Student expectations in introductory physics[a)]

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Students' understanding of what science is about, how it is done, and their expectations as to what goes on in a science course, can play a powerful role in what they get out of introductory college physics. In this paper, we describe the Maryland Physics Expectations survey; a 34-item Likert-scale (agree–disagree) survey that probes student attitudes, beliefs, and assumptions about physics. We report on the results of pre- and post-instruction delivery of this survey to 1500 students in introductory calculus-based physics at six colleges and universities. We note a large gap between the expectations of experts and novices and observe a tendency for student expectations to deteriorate rather than improve as a result of the first term of introductory calculus-based physics.

I. INTRODUCTION

What students expect will happen in their introductory calculus-based (university) physics course plays a critical role in how they respond to the course. It affects what they listen to and what they ignore in the firehose of information provided during a typical course by professor, teaching assistant, laboratory, and text. It affects which activities students select in constructing their own knowledge base and in building their own understanding of the course material.[1] The impact could be particularly strong when there is a large gap between what the students expect to do and what the instructor expects them to do.

This paper explores student attitudes and beliefs about university physics and how those attitudes and beliefs change as a result of physics instruction. In this paper, we present the *Maryland Physics Expectations* (MPEX) *survey*, a Likert-style (agree–disagree) questionnaire we have developed to probe some aspects of what we will call student expectations. We have used this survey to measure the distribution of student views at the beginning and end of the first semester of calculus-based physics at six colleges and universities. The survey items are included as an Appendix.[2]

Because so little is known about the distribution, role, and evolution of student expectations in the university physics course, many questions can be asked. To limit the scope of this paper, we restrict ourselves to three questions.

Q1. How does the initial state of students in university physics differ from the views of experts?
Q2. To what extent does the initial state of a class vary from institution to institution?
Q3. How are the expectations of a class changed as the result of one semester of instruction in various learning environments?

Other questions, such as what happens over the longer term and how items of the various clusters correlate with each other and with success in the course, are left for future publications.

We begin by reviewing previous work on the subject in Sec. II. The structure and validation of the survey are described in Sec. III. Section IV contains the results of the survey for five calibration groups, ranging from novice to expert. The results of our survey with students are presented in Sec. V, and Sec. VI discusses the implications of our work.

II. BACKGROUND AND REVIEW OF PREVIOUS WORK

A. Recent progress in physics education: Concepts

In the past 15 years, there has been a momentous change in what we know about teaching and learning in the introductory calculus-based physics course. Beginning about 1980, research began to show that the traditional class leaves most students confused about the basic concepts of mechanics.[3] Subsequent work extended those observations to other areas including optics, heat and thermodynamics, and electricity and magnetism.[4] In studying student understanding of the basic concepts of physics, much has been revealed about what students know and how they learn. The crucial element is that students are not ''blank slates.'' Their experience of the world (and of school) leads them to develop many concepts of their own about how the world functions. These concepts are often not easily matched with those that are being taught in physics courses, and students' previous conceptions may make it difficult for them to build the conclusions the teacher desires. However, it has been demonstrated that if this situation is taken into account, it is often possible to provide activities that induce most of the students to develop a good functional understanding of many of the basic concepts.[5]

Success in finding ways to teach concepts is an excellent start (even though the successful methods are not yet widespread), but it does not solve all of our teaching problems with physics. We want our students to develop a robust knowledge structure, a complex of mutually supporting skills and attitudes, not just a patchwork of ideas (even if correct). We want them to develop a strong understanding of what science is and how to do it. We want them to develop the skills and confidence needed to do science themselves.

B. Student expectations

It is not only physics concepts that a student brings into the physics classroom. Each student, based on his or her own experiences, brings to the physics class a set of attitudes, beliefs, and assumptions about what sorts of things they will learn, what skills will be required, and what they will be expected to do. In addition, their view of the nature of scientific information affects how they interpret what they hear. In this paper, we will use the phrase *expectations* to cover this rich set of understandings. We focus on what we might call students' *cognitive expectations*—expectations about their understanding of the process of learning physics and the structure of physics knowledge rather than about the content of physics itself.

Our model of learning is a growth model rather than a knowledge-transfer model.[6] It concentrates on what happens in the student, rather than what the teacher is doing. We therefore have chosen to focus our study on cognitive attitudes that have an effect on what it is students choose to do, such as whether they expect physics to be coherent or a loose collection of facts. The specific issues our survey covers are discussed in detail in the next section. Other issues, such as students' motivation, preferences, feelings about science and/or scientists, etc., are important but have been probed extensively elsewhere.[7]

Although we don't often articulate them, most physics instructors have expectation-related goals for their students. In our university physics course for engineers and other scientists, we try to get students to make connections, understand the limitations and conditions on the applicability of equations, build their physical intuition, bring their personal experience to bear on their problem solving, and see connections between classroom physics and the real world. We refer to this kind of learning goal—a goal not listed in the course's syllabus or the textbook's table of contents—as part of the course's ''hidden curriculum.'' We are frustrated by the tendency many students have to seek ''efficiency''—to achieve a satisfactory grade with the least possible effort—often with a severe unnoticed penalty on how much they learn. They may spend a large amount of time memorizing long lists of uninterpreted facts or performing algorithmic solutions to large numbers of problems without giving them any thought or trying to make sense of them. Although some students consider this efficient, it is only efficient in the short term. The knowledge thus gained is superficial, situation dependent, and quickly forgotten. Our survey is one attempt to cast light on the hidden curriculum and on how student expectations are affected by instruction.

C. Previous research on cognitive expectations

There are a number of studies of student expectations in science in the pre-college classroom that show that student attitudes toward their classroom activities and their beliefs about the nature of science and knowledge affect their learning. Studies by Carey,[8] Linn,[9] and others have demonstrated that many pre-college students have misconceptions both about science and about what they should be doing in a science class. Other studies at the pre-college level indicate some of the critical items that make up the relevant elements of a student's system of expectations and beliefs. For example, Songer and Linn studied students in middle schools and found that they could already categorize students as having beliefs about science that were either *dynamic* (science is understandable, interpretive, and integrated) or *static* (science knowledge is memorization-intensive, fixed, and not relevant to their everyday lives).[10] Alan Schoenfeld has described some very nice studies of the assumptions high schools students make about learning mathematics.[11] He concludes that ''Student's beliefs shape their behavior in ways that have extraordinarily powerful (and often negative) consequences.''

Two important large scale studies that concern the general cognitive expectations of adult learners are those of Perry[12] and Belenky *et al.* (BGCT).[13] Perry tracked the attitudes of Harvard and Radcliffe students throughout their college career. Belenky *et al.* tracked the views of women in a variety of social and economic circumstances. Both studies found evolution in the expectations of their subjects, especially in their attitudes about knowledge.[14] Both studies frequently found their young adult subjects starting in a ''binary'' or ''received knowledge'' stage in which they expected everything to be true or false, good or evil, etc., and in which they expected to learn ''the truth'' from authorities. Both studies observed their subjects moving through a ''relativist'' or ''subjective'' stage (nothing is true or good, every view has equal value) to a ''consciously constructivist'' stage. In this last, most sophisticated stage, the subjects accepted that nothing can be perfectly known, and accepted their own personal role in deciding what views were most likely to be productive and useful for them.

