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ABSTRACT

This paper considers what physics can offer students, both as physics majors and in other sciences. The recent increases in the technological character of the workplace appear likely to continue, leading to increasing numbers of individuals who should learn something about science. For many of these people, understanding the character of science, including learning new ways to think about and analyze the physical world, is an essential component of what they need to learn. In the next few years, there will be a need to figure out exactly what can be usefully taught and how to do it effectively in the short time that students are in a physics class. The critical information for this discussion comes from a careful consideration of what it means to think about and understand science and from careful observations of the actual thinking processes of incoming physics students. (Contains 25 references.) (Author/DDR)

WHO NEEDS TO LEARN PHYSICS IN THE 21st CENTURY – AND WHY ?

EDWARD F. REDISH

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ABSTRACT

In this talk I consider what physics can offer to students, both as physics majors and in other sciences. The recent increases in the technological character of the workplace appear likely to continue, leading to increasing numbers of individuals who should learn something about science. For many of these people, understanding the character of science, including learning new ways to think about and analyze the physical world, is an essential component of what they need to learn. In the next few years, we will need to figure out exactly what we can usefully teach them and how to do it effectively in the short time they are in a physics class. The critical information for this discussion comes from a careful consideration of what it means to think about and understand science and from careful observations of the actual thinking processes of incoming physics students.

1. PERSPECTIVE: SETTING THE HISTORICAL FRAME

When Columbus returned from his journey of discovery, bringing six Caribbean natives back to Spain in 1493, in the era when the modern shape of Spain was being formed, the grand journey of science was just beginning. Copernicus had not yet penned his monumental work on the shape of the solar system and Galileo was not yet born. Over 95% of all people in Europe worked in agriculture. By the year of my grandfather's birth in Europe in the year Maxwell wrote down his equations (1865), the discoveries of science had begun to change people's lives. The development of thermodynamics and the steam engine led to the railroad and the steamship that made my grandfather's travel to America as a young man possible. In between the times that Antoni Gaudi designed the Güell palace (1885) and the Casa Mila (1906) the automobile had become important enough — at least for the wealthy — to prompt him to redesign the basement as a parking garage instead of as a stable. By the year of Gaudi's death in Barcelona (1926), ordinary folk were buying automobiles, including my father's family. At the time of my birth in America during the Second World War, most families had automobiles and electricity, but there was no television, computers, or internet, and we were uncertain about the number of chromosomes in a human cell.

In this year of GIREP 2000, the first draft of the human genome has been completed and I was able to send an electronic message to Korea for delivery in less than a second from the Madrid airport. Today, fewer than 5% of the population in Europe and America work on farms.

One element you might perhaps have noticed from this brief chronicle is the increasing pace of change. The increase of knowledge of the physics of matter led to new tools for probing the world which led to new understandings which led to new tools, which ...and so on. This positive feedback system has led to an accelerating ability to probe, describe, and understand more complex systems. Within the past 50 years — partly as a result of tools and a knowledge base built in physics — many new sciences have grown to a robust maturity, including

- chemistry
- biology
- materials science
- information science.

The growth of science

In one sense, the growth of these other sciences is putting pressure on physics. Despite incredible opportunities for new research, physics departments around the world are beginning to have some difficulty recruiting the best students into physics. In some countries, the number of physics majors has stopped growing, in others it has begun to decline.

By many measures, science — and physics in particular has grown exponentially since about 1750. This is illustrated in figure 1 (taken from Goodstein's provocative article on the future of physics [1]). But in the USA, the exponential growth in the number of PhDs granted in physics stopped in about 1970. For the past 30 years, we have been in a static period, where we tend to over-react to small increases or decreases in the number of physics students.

Despite the slowing in the growth of physics, in the USA, the total number of scientists has doubled in the past 20 years and, what is more important, it has nearly doubled as a fraction of the workforce, as shown in figure 2 from a recently published study of the US NSF [2].

