and rollovers.

ferent approaches fit together and give a consistent set of answers. Students learn this as they develop process skills to go with the content they have learned.

One particular difficulty that introductory students often have is that physics is highly multi-representational. Physics begins by selecting a phenomenon to analyze -- a narrow slice of the real world. This slice is then modelled by an idealization -- a "schematic" or "cartoon". In creating this, we decide what in our slice of the real world matters and what is irrelevant for the problem at hand. Then, that cartoon is translated into a variety of forms: words, equations, tables of numbers, graphs, diagrams, and so on. Each of these representations tells us something about our model. We are continually having to create these different representations and translate them, both one into the other, and into their implications as to what they say about the real world. This process is illustrated in Figure 1.

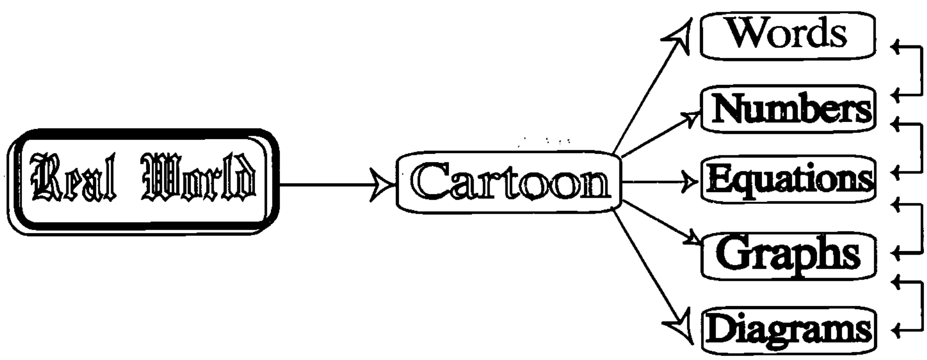

Fig. 1: Physics describes the world with models that have multiple representations.

Students often have trouble with the multi-representational character of physics. Some students have trouble with geometry, some with algebra. Others can draw a graph but not explain what it means in words. The professional physicist has worked with these representations for so long, that he or she tends to see them as identical and not appreciate the difficulty a student may have in getting from one to the other.

A second problem we often encounter is that students rarely see the relations among the parts. Few students in an introductory class know what scientific mental models are like. Many students leave our pre-college educational system with the model that science consists of memorizing a large number of rules, principles, and equations, and learning tricks to spin obscure and meaningless words ("physics problems") into numbers ("correct answers").

When students see physics as a collection of independent equations to memorize, they lose the structure of the material. They do not realize why they are studying a particular equation or what implications it might have for their future studies. The process used and expected by physicists includes a continual calibration of the model against the real world and a dense interdependence of principles that provide numerous ways of looking at and checking each result. Introductory students often fail to gain the ability to apply the complex and tightly interwoven network of cross-checks that physics offers. (The professional would say: "Well, I got a solution. Is it right? Let's check that I used the right equation by deriving it from first principles. Let's check my units. Let's see if energy is conserved. What if I take limiting values? Does it make physical sense when I imagine what's happening in the real world. ....")

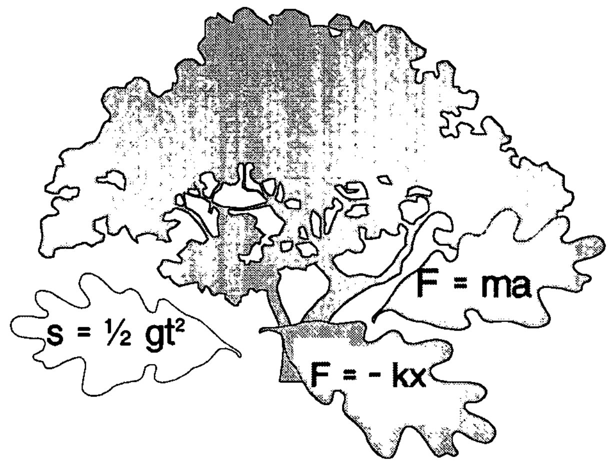

Fig. 2: The "dead-leaves model" of physics

We refer to the "independent-equations" way of thinking about physics as the *dead-leaves model.* Each equation is written on a leaf (or file card) and is inappropriately considered equal in importance and relevance. This is illustrated in Figure 2.[7] We would much prefer our students to see physics as a living tree.

4. Can the computer help?

The immense growth of computer power in the past decade has made possible a number of innovative approaches to the problems discussed above. In this section, we consider a few of the approaches that have been tried and proven successful in attacking some of the fundamental issues.

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[7] The three equations represented here, F=ma (Newton's second law of motion), F=-kx (Hooke's law for springs), and $s = \frac{1}{2} gt^2$ (distance a particle falls in time t under the influence of flatearth gravity) are *de riguer* in any beginning physics course. Yet they have widely different structures and ranges of validity. Newton's second law is the general principle of classical dynamics. It determines the response of any particle to forces and holds for all systems from the scale of molecules to galactic clusters. Hooke's law is a phenomenological principle that describes how some systems deform in response to (small) forces. The projectile equation is a very special case, useful only for describing the motion of projectiles as long as the earth is approximated as flat and air resistance effects can be ignored.