Although these studies both focused on areas other than science,[15] most professional scientists who teach at both the undergraduate and graduate levels will recognize a binary stage, in which students just want to be told the ''right'' answers, and a constructivist stage in which the student takes charge of building his or her own understanding. Consciously constructivist students carry out their own evaluation of an approach, equation, or result, and understand both the conditions of validity and the relation to fundamental physical principles. Students who want to become creative scientists will have to move from the binary to the constructivist stage. This is the transition that we want to explore.

An excellent introduction to the cognitive issues involved is given by Reif and Larkin,[16] who compare the spontaneous cognitive activities that occur naturally in everyday life with those required for learning science. They pinpoint differences and show how application of everyday cognitive expectations in a science class causes difficulties. Another excellent introduction to the cognitive literature on the difference between everyday and in-school cognitive expectations is the paper by Brown, Collins, and Duguid, who stress the artificiality of much typical school activity and discuss the value of cognitive apprenticeships.[17]

All the above-cited works stress the importance of expectations in how teens and young adults make sense of their world and their learning. If inappropriate expectations play a role in the difficulties our students commonly have with introductory calculus-based physics, we need to find a way to track and document them.

III. CONSTRUCTING THE SURVEY

A. Why a survey?

Our interactions with students in the classroom and in informal settings have provided us with preliminary insights into student expectations. As is usual in physics education research, repeated, detailed, taped, and transcribed interviews with individual students are clearly the best way of confirming or correcting informal observations and finding out what a student really thinks. The education literature contains particularly relevant transcripts of student interviews, especially in the work of David Hammer. In his Ph.D. thesis at Berkeley, Hammer followed six students throughout the first semester of their university physics course, tracking their progress through detailed problem-solving interviews. Each student was interviewed for approximately 10 h. The interviews were taped and transcribed, and students were classified according to their statements and how they approached the problems. However, conducting interviews with large numbers of students would be prohibitively expensive, and they are unlikely to be repeated at many institutions. Interviews therefore cannot yield information about the distribution of student expectations in a large population. In order to study larger populations, a reliable survey is needed which can be completed by a student in less than half an hour and analyzed by a computer. We developed the Maryland Physics Expectations (MPEX) survey to meet this need.

B. The development of the MPEX survey

We began to develop the MPEX survey in the Autumn of 1992 at the University of Washington. Students in the introductory calculus-based physics class were given a variety of statements about the nature of physics, the study of physics, and their relation to it. They rated these statements on a five-point Likert scale from strongly disagree (1) to strongly agree (5). Items for the survey were chosen as a result of a detailed literature review, discussions with physics faculty, and our combined 35 years of teaching experience. The items were then validated in a number of ways: by discussion with other faculty and physics education experts, through student interviews, by giving the survey to a variety of ''experts,'' and through repeated delivery of the survey to groups of students.

The MPEX survey has been iteratively refined and implemented through testing in more than 15 universities and colleges during the last four years. The final version of the survey presented here has 34 items and typically takes 20–30 min to complete. We report here on the results of the MPEX survey given at six colleges and universities to more than 1500 students. These institutions are listed in Table I. All students were asked to complete the survey during the first week of the term[18] (semester or quarter) and at the end of the term.

In the rest of this section, we describe how we chose the items of the survey and how we validated it.

Table I. Institutions from which first semester or first quarter pre- and post-instruction survey data were collected. All data are matched; i.e., all students included in the reported data completed both the pre- and post-instruction surveys.

Institution	Instructional characteristics	*N*
University of Maryland, College Park (UMCP)	traditional lectures, some classes with group-learning tutorial instead of recitation, no lab	445
University of Minnesota, Minneapolis (UMN)	traditional lectures, group-learning research-designed problem solving and labs	467
Ohio State University, Columbus (OSU)	traditional lectures, group-learning research-designed problem solving and labs	445
Dickinson College (DC)	Workshop Physics	115
a small public liberal arts university (LA)	Workshop Physics	12
a medium sized public two-year college (TYC)	traditional	44

1. Choosing the items of the MPEX survey

The cognitive structures that we have referred to as student expectations clearly are complex and contain many facets. We decided to focus on six issues or dimensions along which we might categorize student attitudes toward the appropriate way to do physics. Three of these are taken from Hammer's study and we have added three of our own.

Building on the work of Perry and Songer and Linn cited earlier, Hammer proposed three dimensions along which to classify student beliefs about the nature of learning physics:[19]

(1) *Independence*—beliefs about learning physics—whether it means receiving information or involves an active process of reconstructing one's own understanding;
(2) *Coherence*—beliefs about the structure of physics knowledge—as a collection of isolated pieces or as a single coherent system;
(3) *Concepts*—beliefs about the content of physics knowledge—as formulas or as concepts that underlie the formulas.

In the MPEX survey, we seek to probe three additional dimensions:

(4) *Reality Link*—beliefs about the connection between physics and reality—whether physics is unrelated to experiences outside the classroom or whether it is useful to think about them together;
(5) *Math Link*—beliefs about the role of mathematics in learning physics—whether the mathematical formalism is just used to calculate numbers or is used as a way of representing information about physical phenomena;
(6) *Effort*—beliefs about the kind of activities and work necessary to make sense out of physics—whether they expect to think carefully and evaluate what they are doing based on available materials and feedback or not.

The extreme views associated with each of these variables are given in Table II. We refer to the extreme view that agrees with that of most mature scientists as the *expert* or *favorable* view, and the view that agrees with that of most beginning students as the *novice* or *unfavorable* view. The survey items that have been selected to probe the six attitudes are given in the right-hand column of Table II. We refer to the collection of survey items designed to probe a particular dimension as a *cluster*. Note that there is some overlap, as these dimensions are not independent variables.[20]

Although we believe the attitudes that we have defined as expert correspond to those attitudes needed by most creative, intuitive, and successful scientists, we note that they are not

Table II. Dimensions of student expectations.

	Favorable	Unfavorable	MPEX items
Independence	takes responsibility for constructing own understanding	takes what is given by authorities (teacher, text) without evaluation	1, 8, 13, 14, 17, 27
Coherence	believes physics needs to be considered as a connected, consistent framework	believes physics can be treated as unrelated facts or ''pieces''	12, 15, 16, 21, 29
Concepts	stresses understanding of the underlying ideas and concepts	focuses on memorizing and using formulas	4, 19, 26, 27, 32
Reality link	believes ideas learned in physics are relevant and useful in a wide variety of real contexts	believes ideas learned in physics have little relation to experiences outside the classroom	10, 18, 22, 25
Math link	considers mathematics as a convenient way of representing physical phenomena	views the physics and the math as independent with little relationship between them	2, 6, 8, 16, 20
Effort	makes the effort to use information available and tries to make sense of it	does not attempt to use available information effectively	3, 6, 7, 24, 31

always predictors of success in introductory physics classes. In an earlier study, Hammer studied two students in the algebra-based physics course at Berkeley.[21] One student possessed many novice characteristics but was doing well in the course. The other student possessed many of the characteristics preferred by experts but was having trouble. The second student's desire to make sense of the physics for herself was not supported and she did not begin to succeed until she switched her approach to memorization and pattern matching. In this case the course supported an attitude and an approach to learning that most physics instructors would not endorse and one which certainly would cause her trouble if she were to try to take more advanced science courses.[22]

2. Validating the survey: interviews

We conducted more than 100 hours of videotaped student interviews in order to validate that our interpretation of the survey items matched the way they were read and interpreted by students. We asked students (either individually or in groups of two or three) to describe their interpretations of the statements and to indicate why they responded in the way that they did. In addition, students were asked to give specific examples from class to justify their responses.