The largest component of the recent growth in the number of scientists has been in biology, which has seen huge increases in the funding for research in the USA in the past 20 years, especially in the area of health care. The distribution of scientists in the USA by profession is shown in figure 3 [2]. Within the first half of the 21st century, it is reasonably conservative to predict that biology, information science, and materials engineering will see the most growth and activity.

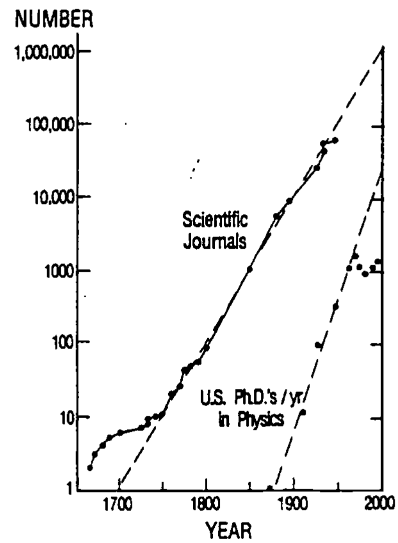

Figure 1 : The exponential growth of science and the saturation of physics in about 1970.[1]

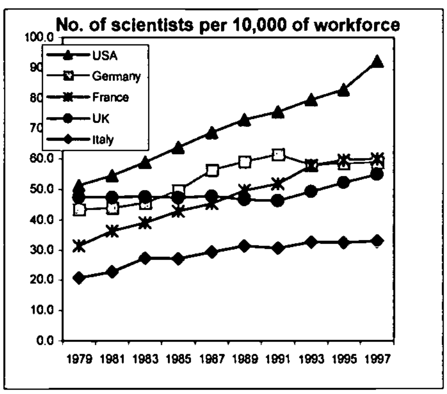

Figure 2 : The number of scientists per 10,000 workers in the USA and some selected European countries.[2]

The growth of technology in the workplace

Science is having an impact on the workforce at many levels. Although there are more scientists than there used to be (indeed, one may easily estimate that a majority of all the scientists in the history of the world today are alive now), we can see from figure 2 that they are still a fairly small fraction of the total workforce (about 1%). But technology and science are having an impact on a much broader section of the workforce. Many workers use high-tech tools without understanding them adequately.

But perhaps those workers don't really need to know much science to be able to use technology. Why can't we just give them instructions on what to do (*i.e.*, specify procedures and protocols)? Although it is important to do this, it doesn't work as well as we might hope. People are not machines. People make errors. Further, people make choices. Workers who do not understand the reasons for procedures are much more likely to be sloppy about them or to ignore them in times of stress. Last year, workers at a Japanese nuclear power plant violated protocols and safety regulations "in order to transport uranium more easily" and wound up producing a near critical mass. The resulting radiation injured hundreds and caused the death of two of the workers. In the USA, dental hygienists responded to a malicious rumor that dark skin "blocked x-rays" and wound up giving dark-skinned patients unnecessarily large doses of radiation. Many more such examples could be cited in which technical workers' lack of scientific knowledge resulted in death, injury, or harm. As technology plays an increasing role in our everyday lives, such incidents are sure to increase.

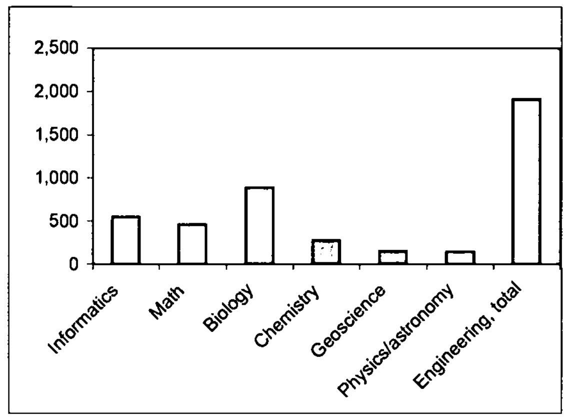

Figure 3 : The number of scientists by area of research in the USA (1997) in thousands.[2]

Rethinking the role of physics in education

This growth of science and technology leads us to consider two questions. First, given that in the 21st century an increasing proportion of the workforce will need to be trained scientifically we can ask:

What should the role of physics be in the education of scientists and technical workers?