4.1. Using the computer to build better mental models

A number of the developments in computer technology can help solve the problem of building good mental models. Microcomputer based laboratories (MBL) have already proven to be powerful and effective. Combining hypermedia with concept mapping should also prove to be a powerful technique.

4.1.1. MBL

The microcomputer can be used in the laboratory to collect and analyze data from measurements in real experiments. Microcomputer based labs (MBL) have been demonstrated to significantly help students break down their naive preconceptions and build up a strong set of underlying physical concepts. [21] [22] It is the following characteristics of these laboratories that seem to be important:

- The instruments have short response times.
- Students can become the test objects, a get a strong kinesthetic interaction
- It is easy to collect high quality data.
- The equipment is highly modularized into easy-to-comprehend and manipulate chunks.

Modern data-collection systems for educational applications[8] consist of an analog-to-digital converter (ADC) -- a device that converts an analog signal from a measuring device (a *probe*) into a digital signal that can be analyzed by the computer. A variety of probes (distance, temperature, voltage, current, force, magnetic field, ...) can be plugged into the ADC which is in turn plugged into the computer. Students can learn to set up this equipment easily and to take excellent data in a few minutes. They can then quantify a wide variety of physical phenomena and see the result on the computer screen immediately.

One group that has been developing and using these tools in introductory physics teaching in especially effective ways is Ron Thornton in his project *Tools for Scientific Thinking* at Tufts University [22] and Priscilla Laws in her project *Workshop Physics* at Dickinson College [11]. Thornton has developed a series of labs that use the ADC plus computer to help students build the fundamental concepts of the physicist's world view. Laws has used these tools to develop a complete introductory physics course based on discovery labs and without traditional lectures.

When they use these systems to explore the real world, students can see the translation of their real world observations into graphs and numbers quickly and easily. Thornton, Laws, and their collaborators have shown that these methods produce the strong conflicts with a student's naive preconceptions needed to motivate change and help them develop good experimental skills, including an empathy for the apparatus.

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[8] Two excellent examples of such systems are the Personal Science Laboratory (PSL) from IBM and the Universal Laboratory Interface (ULI) from Vernier Software.

4.1.2. Hypermedia

One of the problems students have in building up a good mental model of the content of the physics course is their inability to integrate the material into a coherent whole. The individual lecture and the "chapter a week" in the textbook may play a role in this difficulty. Certainly the tendency of textbook authors to summarize the material at the end of a chapter by a list of equations facilitates problem solving without thinking.

A textbook has a built-in tendency to linearity: the pages are numbered successively. The "space" in which a computer presents information is not so constrained. Any structure, any connection between parts can be displayed in effective and compelling ways. This has an important implication.

The structure of the material presented on the computer is not restricted to a single form. It can be organized in many different fashions and can emphasize non-linear links.[9] Hypermedia makes it possible to structure a student's access to materials and his or her view of the relation of the parts.

PhysNet is Peter Signell's project at Michigan State that modularizes the physics curriculum into more than 600 units and focuses on developing student learning skills. The PhysNet project has used a hypermedia-like approach (on paper!) with considerable success. Signell reports that the students understand the relations of units throughout the course better than with the traditional presentation. [20] Although this approach has proved successful at Michigan State and has been adopted at a few other institutions, the difficulty of administering and managing the system has limited the use of this approach. It's much easier to order a single textbook for all students than to provide each student access to hundreds of pigeonholes, each containing a unit, and to design an individualized content for each student. The advent of large data storage capabilities and hypermedia controlled access promises to free this interesting approach of its managerial chains.

4.2. Using the computer to develop appropriate skills

The computer can help substantially in introducing more professional skills in an introductory physics course. On the theoretical side, the traditional approach suppresses the fundamental idea of approximation since that requires too much mathematical skill. On the experimental side, the laboratory is frequently used to "demonstrate the truth of the equations taught in lecture". Labs are pre-set up, since there is too little time to have the students assemble and learn complex equipment. The result in both cases is a severe distortion of what the professional does. The general skills in Table 2 are rarely included in an introductory course.

4.2.1. Professional productivity tools and theoretical skills

The introduction of more powerful and professional tools, such as programming languages, graphers, data accumulators, and symbolic manipulators gives even the introductory student the

[9] This is not to imply that material should always be presented in a non-linear fashion. Some material is inherently linear; and while people are learning to work in more flexible environments, linear approaches will continue to be valuable.

power to address more realistic problems than are possible with analytic hand calculations. In order to produce analytically solvable problems, introductory physics classes occasionally simplify the life out of a real world problem until it loses all interest. Einstein has been quoted as saying: "Physics should be as simple as possible -- but not more simple than possible." The inclusion of professional productivity tools gives even the introductory student a much wider field to play on. [13]

By putting programming tools in the hands of the physics major in the introductory class, the Maryland University Project in Physics and Educational Technology (*M.U.P.P.E.T.*) [19] demonstrated that introductory students could learn to solve complex physics problems using numerical methods. This resulted in a good first introduction to estimation, approximation, and numerical methods.

In fact, in one semester, the students learned (some came in with) enough programming skills to be able to design and carry out successful and interesting independent research projects in the second and third semesters of the class.