From these interviews, we have found that students are not always consistent with their responses to what appear to us to be similar questions and situations. We feel that this does not represent a failure of the survey, but properly matches these students' ill-defined understanding of the nature of physics. One reason for this was described by Hammer. He observed that some students in his study believed that professional physics operated under the favorable conditions, but that it sufficed for them to behave in the unfavorable fashion for the purposes of the course. He referred to this by adding the marker ''apparent'' to the characteristic. This is only one aspect of the complex nature of human cognition. We must also be careful not to assume that a student exists in one extreme state or another. A student's attitude may be modified by an additional attitude, as in Hammer's observations, or even exist simultaneously in both extremes, depending on the situation that triggers the response.[23] One must therefore use considerable care in applying the results of a limited probe such as our survey to a single student.

We are also aware that students' self-reported perceptions may not match the way they actually behave.[24] However, the interviews suggest that if a student's self-perception of the learning characteristics described in Table II differs from the way that student actually functions, the self-perception has a strong tendency to be closer to the side chosen by experts. We therefore feel that while survey results for an individual student may be misleading, survey results of an entire classroom might *understate* unfavorable student characteristics.

IV. EXPERT EXPECTATIONS: THE CALIBRATION GROUPS

In order to test whether the survey correctly represents elements of the hidden curriculum, we gave it to a variety of students and physics instructors. We defined as ''expert'' the response that was given by a majority of experienced physics instructors who have a high concern for educational issues and a high sensitivity to students. We conjectured that experts, when asked what answers they would want their students to give, would respond consistently.

A. The calibration groups

We tested the response of a wide range of respondents by comparing five groups:

- Group 1: engineering students entering the calculus-based physics sequence at the University of Maryland,
- Group 2: members of the US International Physics Olympics Team,
- Group 3: high school teachers attending the two-week Dickinson College Summer Seminar on new approaches in physics education,
- Group 4: university and college teachers attending the two-week Dickinson College Summer Seminar on new approaches in physics education,
- Group 5: college faculty who are part of a multi-university FIPSE-sponsored project to implement Workshop Physics at their home institutions.

Table III. Prevalent responses of our expert group. Where the respondents did not agree at the >80% level, the item is shown in parentheses and the majority response is shown. The response ''A'' indicates agree or strongly agree. The response ''D'' indicates disagree or strongly disagree.

1	D	8	D	15	D	22	D	29	D
2	D	9	(D)	16	D	23	D	30	A
3	A	10	D	17	D	24	D	31	A
4	D	11	A	18	A	25	A	32	A
5	A	12	D	19	D	26	A	33	D
6	A	13	D	20	D	27	D	34	(A)
7	(A)	14	D	21	D	28	D		

The University of Maryland students are a fairly typical diverse group of engineering students at a large research university. The number of students in the sample is $N = 445$.

The US International Physics Olympics Team (USIPOT) is a group of high school students selected from applicants throughout the USA. After a 2-week training session, five are chosen to represent the US in the International Physics Olympics. In 1995 and 1996, this group trained at the University of Maryland in College Park and we took the opportunity to have them complete survey forms. The total number of respondents in this group is $N = 56$. Although they are not teachers, they have been selected by experts as some of the best high school physics students in the nation. Our hypothesis was that they would prove to be more expert than the average university physics student, but not as expert as our groups of experienced instructors.

The physics instructors who served as our test groups were all visiting Dickinson College. Attendees came from a wide variety of institutions. Many have had considerable experience in teaching, and all of them were sufficiently interested in educational development to attend a workshop. We separated them into three groups: Group 3—high school teachers attending a two-week summer seminar $(N = 26)$, Group 4—college and university teachers attending the two-week summer seminar $(N = 56)$, and Group 5—college and university teachers implementing Workshop Physics in their classroom $(N = 19)$. The teachers in Group 5 were committed to implementing an interactive engagement model of teaching in their classroom. We asked the three groups of instructors to respond with *the answer they would prefer their students to give*. We expected these five groups to show an increasing level of agreement with answers we preferred.

B. The responses of the calibration groups

The group we expected to be the most sophisticated, the Group 5 instructors, agreed strongly as to what were the responses they would like to hear from their students. On all but three items, ~80% or more of this group agreed with a particular position. Three items, Nos. 7, 9, and 34, had a strong plurality of agreement, but between 1/4 and 1/3 of the respondents chose neutral. We define the preferred response of Group 5 as the *expert response*. We define a response in agreement with the expert response as *favorable* and a response in disagreement with the expert response as *unfavorable*. For the analysis in this paper, the agree and strongly agree responses (4 and 5) are added together, and the disagree and strongly disagree responses (1 and 2) are added together. A list of the favorable responses to the survey items is presented in Table III.

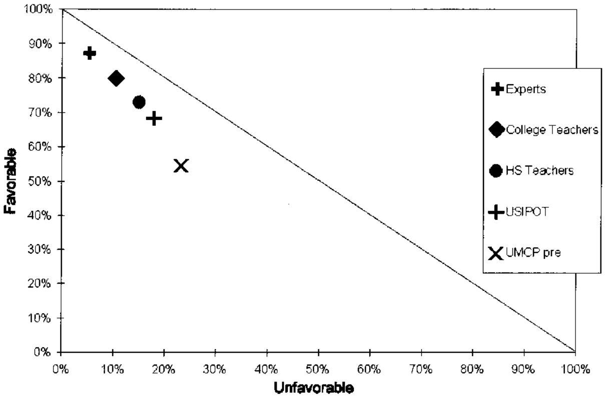

Fig. 1. A–D plot for calibration groups, average of all items. The percentage of respondents agreeing with the majority of experts' views (favorable responses) is plotted against the percentage disagreeing with those views (unfavorable responses).

To display our results in a concise and easily interpretable manner, we introduce an *agree–disagree* (A–D) *plot*. In this plot, the percentage of respondents in each group answering favorably are plotted against the percentage of respondents in each group answering unfavorably. Since the fraction of students agreeing and disagreeing must add up to less than or equal to 100%, all points must lie in the triangle bounded by the corners (0,0), (0,100), (100,0). The distance from the diagonal line is a measure of the number of respondents who answered neutral or chose not to answer. The closer a point is to the upper left-hand corner of the allowed region, the better the group's agreement with the expert response.[25]

The results on the overall survey are shown in Fig. 1. In this plot, the percentages are averaged over all of the items of the survey, using the preferred responses of calibration Group 5 as favorable. The groups' responses are distributed from less to more favorable in the predicted fashion.[26]

Although the overall results support our contention that our survey correlates well with an overall sophistication of attitudes toward doing physics, the cluster results show some interesting deviations from the monotonic ordering. These deviations are quite sensible and support our use of clusters as well as overall results. In order to save space and simplify the interpretation of results, we present the data in Table IV. Displayed in this table are the percentages of each group's favorable and unfavorable responses (in the form favorable/unfavorable). The percentage of neutrals and not answering can be obtained by subtracting the sum of the favorable and unfavorable responses from 100.