Second, given the increasingly technical nature of the workplace, an increasing proportion of non-scientists will need some scientific training, we can ask:

What should the role of physics be in the education of non-scientists?

Both questions are very important. In my own research, I have chosen to work mostly on issues related to the first question. In this talk, I will therefore focus most of my discussion on pre-professional training of scientists and engineers in introductory university physics.

In the USA, the role of physics in training professionals in the new sciences is in flux. Engineers traditionally take 1 to 1.5 years of university physics. But pressures on engineering departments to include instruction on modern topics lead to pressures to eliminate some of the traditional courses. Many universities that have offered three semesters of physics are being asked to cover the same topics in two. New national engineering standards (ABET 2000) open the possibility of eliminating physics for some engineers or having it taught outside of physics departments.

Pre-medical students and biologists traditionally study one year of physics at university in the USA but success in physics shows no correlation with success in medical school. Will the need to include the rapidly growing new content in biology also lead to pressures to drop physics? Perhaps not, since many leading biologists are deeply aware of the need for physics in the "new biology"[3]. Nonetheless, we have a strong obligation to understand these students — what they need to know and what we can effectively teach them.

2. NEW OPPORTUNITIES: WHAT DOES PHYSICS HAVE TO OFFER?

The growth of science and the need for educating a larger population in science offers a tremendous opportunity for physics educators. After all, isn't physics the best place to start really learning what science is about and how to do it? To make our case for the value of physics in the education of scientists and engineers, we have to both explain why we think learning physics is valuable and document that we can add that value.

Numerous studies [4] show that training as a physics major is of considerable value in a wide variety of professions. Abilities such as

- complex problem solving
- physical modeling
- estimation

and other general skills can be of great value in a wide variety of professions ranging from biology to financial modeling. Physicists have made numerous contributions to other fields of science including many Nobel prizes in fields not now considered to be "physics" (DNA, transistors, CT scan, patch clamping,...)

While a physics bachelor's degree or a PhD may be of great value, it is by now well documented that even physics majors do not gain a solid understanding of introductory physics in their first college physics course [5][6]. They develop that understanding through repeatedly treating the subject from different angles and from eventually teaching it. However, other scientist and engineers may take only one year of physics. This leads us to ask the following question.

Is the first step in the multi-step process of physics education of significant value for students in other sciences?

Can much of lasting value be accomplished in a one- year course? Typically, my engineering and biology students memorize lots of problems and can replay anything they've seen before, but they often can't do any problem they haven't seen — even if the changes are small. Many of my students can solve a problem mathematically but can't tell me what the problem is about, or what the answer means. Is there any value to the skills obtained at this level? Many students remember little physics after the course is over.

The apparent inconsistency in what students appear to do suggests we have to think more carefully about what we are trying to accomplish. To reiterate the point made so strongly by GIREP President Manfred Euler in his keynote speech earlier in the conference: If we want to understand what elements to look for and what to try to evaluate, we need to understand something about how students think.

3. THE PROBLEMS OF TEACHING AND LEARNING

If we want to understand both what we have to offer and why what we traditionally offer only has limited success, we need to treat the problem of teaching and learning in the same way we do any research problem: using observation, analysis, and modeling.

For about the past 20 years, researchers have carried out numerous studies of how children and adults learn physics, with much of the activity occurring in Europe, America, and Israel [5]. In the USA during the past decade, a growing community of physicists are joining forces with education specialists to study university level physics learning for the purpose of developing a better understanding of the goals we want to achieve and in order to develop learning environments that help us achieve them [7].

A Model of Learning

As with any physical system it helps to begin with some model of how it functions. The fundamental model I like to use has been built by the interaction of three kinds of scientific research: phenomenological observations of normal behavior, careful studies of responses to highly simplified experiments designed to get at basic issues, and neurological studies of how the brain works and breaks — through electromagnetic probes of brain function during different activities and through studies of the effects of brain injury.