4.2.2. Modular laboratory tools and experimental skills

In her project, Workshop Physics, at Dickinson College [11], Priscilla Laws demonstrated that students could learn to assemble their equipment and take high quality data very quickly by using modular computerized data gatherers. This allows them to get a clearer picture of the experiment and to use the apparatus to think about and build an intuition for the physical system.

In her laboratory-based introductory class, Laws's students develop good experimental skills. By the end of the class, many are comfortably designing and assembling equipment to answer generally posed physics questions.

4.2.3. Developing generalized skills

In Signell's PhysNet project, much emphasis is placed on generalized skills. Students are evaluated on their ability to use resource materials. Their problem solutions are graded for quality and clarity of presentation as well as for content. (The grades are multiplied together so no credit is obtained for doing a problem wrong, but clearly.) Students develop self-pacing skills and are encouraged to carry out self-evaluations.

In M.U.P.P.E.T., students carrying out project work begin to learn how to work with large problems and they have the opportunity to learn communication skills by presenting their work both in written and oral form.

5. The CUPLE Project

The Comprehensive Unified Physics Learning Environment (CUPLE) is a multi-university project to develop an open-ended learning environment that incorporates and integrates the approaches discussed above. The idea of CUPLE is to build a working environment for the student that contains a rich set of materials that can present physics in a variety of ways. The resulting product should be able to address both the need to do research on student responses to different environments and to deal with the problem of diverse learning styles. Prototypes and developer tools have been produced and went into beta test in the Fall of 1991. A full course in the CUPLE environment is expected to be available in the summer of 1993.

The basic CUPLE hardware environment requires:

- An IBM compatible microcomputer, preferably 80386 or 80486
- 4 Megabytes of random access memory
- VGA or super-VGA graphics
- a fixed disk with at least 40 Megabytes of storage
- at least one floppy disk (1.2 Megabyte or greater)

The CUPLE software environment requires:

- DOS (version 3.3 or later)
- Microsoft Windows (version 3.0 or later)
- Asymetrix ToolBook (version, 1.5 or later)
- a spreadsheet (preferably Microsoft Excel for Windows)
- a word processor (preferably Microsoft Word for Windows)
- Borland's Turbo Pascal (preferably for Windows)
- a symbolic math package (preferably MathCad or Mathematica)

A full CUPLE station also includes

- an analog to digital converter (ADC)[10]
- a videodisc player and video overlay card[11].

Eventually, we expect CUPLE to be distributed on CD rather than on floppy disk. As a result, the hardware will eventually need access to

- a CD reader.

5.1. Structure

CUPLE includes a variety of tools for both users and developers. The basic materials included are:

- Instructional text
- Microcomputer based labs (MBL)
- Computer simulation tools

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[10] CUPLE software has been prepared for the PSL and ULI.

[11] CUPLE software support has been developed for the VideoLogic card and IBM's M-Motion card. This software will work with any videodisc players supported by these cards.

- Text describing home labs and demos
- Interactive videodisc laboratories
- Extensive reference material (including video)

The contents of CUPLE will be based on materials from the projects in physics education mentioned above: M.U.P.P.E.T. (Maryland and RPI), PhysNet (Michigan State), Workshop Physics (Dickinson), and Tools for Scientific Thinking (Tufts). In addition, CUPLE will also take advantage of recent innovative uses of videodiscs (particularly those of Dean Zollman at Kansas State). It will include videodisc hooks to *The Encyclopedia of Physics Demonstrations*, *The Mechanical Universe,* and the set of *Physics Cinema Classics* developed by the AAPT National Interactive Media Project. A variety of physics databases will also be included, such as the periodic table and chart of the fundamental particles, and collections of educational resources from the AAPT.[12]

5.2. Tools for the user

The heart of the CUPLE innovation is not only to bring together a number of diverse projects and their approaches to physics education, but to provide the student from the beginning with a working environment analogous to that of a professional. The emphasis is on tools that permit easy manipulation of the different representations so critical to understanding physics: graphs, numbers, data, and pictures. In addition to these tools for the user, the environment provides tools for developers that facilitate producing new modules and linking them into the full system. The prototype system contains several tools for dealing with a variety of modalities. Most of the basic tools and the system management structure are being built by the Academic Software Development Group at the University of Maryland.

5.2.1. Tools for exploring text

Text materials are presented as units or "books" in ToolBook from Asymetrix. This hypertext product forms the backbone of the CUPLE environment. A standard frame has been developed with a variety of navigation, help, and annotation tools. (See Figure 3.)

The buttons and icons in the toolbar on the right of the frame let the student access a glossary of physics terms, various forms of help text, or attach a "NoteMark" with his or her own annotations anywhere on the page. Each page may also contain one or more specialized icons. When the student clicks on one of these icons, additional information may be presented or a new activity launched, including graphs, video, animations, reference material and so on.

In addition to whatever links have been built in by the author, the user can bring up palettes of tools shown in Figure 4 by clicking on the toolbox icon. Included are standard tools, such as a word processor, a calculator, and a spreadsheet, and our specially developed tools described below. Although the student's first use of a tool may be through an icon introduced in the text for a specific purpose, the same tool is available through the toolbox at any time for independent exploration.