From Table IV we see that most of the fraction of respondents agreeing with the favorable response tends to increase monotonically from Group 1 to 5 with a few interesting exceptions. The high school teachers (Group 3) are farther than their average from the favorable corner in the coherence and math clusters, while the Physics Olympics Team is closer to the favorable corner in those categories than their average. These results are plausible if we assume that high school teachers are less concerned with their students forming a coherent and mathematically sophisticated view of physics than are university teachers. The results also agree with our personal observations that the members of the USIPOT are unusually coherent in their views of physics and exceptionally strong in their mathematical skills.

Note also that the Olympics team results are very far from

Table IV. Percentages of students giving favorable/unfavorable responses on overall and clusters of the MPEX survey at the beginning (pre) and end (post) of the first unit of university physics.

	Overall	Independence	Coherent	Concept	Reality link	Math link	Effort
Experts	87/6	93/3	85/12	89/6	93/3	92/4	85/4
College	80/10	80/8	80/12	80/8	94/4	84/9	82/6
HS	73/15	75/16	62/26	71/18	95/2	67/21	68/13
USIPOT	68/18	81/12	79/8	73/13	64/20	85/8	50/34
UMCP pre	54/23	54/25	53/24	42/35	61/14	67/17	67/13
UMCP post	49/25	48/27	49/27	44/32	58/18	59/20	48/27
UMN pre	59/18	59/19	57/20	45/27	72/9	72/11	72/11
UMN post	57/20	58/20	61/17	46/28	69/10	72/12	63/16
OSU pre	53/23	51/24	52/21	37/36	65/10	65/13	66/16
OSU post	45/28	46/28	46/26	35/35	54/17	55/20	44/30
DC pre	61/15	62/14	58/17	47/23	76/4	70/10	75/7
DC post	60/19	67/14	66/18	58/23	72/9	71/12	57/26
PLA pre	57/23	57/27	57/26	38/46	71/13	74/11	72/8
PLA post	49/31	52/22	47/33	45/34	52/25	54/19	48/30
TYC pre	55/22	41/29	50/21	30/42	69/16	58/17	80/8
TYC post	49/26	42/32	48/29	35/41	58/17	58/18	65/21

the favorable corner in the effort cluster. The main discrepancies are in items 3 and 7. We suggest that the reader peruse the survey items of that cluster (3, 6, 7, 24, 31). These items represent highly traditional measures of effort (reading the textbook, going over one's lecture notes) which we conjecture are not yet part of the normal repertoire of the best and brightest high school physics students before they enter college. We also conjecture that most of them will have to learn to make these kinds of efforts as they progress to increasingly sophisticated materials and the level of challenge rises.

This analysis of both the overall responses of the calibration groups and the variations in the ordering confirms that the MPEX survey provides a quantitative measure of characteristics which experts hope and expect their students to have.

V. STUDENT EXPECTATIONS: DISTRIBUTION AND EVOLUTION

In this section, we discuss the results obtained from giving the MPEX survey at the beginning and end of the first term of introductory calculus-based physics at six different institutions. In each case, the subject covered was Newtonian mechanics. The schools involved include the flagship research institutions of three large state universities: the University of Maryland (UMCP), Ohio State University (OSU), and the University of Minnesota (UMN); plus three smaller schools: Dickinson College (DC), a small public liberal arts college (PLA), and a public two-year college (TYC). At the named colleges, we have data from multiple instructors. In the case of the last two institutions, data were only collected from a small number of instructors and students. These are included in order to demonstrate how the MPEX survey can be used as a diagnostic tool, but are kept anonymous to protect the identity of the instructors and institutions involved.

At Maryland, Ohio State, and Minnesota, classes were presented in the traditional lecture–lab–recitation framework with some modifications. At Maryland, there is no laboratory in the first semester and some of the recitation sections were done with University of Washington style tutorials.[27] Results for tutorial and recitation classes were comparable. At Minnesota, the laboratory and recitations involve carefully designed problem-solving group work.[28] At Ohio State, lectures are traditional but are enhanced by use of various interactive elements, while recitation and laboratory are done in a group problem-solving format somewhat similar to that developed at Minnesota. At Dickinson College and at the public liberal arts institution, the classes surveyed were done in the Workshop Physics environment which replaces lectures with a combined lab and class discussion.[5(d)] The two-year college used a purely traditional lecture–recitation framework. Like Maryland, they have no lab in the first semester. The schools involved, the structure of their courses, and the number of students in our sample are summarized in Table I.

In order to eliminate the confounding factor of differential drop-out rates, we only include students who completed the survey both at the beginning and at the end of the term. We say that the data is *matched*. Our results show some differences among different classes at the same institution, but the variation is statistically consistent with the sample size. Therefore, we have combined results for similar classes at a given institution.

The overall survey results for the six schools are presented in an A–D plot in Fig. 2. In order to simplify the reading of the graphs, we have displayed the results from the three large research universities in one part of the figure [Fig. 2(a)] and those from the smaller schools in another [Fig. 2(b)]. The pre-course results are shown by filled markers and the post-course results by open markers. The results of the expert group are shown by a cross.

We make two observations.

(1) The initial state of the students at all the schools tested differs substantially from the expert results. The expert group was consistent, agreeing on which survey responses were desirable 87% of the time. Beginning students only agreed with the favorable (expert) responses

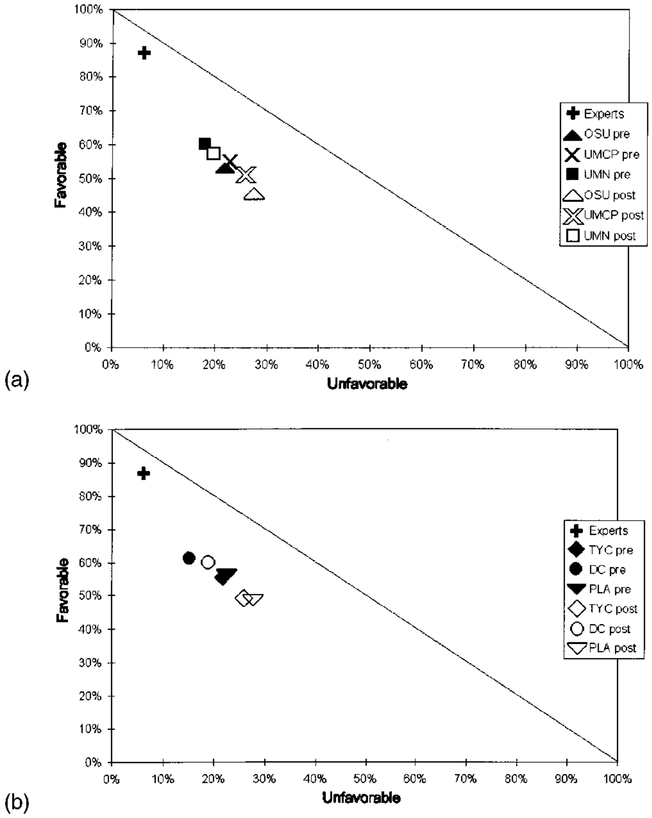

Fig. 2. (a) A–D plot for large schools, average of all items; (b) A–D plot for small schools, average of all items.

about 50%–60% of the time, a substantial discrepancy. What is perhaps more distressing is that students explicitly supported unfavorable positions about 15%–30% of the time.