The critical issue for teaching and learning is memory. A partial map of the structure of memory that has been developed by cognitive and neural scientists is sketched in figure 4.

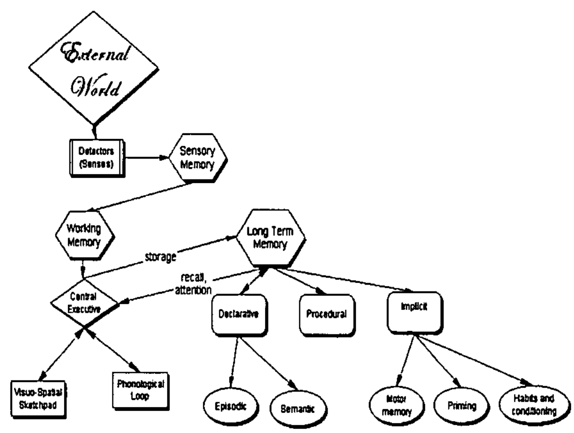

Figure 4: A partial model of structures in memory. (Adapted from Baddely [8] and Squire and Kandel [9].)

For those of us interested in teaching, a few fairly simple ideas may suffice. There are two main components to memory: working memory, a fast storage of small size and short (few seconds) decay time, and long-term memory, a slow storage of very large capacity that may last for many years.

A few principles briefly describe some characteristics of long-term memory that help us better understand the responses of students.

1. Long-term memory can exist in (at least) 3 stages of activation: inactive, primed (ready for use), and active (immediately accessible).
2. Memory is associative and productive. Activating one element leads (with some probability) to the activation of associated elements.
3. Activation and association are context dependent. What is activated and subsequent activations depend on the context, both external and internal (other activated elements).

To help clarify the ideas of activation and association, let me give two brief examples. At this meeting, I met a young researcher whom I had first encountered two years ago at another conference. When I first looked at him, I knew he was familiar but could not place him. But I associated him with the earlier conference and through bringing up the memory of events at that meeting, I could reasonably quickly recall his first name, but his family name continued to escape me. As we engaged in conversation, after about two minutes, his family name suddenly appeared in my mind. Both names were in my long-term memory, but they were associated with different chains of association and took different amounts of time to activate. If I had not met him at a physics meeting but encountered him at an airport, for example, I might have had serious difficulties remembering who he was without further hints.

As a second example, consider a physics equation such as Newton's second law, which I write as shown in Eq. (1):

$$\vec{a} = \frac{1}{m}\vec{F}_{net} \tag{1}$$

In this equation, the small vectors over the symbols prime for me a large series of vector tools, which are then immediately available. The entire package of coordinate and vector manipulation structures do not appear in my working memory, but are ready for quick and easy access whenever I need them.

A fourth dynamical principle reminds us that, except in extraordinary circumstances, learning takes repetition with appropriate time delays.

4. Learning is a growth, not a transfer.

In order to see how these ideas play out in physics classes, let's consider an example to show what I mean by the statement "memory is productive." The idea is that recall from long-term memory is not just a replay of previously recorded data. It's more like the sine function in your calculator. The calculator doesn't store a huge table of previously calculated numbers; it stores a small piece of code that allows it to calculate the sine of any angle using a procedure. That our brain works this way is reasonably clear. I can identify the object you are holding as a book from the pattern of sensory response pixels on my retinas, isolating and separating it from neighboring pixels and building it into the image of a book, even though I may have never seen that particularly book before at that particular angle on that particular part of my retina. Clearly, some generalized pattern is being used in this interpretation, not a match against a large set of previously seen images. In physics problems, students reason to a conclusion using things they know from experience even in novel situations [10].

The problem shown in figure 5 was given by Lillian McDermott's group at the University of Washington to students in their engineering physics class [11].

When monochromatic laser light is shone on a pair of slits, this pattern is produced on a distant screen.

What would happen to the pattern if one of the slits were covered?