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[12] Some of the materials to be included will be from *String and Sticky Tape Experiments* [4] and the *Handbook of Physics Demonstrations*[5].

5.2.2. Graphing tools

The CUPLE prototype includes a number of graphing tools: a three-function grapher, a three-dimensional graph display, and a set of tools for use in student programming. In Figure 5 we show a sample screen from the three-function grapher. With this tool, the student can display up to three different functions, vary parameters, and change limits.

5.2.3. Calculational tools and simulations

A Windows version of the original M.U.P.P.E.T. tool kit (called *Window on Physics* or *WinPhys* for short) has been created for CUPLE by one of us (JMW at RPI). WinPhys is an object-oriented extension to Turbo Pascal that allows faculty and students to create their own programs for problem solving in physics with little more than a rudimentary knowledge of Pascal. Figure 6 illustrates the WinPhys pendulum program. With this program the student can study the damped driven pendulum, resonance, or the onset of chaos. The student can even modify the computer model in Fig. 6 through the use of the WinPhys system.

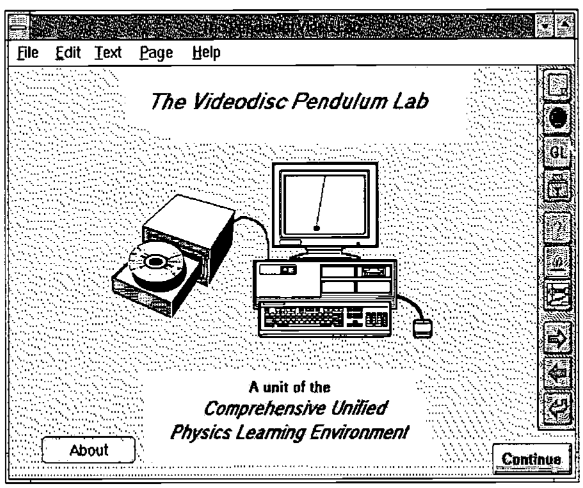

Fig. 3: Title page and frame from a CUPLE unit

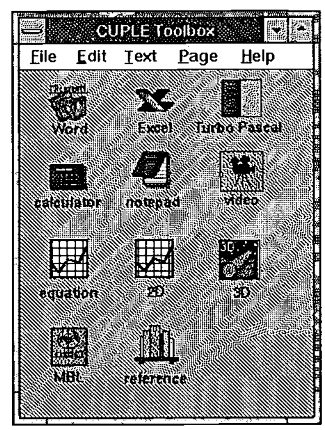

Fig. 4: The CUPLE toolbox

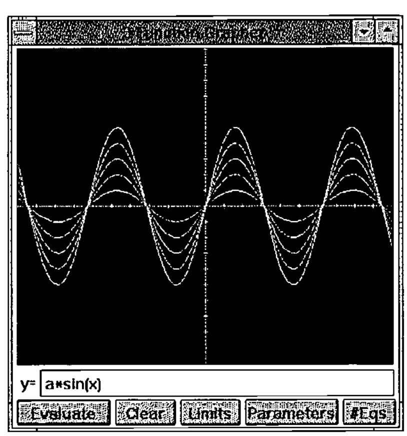

Fig. 5: The three-function grapher

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The Window on Physics materials allow students to include significant and powerful programming in their tool kit and thereby expand the activities they perform as part of their physics learning experience within CUPLE. The environment includes the WinPhys tools and a large number of sample programs. The tools let students and faculty develop programs easily and efficiently. The sample programs have their own intrinsic use at specific places in the curriculum. Because of their highly modular structure, they also serve as templates for cutting and pasting pieces of code into new programs. This structure greatly facilitates the development of new software.

The M.U.P.P.E.T. group has developed a number of simulation programs that can be used both to train the student's intuition and as productivity tools for student projects. These will be ported to CUPLE and integrated with the text materials.

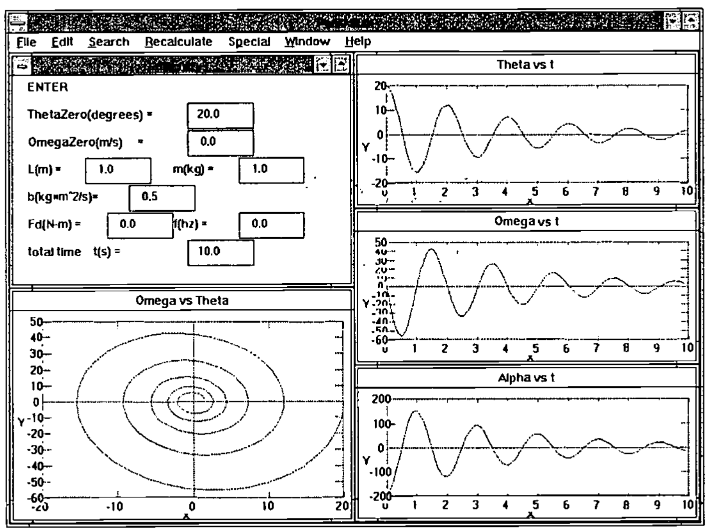


Fig. 6: The WinPhys pendulum program

5.2.4. Data-taking tools

The CUPLE project gets a powerful and important window on the real world through analog-to-digital converters. These devices come with a "shoebox of probes" that permit the user to take a wide variety of real world data directly into the computer. Figure 7 shows a sample screen from the program MOTION, which is designed to display data collected by a distance probe. The example shown is data taken from a sonic ranger positioned below a mass oscillating on a hanging spring. The data displayed includes the position, velocity, and acceleration of the mass. Two other plots that facilitate understanding of the theory, position vs. velocity, and position vs. acceleration are also shown.