(2) In all cases, the result of instruction on the overall survey was an *increase* in unfavorable responses and a decrease in favorable responses (though some changes were not significant). *Thus instruction produced an average deterioration rather than an improvement of student expectations.*

The overall survey includes items that represent a variety of characteristics, as displayed in Table II. In order to better understand what is happening in the classes observed, let us consider the initial state and the change of student expectations in our various clusters. The results are presented in Table IV.

A. The independence cluster

One characteristic of the binary thinker, as reported by Perry and BGCT, is the view that answers come from an authoritative source, such as an instructor or a text, and it is the responsibility of that authority to convey this knowledge to the student. The more mature students understand that developing knowledge is a participatory process. Hammer classifies these two extreme views as ''by authority'' and ''independent.'' Survey items 1, 8, 13, 14, 17, and 27 probe students' views along this dimension. On this cluster, students' initial views were favorable in a range from 41% (TYC) to 62% (DC). All groups showed essentially no significant change as a result of one term of instruction. For comparison, the USIPOT showed favorable views on these items 81% of the time.

Survey items 1 and 14 are particularly illuminating and show the largest gaps between experts and novices.

> #1: *All I need to do to understand most of the basic ideas in this course is just read the text, work most of the problems, and/or pay close attention in class.*
>
> #14: *Learning physics is a matter of acquiring new knowledge that is specifically located in the laws, principles, and equations given in the textbook and in class and/or in the textbook.*

The expert group was in 100% agreement that students should disagree with item 1 and in 84% agreement that they should disagree with item 14. Disagreeing with these items represents a rather sophisticated view of learning, but favorable shifts on these items are exactly the sort of changes that indicate the start of a transition between a binary and a more constructivist thinker. The interviews strongly support this view. Students who disagreed with both these items were consistently the most vigorous and active learners.

This cluster of items, and items 1 and 14 in particular, appear to confirm that most students in university physics enter with at least some characteristics of binary learners, agreeing that learning physics is simply a matter of receiving knowledge in contrast to constructing one's own understanding. We would hope that if a university education is to help students develop more sophisticated views of their own learning, that the introductory semester of university physics would begin to move students in the direction of more independence. Unfortunately, this does not appear to have been the case. In the touchstone items of 1 and 14, the only significant improvement was DC on item 14 (26%–53%), and overall, only DC showed improvement.

B. The coherence cluster

Most physics faculty feel strongly that students should see physics as a coherent, consistent structure. A major strength of the scientific worldview is its ability to describe many complex phenomena with a few simple laws and principles. Students who emphasize science as a collection of facts fail to see the integrity of the structure, an integrity that is both epistemologically convincing and useful. The lack of a coherent view can cause students many problems, including a failure to notice errors in their reasoning and an inability to evaluate a recalled item through cross checks. Survey items 12, 15, 16, 21, and 29 have been included in order to probe student views along this dimension.

Our expert group was in agreement as to what responses were desirable on the elements of this cluster 85% of the time. The initial views of students at our six schools were only favorable between 50% and 58% of the time. Most classes showed a small deterioration on this cluster, except for UMN (slight improvement from 57% to 61% favorable responses) and DC (improvement from 58% to 66% favorable responses).

Two specific items in this cluster are worthy of an explicit discussion.

> #21: *If I came up with two different approaches to a problem and they gave different answers, I would not worry about it; I would just choose the answer that seemed most reasonable. (Assume the answer is not in the back of the book.)*

#29: A significant problem in this course is being able to memorize all the information I need to know.

Item 21 is a touchstone. Coming up with two different answers using two different methods indicates something is seriously wrong with at least one of your solutions and perhaps with your understanding of the physics and how to apply it to problems. Our expert group and USIPOT students feel strongly that students should disagree with item #21 at the 85% level. Initially, only 42%–53% of students produced a favorable response for this item, and only DC showed any significant improvement on this item (from 52% to 59%). One school (PLA) showed a substantial deterioration (from 42% to 17%).

The interpretation of item #29 may depend significantly on the details of the examination structure of the course being probed. A sophisticated student will realize that the large number of different equations and results discussed in a physics text can be structured and organized so that only a small amount of information needs to be memorized and the rest can be easily rebuilt as needed. Item #29 is part of a probe into whether or not students see this structure or are relying on memorizing instead of rebuilding. However, if students are permitted to use a formula sheet or if exams are open book, they may not perceive memorization as a problem. This does not mean that they see the coherence of the material.[29] If extensive information is made available to students during exams, item #29 needs to be interpreted carefully. A variety of examination aids were used for the classes of this study, ranging from open-book exams (DC) to no aids (UMCP). Omission of item #29 does not change the distributions in this cluster significantly.

C. The concepts cluster

The group of items selected for the concepts cluster (items 4, 19, 26, 27, and 32), are intended to probe whether students are viewing physics problems as simply a mathematical manipulation of an equation, or whether they are aware of the more fundamental role played by physics concepts in complex problem solving. For students who had high-school physics classes dominated by simple ‘‘problem solving’’ (find the right equation, perhaps manipulate it, then calculate a number), we might expect largely unfavorable responses on our items. We would hope, however, for substantial improvement, even as the result of a single college physics course.

Our experts agree on their responses to the items of this cluster 89% of the time. The initial views of the students at the six schools were favorable between 30% (TYC) and 47% (DC) of the time. All schools showed some improvement on this cluster except OSU, which showed a small deterioration (from 37% to 35% favorable responses). The two Workshop Physics schools showed the largest gains in favorable responses (DC 47% to 58%, PLA 38% to 45%).

Within this cluster, the results on items 4 and 19 are particularly interesting.

#4: ‘‘Problem solving’’ in physics basically means matching problems with facts or equations and then substituting values to get a number.

#19: The most crucial thing in solving a physics problem is finding the right equation to use.

While these items are similar, they are not identical. Agreeing with item 4 indicates a naive view of physics problems or a lack of experience with complex problems. A more experienced student could reject 4 but still agree with 19 because of the phrase ‘‘most crucial.’’ One would, however, hope that increased experience with complex physics problems would lead a student to disagree with this item as well. For example, 54% of the USIPOT students gave a favorable response on this item as compared to only 22% of beginning students at UMCP. Our personal observations of these students indicate that as expected, the USIPOT students have considerably more experience with complex problem solving than the typical beginning engineering student.

Most of the schools begin with favorable responses on item #4 of 50%–55%. Our TYC is an anomaly, with only 16% of the students responding favorably on this item. This suggests that the group of students in our TYC may be considerably less sophisticated, at least along this dimension, than the average beginning university student. The shifts on this item tend to be favorable and significant (e.g., UMCP 47%→59% favorable, DC 52%→64% favorable) with the exception of our PLA institution which showed a shift toward neutral.

All groups showed a low initial favorable response on item 19 [13% (TYC) to 31% (UMN)] but all showed a shift toward the favorable by the end of the semester.

D. The reality link cluster

Although physicists believe that they are learning about the real world when they study physics, the context dependence of cognitive responses (see Ref. 6) opens a possible gap between faculty and students. Students may believe that physics is related to the real world in principle, but they may also believe that it has little or no relevance to their personal experience. This can cause problems that are both serious and surprising to faculty. The student who does a calculation of the speed with which a high jumper leaves the ground and comes up with 8000 m/s (as a result of recalling numbers with incorrect units and forgetting to take a square root) may not bother to evaluate that answer and see it as nonsense on the basis of personal experience. When an instructor produces a demonstration that has been ‘‘cleaned’’ of distracting elements such as friction and air resistance, the instructor may see it as displaying a general physical law that is present in the everyday world but that lies ‘‘hidden’’ beneath distracting factors. The student, on the other hand, may believe that the complex apparatus is *required* to produce the phenomenon, and that it does not occur naturally in the everyday world, or is irrelevant to it. A failure to make a link to experience can lead to problems not just because physics instructors want students to make strong connections between their real-life experiences and what they learn in the classroom, but because learning tends to be more effective and robust when linked to real and personal experiences.