Figure 5: A problem given to students in engineering physics at the University of Washington. (Since the interference arises from the waves from the two slits interfering with each other, the pattern would go away and be replaced by an almost uniform brightness.)

Even after instruction, more than half of the students expected part of the pattern would remain. Some said the left half of the lines would remain. Some said every other line would remain. Clearly, they are not "remembering" this result, since this is not what happens. Rather, they are making analogs to other situations they have seen (such as, perhaps, with light and shadow situations where interference effects are not noticeable) and reasoning using remembered general principles. (I conjecture a plausible one that might be working here is "a reduced cause leads to a reduced effect.")

A second example illustrates the implications of the context dependence of recall. Steinberg and Sabella asked two equivalent questions on Newton's first law to students in engineering physics at the University of Maryland [12]. In both, the students were asked to compare the forces acting on an object moving vertically at a constant velocity. One question was phrased in physics terms using a laboratory example ("A metal sphere is resting on a platform that is being lowered smoothly at a constant velocity..."). The other was phrased in common speech using everyday experience ("An elevator is being lifted by a cable...") In both problems, students were instructed to ignore friction and air resistance.

On the physics-like problem, 90% of the students gave the correct answer that the normal force on the sphere is equal to the downward force due to gravity. On the everyday problem, only 54% chose the correct answer: the upward force on the elevator by the cables equals the downward force due to gravity. More than a third, 36%, chose a common misconception: the upward force on the elevator by the cables is greater than the downward force due to gravity.

A strong context dependence in student responses is very common, especially when students are just beginning to learn some new physics. Students are unsure of the conditions under which rules they have learned apply and they use them either too broadly or too narrowly. Students often treat quite differently problems that look equivalent to an expert.

Some cognitive goals

Given this rudimentary cognitive framework, we may consider more broadly what we want our students to get out of our physics courses. First, we want our students to have strong core elements in their long-term memory. Second, we want them to organize that memory in a coherent way, both so that patterns of activation lead to an overall consistent structure and to activation in appropriate circumstances.

In less cognitive terms, we may restate these goals as: In addition to having students master the physics content, we also want them to have a good understanding of the basic physics concepts (see the physics as "making sense") and to organize their knowledge functionally (develop a coherent and consistent view of the physics they are learning so they can use it effectively). Additional goals are possible, but this gives an idea of the role a (sometimes implicit) cognitive model plays in setting goals. Furthermore, these are two areas in which there has been significant research.

4. RESEARCH RESULTS: WHAT HAS BEEN LEARNED?

General cognitive goals are particularly important for students who will not go on to study more physics. Traditional evaluations often focus on superficial recall of content and miss these broader goals. We have to develop ways of testing our students that test not just the presence of the correct concepts, but their robustness in a variety of contexts.

Evaluating Concept Learning: The Force Concept Inventory (FCI)

One example of a standardized test designed to probe the robustness of student concept learning is the Force Concept Inventory (FCI) [13]. This is a 30 item multiple choice probe of student's understanding of basic concepts in mechanics developed by David Hestenes and his collaborators. The choice of topics is based on careful thought about the fundamental issues in mechanics. But the critical element is that the distractors (wrong answers) are based on research that probes the students' most common responses. When physics faculty consider these questions, they often consider them trivial — "too easy for my students". When students look at them, the distractors are often so close to what they really think that they choose them, even though they may know the "official physics" answers. The real-world contexts of most of the items encourage them in this. An example is shown in figure 6.

Imagine a head-on collision between a large truck and a small compact car. During the collision:
–(A) the truck exerts a greater amount of force on the car than the car exerts on the truck.
–(B) the car exerts a greater amount of force on the truck than the truck exerts on the car.
–(C) neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck.
–(D) the truck exerts a force on the car but the car does not exert a force on the truck.
–(E) the truck exerts the same amount of force on the car as the car exerts on the truck.

Fig. 6: An item from the Force Concept Inventory.[13]

Few physics professors writing a multiple-choice item would include a choice like (C): "neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck." Yet many students respond this way in interviews and about ¼ of a class of university physics students will typically select this choice.