5.2.5. Video display and measurement tools

Another CUPLE window on the real world is provided by the video display and measurement tools. These allow the user to display the output of video devices on a window in the computer screen. With the proper video equipment, the student can view and control from the computer the output of videodisc, VCR, or even a CCD device to display live output from a microscope.[13]

In addition to display, our video window provides graphing, measurement, and annotation tools that let students collect quantitative data from the video image on the computer screen. This data can then be exported directly to a spreadsheet for analysis and modelling. Figure 8 shows the video tool with data points obtained by following a video of a large amplitude pendulum.

This tool offers a new element of possible great significance. The "world in the frame" that is the fundamental starting point of a physics analysis gets a visual representation right on the screen. This video data does not need to be "canned" from a pre-existing videodisc. Students can use a hand-held video camera in the lab (and out in the world!) to take data that they can then analyze quantitatively. With multi-tasking, they may have one window open where the real-world video-camera data is displayed, another where the graph of the data from that video is displayed, and a third where a mathematical model is built. The linking and translation of the elements from the world to the various representations of physics can take on a new reality.

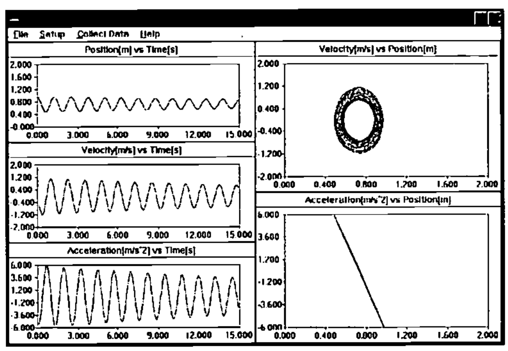
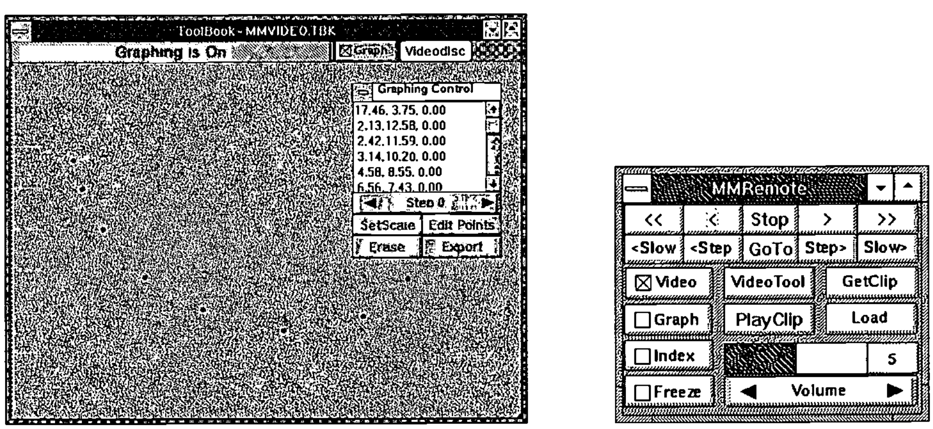


Fig. 7: Data taken from a mass on a spring using the CUPLE program MOTION.



[13] In future versions we also plan to accomodate compressed digital video delivered over high speed networks.

Fig. 8: The CUPLE video window and remote control panel

5.2.6. The browser

One essential element of the full CUPLE system will be the Browser. This will be a graphical display that will allow the user to explore the systems and to understand the relation of the parts at a variety of levels of chunking. The next stage of CUPLE development will involve building the Browser software.

One way to help students build a structured model is to give them access to the course material via a structured hierarchical map. At the coarsest level, this map displays the universe of scientific thought as divided into broad areas of study - physics, chemistry, mathematics,.... This is represented by a series of nodes or bubbles on the computer screen. The student begins by "entering physics country"[14] by clicking on the "physics node". The node then opens up to show the next level of the hierarchy, a series of main topics or "states" -- classical mechanics, electricity and magnetism, thermodynamics,... Clicking on a state opens the hierarchy one more level to display the structure of basic units or "towns". These units are approximately equivalent to the material usually presented in one lecture. The relation between these parts is shown in a *Signell* or *prerequisite map*. The elements are linked to show which units should be mastered before starting any particular unit. A piece of this map is shown schematically in Figure 9.