The four items we have included as the reality link cluster (items 10, 18, 22, and 25) do not just probe whether the students believe the laws of physics govern the real world. Rather, our items probe whether the students feel that their personal real-world experience is relevant for their physics course and vice versa. In our interviews, we observed that many students show what we would call, following Hammer, an ‘‘apparent reality link.’’ That is, they believe that the laws of physics govern the behavior of the real world in principle, but that they do not need to consider that fact in their physics class.

Our three groups of instructors were in almost unanimous agreement (93%–95%) with the favorable response on our reality cluster. An interesting anomaly was the response of the USIPOT students, who only gave favorable responses at the 64% level. Examining their written comments as well as their responses gives one possible explanation: A significant number of USIPOT students saw physics as being associated primarily with interesting and exotic phenomena, such as cosmology, relativity, and particle physics. Some of these students did not see a link between this physics and their personal experiences.

The student groups at our six schools started out with fairly strong favorable responses, ranging from 61% (UMCP) to 76% (DC). Unfortunately, every group showed a deterioration on this measure as a result of instruction, and some of the shifts were substantial (OSU—from 65% to 54%; PLA—from 71% to 52%, and TYC—from 69% to 58% favorable responses).

E. The math link cluster

An important component of the calculus-based physics course is the development of the students' ability to use abstract and mathematical reasoning in describing and making predictions about the behavior of real physical systems. Expert scientists use mathematical equations as concise summaries of complex relationships among concepts and/or measurements. They can often use equations as a framework on which to construct qualitative arguments. Many introductory students, however, fail to see the deeper physical relationships present in an equation and instead use the math in a purely arithmetic sense—as a way to calculate numbers. When students have this expectation about equations, there can be a serious gap between what the instructor intends and what the students infer. For example, a professor may go through extensive mathematical derivations in class, expecting the students to use the elements of the derivation to see the structure and sources of the relationships in the equation. The students, on the other hand, may not grasp what the professor is trying to do and reject it as irrelevant ''theory.'' Students who fail to understand the derivation and structure of an equation may be forced to rely on memorization—an especially fallible procedure if they are weak in coherence and have no way to check what they recall.

The survey items probing students' apparent expectations[30] of the role of mathematics are 2, 6, 8, 16, and 20. Our expert group is in strong agreement on the favorable answers for this cluster, agreeing at the 92% level. Since high school physics courses tend to be decidedly less mathematical than university physics courses, we were not surprised that the high school instructors have much lower expectations for their students on this cluster, agreeing with its elements only 67% of the time. This is comparable to the initial percentages of most of the students in our test classes, which range from 58% to 74%.

Although these lower expectations may be appropriate for high school students and therefore for beginning university students, one might hope that these attitudes would change toward more favorable ones as a result of a university physics class. Unfortunately, none of the classes probed show improvement in the favorable/unfavorable ratio and three (UMCP, OSU, PLA) show a significant and substantial deterioration.

Among the items of the cluster, the results on item 2 are particularly interesting.

> #2: *All I learn from a derivation or proof of a formula is that the formula obtained is valid and that it is OK to use it in problems.*

From our interviews and informal discussions, we note that many students today have had little or no experience with formal mathematical proof. A few did not understand the meaning of the word ''derivation,'' mistaking it for ''derivative.''[31] This lack of experience can produce a severe gap between the expectations of instructors and students and cause serious confusion for both groups. On item 2, the students at no institution showed favorable responses (disagree) at higher than the 44% level (UMN). At our TYC, only 20% gave a favorable response with item 2 initially, and 48% of the students gave the unfavorable response. (We write this response as 20/48.) They improved somewhat after the class (to 33/41), but our PLA deteriorated significantly (from 36/18 to 25/33). This deterioration did not appear to be associated with the Workshop Physics structure which tends to emphasize hands-on and laboratory activities over purely abstract and mathematical reasoning. The DC students changed on item #2 from 39/25 to 45/31. This maintains approximately the same ratio, but fewer students are undecided.

F. The effort cluster

Many physics lecturers do not expect most of their students to follow what they are doing in lecture during the lecture itself. They expect students will take good notes and figure them out carefully later. Unfortunately, many students do not take good notes and even those who do may rarely look at them. When physics begins to get difficult for students, most instructors expect them to try to figure things out using a variety of techniques—working through the examples in the book, trying additional problems, talking to friends and colleagues, and in general trying to use whatever resources they have available to make sense of the material. Some students, on the other hand, when things get difficult, may be at a loss for what to do. Some students do not have the idea that if they do not see something right away, there are steps they can take that will eventually help them make sense of the topic.[32] An important component of the tools that help build understanding is the appreciation that one's current understanding might be wrong, and that the mistakes one makes can give guidance in helping to correct one's errors. This dimension is probed by items 3, 6, 7, 24, and 31 on the survey.

For this cluster, the results are striking enough that we display them in an A–D plot in Fig. 3. Our experts are in strong agreement on the answers to the items of this cluster, at an 85% level. The initial views of the students at the various institutions begins quite high, ranging from 66% favorable (at OSU) to 80% favorable (at our TYC). By the end of the semester, the shift is dramatically downward, with three institutions dropping in the favorable percentages by about 20% (UMCP, OSU, and PLA), and three dropping by 10%–15% (UMN, DC, and TYC). In one sense, this may be interpreted that the students expected to make more of an effort in the course than they actually did, as the shifts were largest on items 3 and 6, but the downward shifts on items 24 and 31 were also substantial.

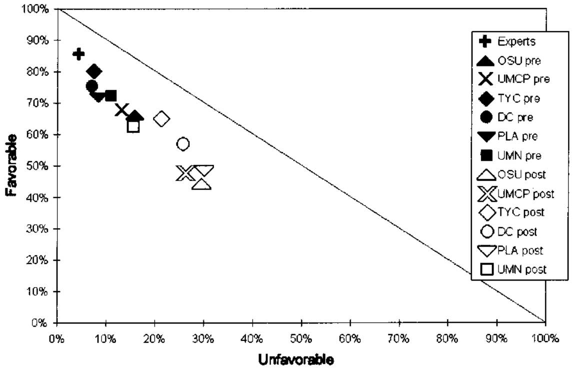

Fig. 3. A–D plot for all schools, effort cluster.

G. Statistical significance

Every finite set of data contains fluctuations which have no real significance but arise from the details of a particular sample. In this paper, our research questions involve comparisons of groups—experts and novices, novice students at different institutions, and students at the beginning and end of their first semester of physics. In order to compare these groups, we are comparing their averaged responses (agree versus neutral versus disagree). In order for us to understand whether two responses are significantly different, we have to have some model of the random variable in our sample.

Our interviews, our intuitions, and many discussions in the cognitive literature suggest that a human attitude is a highly complex object. As we noted above, some students gave clear evidence in interviews of being in two contradictory states at the same time. What this implies is that the random variable we should be averaging is itself a probability, rather than a set of well-defined values. Unfortunately, the average of probabilities may depend significantly on the structure of the constraints and parametrization of the probabilities, as is well known from quantum statistics. Since detailed models of student attitudes do not yet exist, we will estimate our significances by using a cruder model.