Overall, traditional classes at the university level in the USA typically begin with scores ~30-50% correct on the FCI. A collection of pre and post-instruction results from 60 classes by Dick Hake [14] shows that across a wide range of classes the fraction of the possible gain is similar for classes of a similar structure.

$$h = \frac{(posttestaverage - pretestaverage)}{(100 - pretestaverage)} \qquad (2)$$

For traditional classes $h \sim 0.20 \pm 0.05$, so classes entering with a 50% average tend to leave with a 60% average.

This is rather disappointing, especially on a test that most physics faculty would agree (1) deals with basic conceptual issues and (2) students who understand the material should score in the 90%s. What can we do to improve this situation?

Research-Based Curriculum Design

One approach to designing curriculum to improve concept learning is to make use of the same sort of educational research to design the curriculum as was used to discover the difficulties. To make the most effective use of our partial knowledge about student learning, research-based curricula are developed on a research / redesign cycle of observation, development, application, and evaluation, all based on and informing a theoretical model of student learning. This cycle is illustrated in figure 7.

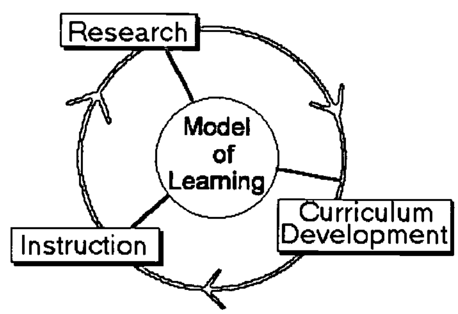

Figure 7: The research and redesign cycle for the development of reformed curricula.

In the USA over the past decade, about a dozen research groups have developed materials to modify part or all of instruction in introductory university physics [5]. I will mention four.

<u>Tutorials</u> (U WA, L. C. McDermott et al)—
These materials are intended to modify a one-hour small (N~25) class recitation each week. The rest of the class is usually traditional lecture (N ~ 50-300) and laboratory (N~25). The method uses group learning with carefully designed worksheets [15].

<u>Group Problem Solving</u> (U MN, P. and K. Heller)
This method also only modifies one hour of small class instruction per week (though at Minnesota the Hellers also modify laboratory and lecture classes as well). In the classes, students work in structured groups to solve "context-rich" (complex, real-world, and sometimes incompletely defined) problems [16].

<u>Physics by Inquiry</u> (U WA, McDermott et al)
This approach modifies the entire structure of the class, teaching students in classes of N~25-30. There are no lectures. Students use a carefully structured activity guide to discover and apply physical laws in principles in a laboratory context. This class was developed for non-science

majors, especially pre-service teachers, and focuses on building a coherent understanding of physical ideas directly from observation with reasoning rather than with mathematics [17].

Workshop Physics (Dickinson College, P. Laws)
This approach is similar in structure to Physics by Inquiry, but focuses on science majors. A key element is the presence of sophisticated computer-assisted data gathering and modeling tools [18].

As part of a study to evaluate instruction in introductory calculus-based university physics [19] we gave the FCI before and after instruction in 1st semester university physics in 15 universities who used 4 instructional models:

traditional (lecture) with recitation
traditional (lecture) with tutorials
traditional (lecture) with group problem solving
workshop physics.

We observed both primary and secondary implementations of group problem solving and workshop physics. Only secondary implementations of tutorials were observed.

The research-based curricula showed improvement in concept learning as measured by the FCI.

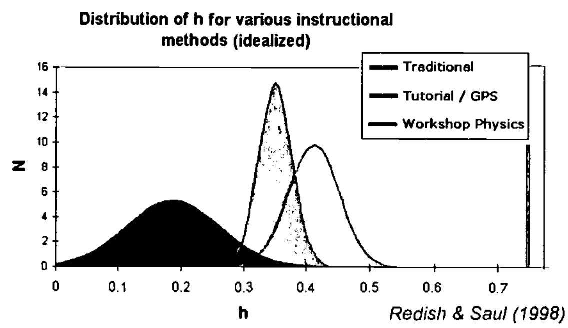

Fig. 8: The distribution of the fraction of possible gains on the FCI in four different instructional methods [21].