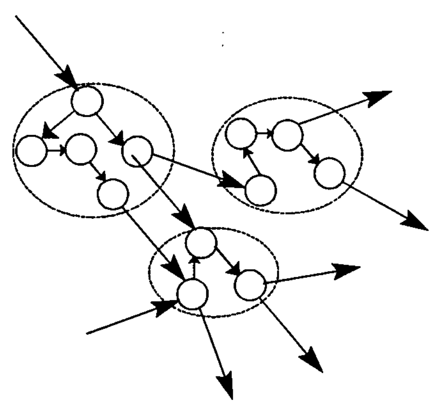


Fig. 9: A piece of a Signell map (schematic)

Once the student selects a particular unit, the screen will open up to yield a "town guide". The unit will contain a variety of activities -- readings, labs, home experiments, demonstrations, programming, etc. It is at this level that detailed guidance will be provided by the CUPLE system. The path through the town will be selected by the teacher, just as he or she now selects readings

[14] We have chosen the map metaphor to explicitly invoke what is perhaps most people's most common experience with non-linear structured information.

and homework problems from a text.[15] The town guide will provide the student with a floating view of the structure of the unit and where he or she is in the unit. Students will also be able to mark parts of a unit as complete when they are satisfied they understand it.

6. Can CUPLE help?

We believe CUPLE can provide an environment and tools that can help solve many of our basic problems with physics education.

6.1. CUPLE can be used to help build better mental models

Let's consider two examples of how the CUPLE system could be used: an introduction to projectile motion for underprepared students and a study of the pendulum by honors physics majors.

6.1.1. Enhancing a lecture

CUPLE provides a number of powerful tools that can enhance a lecture demonstration in ways that should facilitate a student's understanding of the underlying concepts and of the multi-representational character of physics. Some of these uses include: as an electronic blackboard for presenting high quality graphs, for quick and accurate collection and display of data, and for the use of video, from videodisc to videotape to a live camera.

The graphing tools can be used in a compelling way to deliver graphs that can be a significant improvement over hand-drawn graphs. One specific example is to consider a demonstration of the meaning of the derivative. Using the WinPhys function display, one can enter any function and show a graph of that function. By clicking with the mouse cursor on any point on the curve, the tangent to the curve is also drawn. Then one can "zoom in" on the neighborhood of that point, magnifying the view of the curve more and more. This displays in a clear and compelling fashion that when one looks at the curve in smaller and smaller regions, the curve and its tangent become indistinguishable.

The display of data associated with a lecture demonstration can also become more accurate and convincing. The PSL and ULI data accumulation tools together with the CUPLE data display programs allow the teacher to collect and display data in lecture in real time without the need to take large amounts of time or use pre-cooked data. The data can then be analyzed in class using a spreadsheet. The power of the tools is sufficient that the time required is not excessive for a lecture demonstration and the quality of both the data and the fits can be excellent.

Video can add an important component to the student's understanding of the relation of the real world and physical laws. For example, since their mental models of motion are strongly dominated by the concept of position, students often have difficulty accepting the idea that both posi-

[15] The teacher will do this with "course-design software" associated with the Browser. The main outline of the selections will be chosen by the software in response to the teacher's selection of style and orientation. After this selection, the teacher will be able to modify the choices recommended by the system.

tion and velocity are needed to specify an object's state of motion at any given time. A frame-by-frame video display of two children throwing a ball back and forth can provide a compelling demonstration for this requirement. From a single frame, the student cannot tell which way the ball is travelling and where it will be in the next frame. At least two successive frames are needed to decide what the ball will do. As in the live-data demonstration, the CUPLE video tool can be used to extract data from the videodisc and fit it with a model using a spreadsheet. And it can be done in a sufficiently short time to permit it to be done as a lecture demonstration.

6.1.2. Training the underprepared student

Underprepared students often come to a physics class with many problems that make learning physics difficult. Among these is a lack of fluency with algebraic manipulations, difficulty reading and interpreting graphs, and an inability to relate these subjects to the real world. The result is often "encapsulation" -- the student breaks the course materials up into small pieces suitable for memorizing but does not build the relations between the parts that constitute a good understanding of physics.

One can begin to address these difficulties early in the semester with a three hour CUPLE lab on projectile motion. The students begin in a lab where stations are available with MBL's and videodiscs. They perform an experiment with objects rolling up and down an inclined plane, accumulating and displaying data as the object moves. Their data is saved to a file. They then can move to the videodisc and take data both from a thrown projectile and a falling diver. Again, their data is saved to a file.

The students then move to a computer for a one hour session in which they first use the three-function grapher to see how the coefficients in the equation of a parabola effect the shape of its graph. They then work with a previously prepared spreadsheet to see how the formula for the motion of an object can be fit with parabolas and produce both tables of numbers and graphs. They then load the file with their data from the MBL into the same spreadsheet and fit the parameters to match (and incidentally extract the angle of inclination of the plane -- which can be checked against a physical measurement). The data from the video can then be recalled and the data put into the same spreadsheet and the parameters extracted. Both the path of the projectile motion (x-y plot) and the height of the diver (y-t) are modeled with parabolas.

These activities provide a number of different ways of looking at the same subject: a parabola provides a good fit to many aspects of projectile motion. The student has the power to carry out many different activities, both in a guided and independent fashion. The multi-representational character of physics as a description of the real world is dramatically illustrated.