Let us assume that a class is drawn from a very large homogeneous[33] group of students and that in the large population, a percentage p_0 of responses to an item or cluster will be favorable and a percentage q_0 will be unfavorable with $p_0+q_0 \approx 1$. (For now, we will ignore the possibility of neutral responses.[34]) In a finite sample of n students, we want to know what is the probability of finding n_1 favorable and n_2 unfavorable responses with $n_1+n_2 \approx 1$. Using the Gaussian approximation to the binomial distribution, we get that the probability of finding fractions $p=n_1/n$ and $q=n_2/n$ is $P(p)=Ae^{-(p-p_0)^2/2\sigma^2}$ where A is a normalization constant and

$$\sigma = \sqrt{\frac{p_0 q_0}{n}}.$$

For this distribution, the probability that a sample will have a mean that falls within 1σ of the true mean, p_0, is 0.684 and the probability that a sample will fall within 2σ of the true mean is 0.954.

Since the fraction of neutral responses tends to be small, and since the binomial model is crude for this set of data, we treat our trinomial data as if it were approximately binomial by renormalizing the observed p and q into $p'=p/p+q$ and $q'=q/p+q$. We consider a difference or shift in means to be significant if it is at less than the 5% probability level, that is, if the difference or shift is greater than twice $\sigma = \sqrt{p'q'/n}$. For example, at values of $p=60\%$, $q=20\%$ for $N=450$, we get $\sigma \sim 2\%$. This doesn't change much over the typical values of p and q seen in Table III. We therefore consider a 5% shift to be significant for our large schools. For $N=115$, those values of p and q give $\sigma \sim 4\%$. We therefore consider a 10% shift to be significant for Dickinson.

VI. CONCLUSIONS

A. Summary

In this paper we have discussed the creation and use of the MPEX survey of student cognitive attitudes in physics. The survey was constructed to probe student expectations with a focus on six structures: independence, coherence, concepts, the link between physics and the real world, understanding of the role of math in physics, and the kind of effort they expect to make. The survey was calibrated using five groups. The group expected to be most sophisticated was in strong agreement (better than ~80% on almost all the items) as to the desired responses on the items of the survey and their preferred response was defined as favorable. The other calibration groups showed increasing agreement with the expert group in the predicted manner.

We tested the survey in classes at six schools that had varying entrance selectivity and that used a variety of approaches. We find explicit answers to the research questions we posed in the introduction.

Q1. How does the initial state of students in university physics differ from the views of experts?

At the six schools tested, the initial state of students deviated significantly from that of the expert calibration group with overall responses ranging from 50% to 60% favorable. The results on the concept cluster were particularly low (30%–45%) and on the reality cluster were particularly high (60%–75%).

Q2. To what extent does the initial state of a class vary from institution to institution?

At our three large state flagship institutions (UMCP, OSU, UMN) student attitudes as measured by the survey were very similar. The attitudes of beginning students at our selective liberal arts institution (DC) were consistently more favorable and those at our two-year college (TYC) were consistently less favorable than those at our state flagship institutions.

Q3. How are the expectations of a class changed as the result of one semester of instruction in various learning environments?

At every school we studied, the overall results deteriorated as the result of one semester of instruction. A significant part of this deterioration was the effort cluster: at every school tested, in their judgments at the end of a semester, students felt that they did not put in as much effort as they had expected to put in at the beginning of the semester. This part of the result is well-known and neither surprising nor particularly disturbing. What is more troublesome is the result that many of the schools showed deteriorations on the cognitive dimensions as well: half deteriorated on the independence dimension, two-thirds on the coherence dimension, half on the math link (with the others showing no gain), and all on the reality link.

B. Implications

The workplace and the role of physics in the educational milieu is changing. Modern industry now requires a much larger fraction of its workers to have some technical expertise than was the case 30 years ago, and this trend is likely to continue. Our mandate now is to provide a much larger fraction of our students with successful training in technological thinking skills than ever before.

The small fraction of students who enter our classes with expectations that match the instructors may be identified as ''good'' students and achieve success with a high probability. Some of these may go on to become physicists. The students who have inappropriate expectations may work extremely hard but still find themselves unable to succeed. Our courses then serve as filters to eliminate those students rather than helping to transform them. Worse yet, some courses may actually reward students with inappropriate attitudes, such as those who prefer memorizing to understanding, while driving away students who might excel in science given a more supportive structure.[35] If we degrade the requirements in our courses so that students can succeed without developing an understanding of the nature of science, the scientific process, or how to learn science and do it, those students who come to college with a mature set of attitudes may survive this approach without damage. But for those who will need to learn and do science at a more advanced level, and who need help with their understanding of what science is and how to think about it, this approach is a recipe for guaranteed failure.[36]

It is inappropriate to respond to the new mandate by ''blaming the victim'' or claiming that ''some students just can't do physics.'' This is particularly destructive in those cases where students have had previous training in science and math classes that discourages understanding, questioning, and creative thinking. Some students have had great success in courses in this mode over many years in elementary, middle, and high school (and even in college). As has been demonstrated in many areas of cognitive psychology and education research, changing a long-held view is a nontrivial exercise. It may take specifically designed activities and many attempts.

Anecdotal evidence suggests an ''existence theorem.'' Some students who come to college with serious misconceptions about how to do physics make the transition to become excellent students and successful scientists or engineers.

Much of what we do in introductory classes does not address the hidden curriculum of improved understanding and attitudes. Indeed, some of what we do may be counterproductive. If we are to learn the extent to which it is possible to help introductory students transform their approach toward physics, we must observe our students carefully and try to explicate the elements of an appropriate set of expectations.

The failure to begin to move students from a binary view of learning to a more constructivist set of attitudes in the first term of university physics is most unfortunate. The start of college is a striking change for most students. This change of context gives instructors the valuable opportunity to redefine the social contract between students and teachers. This redefinition offers an opportunity to change expectations. If students are told at the beginning of their first college science course: ''In high school you may have gotten away with memorizing equations without understanding them, but here that won't be enough'' and if that mandate is followed through in both assignments and grading, students are more likely to be willing to put in the effort to change and grow. If students experience a series of science courses that do not require deeper understanding and a growth of sophistication, they will be much more reluctant to put in the time and effort to change in a later course.

The survey presented here is a first step toward exploring these issues and expanding our understanding of what is really going on in our classrooms.

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APPENDIX: THE MPEX SURVEY

On the next page is given the complete list of the items of the MPEX survey. A version suitable for printing, copying, and using in class may be obtained on the WWW (see Ref. 2). Note that individual items should not be used to evaluate individual students. On any single item, students may have atypical interpretations or special circumstances which make the ''nonexpert'' answer the best answer for that student. Furthermore, students often think that they function in one fashion and actually behave differently. A more detailed observation is required to diagnose the difficulties of individual students. This survey is primarily intended to evaluate the impact of one or more semesters of instruction on an overall class. It can be used to illuminate some of the student reactions to instruction of a class that are not observable using traditional evaluations. In this context, it, together with evaluations of student learning of content, can be used as a guide for improving instruction.