The results are

$h \sim 0.20 \pm 0.03$	traditional
$h \sim 0.34 \pm 0.01$	recitation modifications (tutorials and group problem solving)
$h \sim 0.41 \pm 0.02$	Workshop Physics (secondary implementations)
$h \sim 0.73$	Workshop Physics (Dickinson College)

The distribution of results are shown in figure 8 [20]. For ease of interpretation, the histogram of h values for each type of instruction is fit by a Gaussian adjusted to match the mean and standard deviations of the distributions. The Gaussian is then normalized. The distributions for *Tutorials* and for *Group Problem Solving* were similar and therefore combined.

We can draw a number of tentative conclusions from these studies.

- By paying attention to what students know and how they learn, it is possible to create educational environments that result in much more effective concept learning than can be obtained with traditional methods.
- These methods do not necessarily take additional time. (Changing one hour / week can double the gains.)
- Algorithmic problem solving is not deteriorated — but is usually not much improved. (This last point has not been documented here but is explored in great detail in the dissertation research of Saul [19] and Sabella [21].)

Evaluatiug Connections :
The Maryland Physics Expectations Survey (MPEX)

The second cognitive goal I proposed earlier was to help students to organize their scientific knowledge in a coherent way. This is a more complex issue than concepts and more difficult to evaluate. Students continually make judgments as to what information to use and what is relevant. (These decisions are not necessarily conscious ones.) What determines what they look for?

Students entering a physics class not only bring in to the class knowledge of what to expect of the physical world, they bring a whole set of expectations as to the nature of the knowledge they are going to learn and what they have to do to learn it. The expectations they bring are often barriers to the kind of coherent and organized learning we hope they will achieve. For example:

- Some students believe that physics consists of unrelated "facts".
- Some students believe that they don't need to understand why we believe something in physics is true — just that it is.
- Some students believe that they don't need to understand the meaning behind an equation — just to use it to calculate the "right" number.

The best way to determine how students use their scientific knowledge is to observe them actually doing science — reasoning through a wide variety of problems and situations. Unfortunately, this is both time consuming and difficult. Often, interviews are required since what students write in response to exam and homework problems is often incomplete and does not display their underlying reasoning (even when they are asked to give it).

To get a "quick and dirty" probe of student expectations, we have developed a survey instrument: The Maryland Physics Expectations (MPEX) Survey [19][23]. Our goal is to make some crude first measure of the distribution and evolution of students' cognitive attitudes — beliefs that have an effect on what they learn in a physics class. The MPEX contains 34 statements with which students are asked to agree or disagree on a 5-point scale. The MPEX includes items probing the following variables

- independence / authority
- coherence / pieces
- concepts / formulas
- reality link (relation to everyday experience)
- math link (connection of math to meaning)

The MPEX has been delivered at more than 20 colleges and universities to more than 5000 students and has been translated into Chinese, Flemish, Turkish, Spanish, Italian, and Finnish.

The MPEX contains statements like:

In this course, I do not expect to understand equations in an intuitive sense. They just have to be taken as givens. [student should disagree]

Expert physics educators agree on the preferred polarities of the MPEX items [agree or disagree] at the 90% level. (Those who disagree with this prevailing view don't disagree with the desirability of the expert polarity but with the need to develop that view in the introductory physics class.) When students agree with our experts we consider their responses "favorable"; when they disagree, "unfavorable". Students' responses are obtained before (pre) and after (post) a class. Only students who take both the pre and post survey (matched) are included.

In typical first-semester calculus-based engineering classes, students give favorable results on the MPEX items about 65% of the time. After one semester of instruction, this typically falls to about 55%. These results are very robust and difficult to change with small modifications of a traditional approach [23].