6.2. How CUPLE can be used to expand student activities

6.2.1. Enabling the physics major

More advanced students can use the CUPLE materials to enrich their activities and extend the course materials into modern subjects. As an example, near the end of the first semester, students in a class for physics majors can use the pendulum program to explore the motion of the large-amplitude pendulum. This is a non-linear system with highly complex behavior.

Students can study the qualitative behavior of the damped and driven system and explore the phenomena of resonance and chaos. They can then use the WinPhys system in programming mode and explore the numerical methods used to solve the equation and learn how to determine their accuracy and validate their correctness.

Finally, students can use the pendulum program as the jumping-off point for studying the pendulum and the non-linear harmonic oscillator. This technique has been used in the M.U.P.P.E.T. project and we find that, given the power of the computer, many students can pursue interesting independent scientific research topics for term papers. When they do this, they both get early training in how to do research and develop a better idea of what professional physicists actually do.

6.2.2. Enabling the general student

The CUPLE environment offers the general student in calculus-based introductory physics a number of enhancements over the traditional textbook + problems + lecture + lab. It provides the students with additional power for investigation and exploration through a number of added tools and modalities. CUPLE should have a number of advantages for student learning.

- CUPLE encourages active learning by putting more power to explore in the hands of the student.
- CUPLE has an unprecedented flexibility to permit a variety of uses.
- By bringing the various modes of learning together in a single interactive environment, CUPLE enables a synergy to take place. Whichever mode the student is most comfortable with can help bring along their understanding of other modes.
- By linking a large data base of materials, CUPLE will improve accessibility of tools and information for the student.
- By controlling the student's access to material through a well-structured browser, CUPLE will encourage appropriate chunking and hierarchical thinking.

6.3. CUPLE as a research environment

Although the computer has been used in physics education for more than a decade, the wide availability of 32 bit, hypermedia, multi-tasking, multi-media materials is new. We believe that this power is bound to have an important impact on the way students learn physics. Nonetheless, it is essential to see what works and what doesn't and to understand the reasons why. CUPLE, because of its flexibility, can be used to test a number of important hypotheses in educational physics. Many important questions can be addressed in this environment, including: how students respond to hypermedia, how they learn to understand and translate multiple representations, and how to best classify and handle the variety of learning styles present in an introductory class.

The use of hypermedia has been studied extensively by workers in the field of Human-Computer Interaction. A number of workers have pointed out the dangers of giving a user free access to a large body of unstructured material. The result is often referred to as the user getting "lost in hyperspace". But the traditional lecture + text + lab course is also hypermedia. Even the material contained in a text by itself has substantial cross-linking. When the student fails to see the relation of the parts in different chapters of a text, or when the link between the lecture and lab is not made (a common complaint), the student could also be justifiably described as "lost in hyper-space". The CUPLE Browser is being designed to have a flexibility that will permit research on how the structure of the material presented effects learning.

Although it has often been observed that physics as a discipline depends heavily on multiple representations, there has been very little study on how the mode of presentation affects the student's ability to build the skills of understanding and translating these representations. CUPLE is an almost ideal environment for testing this, since it permits different representations on the screen at the same time.

Work with MBL tools has shown that its success is dependent on promptness. The graph must be displayed at essentially the same time as the event is occurring. How will this work when video measurement is used? In this case the event is "frozen" -- recorded. It can be shown many times or in "instant replay" slow motion. Can the video serve a similar purpose as the MBL in helping students to learn to translate between the physical world and graphical representations? And if it can, does the timing of the link between the event and the graph remain and important factor?

CUPLE will also be useful for studying how a student's preferred learning style affects his or her learning. Is it best to work with a student's strength at first in order to establish the basic concepts firmly? Or is it better to work on their weaknesses so they develop a more balanced approach? It is very difficult to address questions like these with significant numbers of students in a paper and pencil environment. In the CUPLE environment students could be given a variety of choices for emphasizing different approaches: solve this algebraically, work with a graph, use video or real world data. If tracking were added, we could follow the students' choices and see the impact on their learning.

7. The Evolution of the Curriculum

Even though significant changes in how physics can be taught are beginning to be possible, and evidence regarding their effectiveness is beginning to accumulate, there will still be major barriers to getting widespread adoption of new teaching ideas. Physics has changed significantly since the modern introductory physics course was set up at the beginning of this century (see for example Millikan's work, Ref. [16]), but the teaching of physics has changed very little.[16]

A particularly stark contrast exists between the drastic changes in physics as practiced and the nearly stagnant way physics is taught. This contrast exists both with regard to content and tools. Modern professional approaches, such as numerical calculations, symbolic manipulation, and the use of off-the-shelf modular experimental apparatus, are rarely introduced at the introductory level. Since most of our students never take courses beyond that level, they are never exposed to

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[16] There have been changes since then, but Robert Millikan's 1902 course [16] is remarkably similar to what is taught today. The overlap in content (excluding electromagnetism which is not covered in Millikan's text) is approximately 75%.

them. This severely distorts the way the students view what physics is and isolates them from many powerful ideas and methods[17] that could positively affect the way they think about their own profession and broaden their skills significantly.

7.1. Why is it so difficult to change the way we teach?

If we want to make a change in the way physics is taught, we encounter what appears to be a structural problem. The content and method of physics teaching, especially at the introductory level, have been too slow to change. Those changes that have occurred in our teaching have been primarily along the lines of emphasis. Two observations on the evolution of physics teaching are important.

- Changes in physics education appear to occur via a "stick-slip" or "punctuated equilibrium" mode. That is, they happen in sudden jumps with long periods of stability.
- Only a very small fraction of physics teachers contributes to the development of educational innovations.

These contrast strongly with the evolution of physics content by researchers. Although sudden changes ("paradigm shifts" [9]) occasionally appear to occur in physics, most of the time the system evolves in a reasonably steady manner, with new physics being continually learned and adopted by the community. [18] Furthermore, a much larger number of physicists produce cumulative contributions to the research effort than to the educational system.

Why does this happen? One might conjecture that there is no problem in physics education and that therefore nobody needs to work on it. But there is increasing evidence of dissatisfaction with the traditional approach. [8] One might conjecture that few people are interested in innovative teaching. But our personal experience shows that although many physics faculty teach innovatively, very few publish their results, methods, and materials, and the accumulation of innovations among teachers is rare, even within a single college or university.

We believe that part of the problem is in the mechanisms present in the system for accumulating knowledge. In the research arena, the traditional method of presenting results is by publishing papers in a research journal. Dozens of such journals exist and more than ten thousand physics research papers are published every year. In the educational arena, the critical products are materials, not research papers of educational methods.[18] Essentially all of the materials used in physics teaching are in the form of textbooks. The number of new physics textbooks (not updated edi-

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[17] Some of the important developments that are not included in the introductory physics course are: the discovery that the basic laws of the universe are not classical but quantal in character; the understanding of the microscopic structure of matter and how that structure determines the properties of materials; the way phase transitions occur; the fact that "classical" does not mean "predictable"; and many others.

[18] Very few research papers on physics education are produced in a year and they are read by a very small fraction of the physics community.

tions of old books) per year is on the order of ten. Furthermore, innovative textbooks appear rarely, and when they do, they usually have short lifetimes.

Part of the problem appears to be the difference in modularity. Physics research papers rarely create an entire field in one fell swoop. They do so a step at a time. Researchers can adopt new approaches in small bites. Furthermore, the effort to produce a research paper is an order of magnitude smaller than the effort to produce a textbook. A typical active physics researcher may produce two papers per person per year. A typical physics text may take two people five years to produce, or 0.1 papers per person per year. This represents a difference in effort ratios of a factor of 20. Although other important issues (such as the relative difference in prestige or reward for the two activities) cannot be addressed by using a computer, the issue of modularity can be.

7.2. Tools for the developer:

CUPLE is set up to be a modular environment that can be modified or extended by the teacher. In addition to the materials produced for students, the CUPLE prototype includes a basic set of developer's tools. These include the CUPLE linking engine and a set of tools to simplify the construction of linked books.

7.2.1. The CUPLE engine

Producing an open-ended hypermedia system is a substantial challenge. Each unit links to many others, so replacing or adding a new unit can have a "ripple effect" that could produce bugs in many other units. To prevent this from happening, we have developed a management tool for the CUPLE system that keeps track of and manages all calls between files. This is the heart of the system and is responsible for its flexibility and power. The developer can link new units to the system in a simple way.

7.2.2. Linking tools

The authoring environment might be referred to as a "physics processor". The author simply brings up the CUPLE template under the ToolBook hypermedia system, selects author mode, and begins to type. The author can use the standard ToolBook palettes to add new text fields, graphics, colors, or buttons to the page. The CUPLE extensions to the standard menu allow the author to select Video, WinPhys, Laboratory, MBL (data acquisition), Demos, or String-and-Stickytape and the appropriate icon and code are added to the book. The author is prompted to enter the name of the specific video clip or program and the functionality necessary to do this is automatically added to the page.

7.3. The implications of an open system

We refer to the difficulty of producing educational materials in the current publishing environment as "the textbook lock". Educational materials are most conveniently delivered today as textbooks. This causes two problems. Firstly, the effort to produce a textbook is very large, reducing the number of individuals who might contribute innovations. Secondly, in a highly competitive publishing environment, there is great pressure on publishers and from publishers to produce texts that will capture a significant fraction of the market. This leads to pressure from publishers on textbook writers to imitate the most successful books. The result is a large number of books that differ little in content, arrangement, point of view, or types of problems included.

From the point of view of the social construction of knowledge, perhaps the most important innovation of the CUPLE system is that it is designed to be open. CUPLE is an environment that lets a teacher easily modify existing material or add additional material of his or her own. The CUPLE engine is a database that contains tools for linking and finding links. By following the modularized idea inspired by object-oriented programming, we have built a structure in which the interactions of the parts are tightly controlled and monitored by the CUPLE engine.

This tight control opens the system for growth and cumulation. Once the first CUPLE course is complete, we hope to establish CUPLE as a publishing environment -- one in which teachers using it could develop and submit modules for peer review, testing, and incorporation into the full system.

The open structure of the system and the unprecedented modularization of the learning environment should permit many more teachers to add their contributions to an ever-growing and evolving structure, one that can embody a vision of the future that uses computer technology to put new power into the hands of both student and teacher.

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