An example of a specific MPEX result is displayed in figure 9. The fraction of students agreeing with the experts on the five items of the coherence cluster is plotted on the ordinate; the fraction disagreeing with the experts is plotted on the abscissa. Since the students must either agree, disagree, or be neutral, the x and y values must add up to less than 100%: therefore, each point must lie within the triangle formed by the x-axis, the y-axis, and the line descending from (0%,100%) to (100%,0%). The distance from this line measures the fraction of students not answering or neutral.

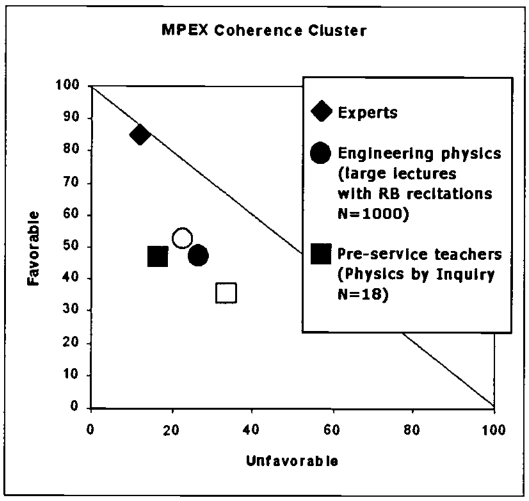

Fig. 9: Results for the MPEX coherence cluster from first semester engineering physics classes using traditional lecture / lab + research-based(RB) recitations and a class of pre-service teachers instructed with Physics by Inquiry [23][24]. Open markers represent pre-instruction; filled markers post-instruction.

On the items of the coherence cluster, the experts agree with the desired polarity of the items at the 85% level. This point is displayed by a diamond in figure 9.

Students at the start of the engineering physics class at two large public universities in the USA (N~1000) agree with the experts about 55% of the time at the beginning of the class (open circle) and deteriorate to about 45% at the end of the class (filled circle). This is a shift of about 2.5 σ. This result has been confirmed numerous times at many universities.

Unfortunately, these results are sufficiently new that there are no research-based curricula that have been designed to try to improve these results. There are, however, a few "existence proofs" that such curricula are possible. A recent report of MPEX results in a pre-service teachers' class using Physics by Inquiry [24] indicate that the mainly non-science students in the teachers' class start out extremely low on the coherence variable, only ~35% agreeing with the expert views and nearly 35% explicitly disagreeing with them (open square). As a result of one semester of instruction with Physics by Inquiry, the students improved rather dramatically (filled square). Results in some high school classes also indicate that carefully designed instruction can positively affect these measures [25].

From these studies, we suggest a number of tentative conclusions:

- Students' views about the nature of scientific knowledge and how to learn it are important in what they do in a physics class and in what they learn from it.
- University physics students (even engineers) start with some inappropriate views.
- Traditional instruction in introductory physics makes the situation worse.
- Research-based curriculum reform focused on concept learning does not help.
- Research-based instruction specifically focused on expectations issues can lead to significant improvements.

5. THE FUTURE: WHERE DO WE GO FROM HERE?

Both of the studies discussed above — on concepts and on coherence — strongly suggest that physics instruction as we normally deliver it does not necessarily help our students develop the knowledge, skills, and attitudes that we hope they will learn as a result of our instruction. These studies also suggest that by conducting research on these issues and by reforming our curriculum in conjunction with this research that we can make substantial improvements in what our students learn.

This sets a frame for expanding our concerns from what physics majors learn in their physics curriculum over many years to what all students learn in their physics courses, even when those courses may be their only instruction in physics .

Let's return to the question I asked in the title. Who should study physics in the 21st century? Answer: Everyone, especially those who will develop or apply science and technology in their careers. The increasing role science and technology have in our lives and work offers an immensely valuable opportunity for placing physics at the core of university education in the 21st century. But to put it there, we have to better understand the goals of our instruction and the means for achieving those goals. Treating our instruction as a scientific research problem can be an important component of maintaining the broad value of physics for all sciences.

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