1	All I need to do to understand most of the basic ideas in this course is just read the text, work most of the problems, and/or pay close attention in class.
2	All I learn from a derivation or proof of a formula is that the formula obtained is valid and that it is OK to use it in problems.
3	I go over my class notes carefully to prepare for tests in this course.
4	Problem solving in physics basically means matching problems with facts or equations and then substituting values to get a number.
5	Learning physics made me change some of my ideas about how the physical world works.
6	I spend a lot of time figuring out and understanding at least some of the derivations or proofs given either in class or in the text.
7	I read the text in detail and work through many of the examples given there.
8	In this course, I do not expect to understand equations in an intuitive sense; they just have to be taken as givens.
9	The best way for me to learn physics is by solving many problems rather than by carefully analyzing a few in detail.
10	Physical laws have little relation to what I experience in the real world.
11	A good understanding of physics is necessary for me to achieve my career goals. A good grade in this course is not enough.
12	Knowledge in physics consists of many pieces of information each of which applies primarily to a specific situation.
13	My grade in this course is primarily determined by how familiar I am with the material. Insight or creativity has little to do with it.
14	Learning physics is a matter of acquiring knowledge that is specifically located in the laws, principles, and equations given in class and/or in the textbook.
15	In doing a physics problem, if my calculation gives a result that differs significantly from what I expect, I'd have to trust the calculation.
16	The derivations or proofs of equations in class or in the text have little to do with solving problems or with the skills I need to succeed in this course.
17	Only very few specially qualified people are capable of really understanding physics.
18	To understand physics, I sometimes think about my personal experiences and relate them to the topic being analyzed.
19	The most crucial thing in solving a physics problem is finding the right equation to use.
20	If I don't remember a particular equation needed for a problem in an exam there's nothing much I can do (legally!) to come up with it.
21	If I came up with two different approaches to a problem and they gave different answers, I would not worry about it; I would just choose the answer that seemed most reasonable. (Assume the answer is not in the back of the book.)
22	Physics is related to the real world and it sometimes helps to think about the connection, but it is rarely essential for what I have to do in this course.
23	The main skill I get out of this course is learning how to solve physics problems.
24	The results of an exam don't give me any useful guidance to improve my understanding of the course material. All the learning associated with an exam is in the studying I do before it takes place.
25	Learning physics helps me understand situations in my everyday life.
26	When I solve most exam or homework problems, I explicitly think about the concepts that underlie the problem.
27	Understanding physics basically means being able to recall something you've read or been shown.
28	Spending a lot of time (half an hour or more) working on a problem is a waste of time. If I don't make progress quickly, I'd be better off asking someone who knows more than I do.
29	A significant problem in this course is being able to memorize all the information I need to know.
30	The main skill I get out of this course is to learn how to reason logically about the physical world.
31	I use the mistakes I make on homework and on exam problems as clues to what I need to do to understand the material better.
32	To be able to use an equation in a problem (particularly in a problem that I haven't seen before), I need to know more than what each term in the equation represents.
33	It is possible to pass this course (get a ''C'' or better) without understanding physics very well.
34	Learning physics requires that I substantially rethink, restructure, and reorganize the information that I am given in class and/or in the text.

[a] Part of this paper is taken from a dissertation to be submitted to the Graduate School, University of Maryland, by JMS in partial fulfillment of the requirements for the Ph.D. degree in Physics.

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[15] Perry specifically excludes science as ''the place where they *do* have answers.''

[16] F. Reif and J. H. Larkin, ''Cognition in scientific and everyday domains: Comparison and learning implications,'' J. Res. Sci. Teach. **28**, 733–760 (1991).

[17] J. S. Brown, A. Collins, and P. Duguid, ''Situated cognition and the culture of learning,'' Educ. Res. **18**(1), 32–42 (Jan–Feb 1989).

[18] Whenever possible, we have tried to have the survey given as the first item in the class. However, this was not always possible. In the cases where the survey was given after the instructor's description of the class on the first day, there was sometimes a small but noticeable effect on some student responses to particular items.

[19] See Refs. 1(b) and (c).

[20] In addition to the items representing these clusters, the survey contains additional items whose results (and shifts) we believe are also interesting, but which are associated with a student's style of approaching physics. Items 5, 9, 23, 28, 30, 33, and 34 fall into this category.

[21] See Ref. 1(a).

[22] Classes such as the one described by Hammer may appear to satisfy both the teacher and some students, but they can do damage if they focus on a superficial success at manipulation of a poorly understood content while neglecting the ''hidden'' curriculum of meta-concept development.

[23] The ability of an individual to hold conflicting views depending on circumstances is a fundamental tenet of our learning model. See Ref. 6 and R. Steinberg and M. Sabella, ''Student performance on multiple choice questions vs. open-ended exam problems,'' Phys. Teach. **35**(3) 150–155 (1997) for more discussion of this point.

[24] How students think, and how students think they think, are not necessarily the same: cf. the chapter ''The Tune's My Own Invention'' from *Through the Looking Glass*, by Lewis Carroll.

[25] The device of plotting three numbers whose sum is fixed in a triangle is well known in elementary particle physics as a Dalitz plot. In our case, the percentage responding agree, disagree, and neutral must add up to 100%.

[26] Note that we have included all items, including those marked with parentheses in Table III. As remarked above, even though the agreement on these items is not as strong, there is still a strong plurality of our experts in favor of the indicated responses. The shift in the position of the overall items resulting from removing these items is on the order of a few percent and the relative order of the groups is not modified.

[27] L. C. McDermott, P. S. Shaffer *et al.*, *Tutorials in Introductory Physics* (Prentice-Hall, Upper Saddle River, NJ, 1998). [See Refs. 5(b), (c), and (e) for published descriptions of the method.]

[28] P. Heller, R. Keith, and S. Anderson, ''Teaching problem solving through cooperative grouping. 1. Group versus individual problem solving,'' Am. J. Phys. **60**(7), 627–636 (1992); P. Heller and M. Hollabaugh, ''Teaching problem solving through cooperative grouping. 2. Designing problems and structuring groups,'' *ibid*. **60**(7), 637–644 (1992).

[29] Indeed, some student comments lead us to suspect that formula sheets may have the tendency of *confirming* student expectations that formulas dominate physics. Their interpretation is that although memorizing lots of formulas is important for professionals, they do not need to do so for the current course. Thus many faculty may be encouraging precisely that attitude they hope to discourage when they permit the use of formula sheets on exams. We are not aware of any research that shows the effect of formula sheets on student perceptions of the coherence of the material.

[30] Note that this is an area where students' beliefs about their abilities may surpass their actual abilities. More detailed investigations will require direct observation of student behavior on solving physics problems.

[31] This led us to include the phrase ''or proof'' in item 2.

[32] In another place, one of us has referred to this failure as a lack of *parsing* skills. These students, when faced with a complex sentence that they do not understand, will try reading it over and over again until it becomes familiar—but they still may not understand it. They seem to lack the ability to decompose a complex sentence into its constituent parts in order to make sense of it. E. F. Redish, ''Is the computer appropriate for teaching physics,'' Comput. Phys. **7**, 613 (December 1993).

[33] ''Homogeneous'' in this case does not of course mean that we assume the students are identical. Rather, it means that the students are ''equivalent''—that they are characteristic of the students who are to be found in ''that type of class in that type of school.''

[34] We choose this reduction from two independent variables to one because the primary variations we observe tend to maintain a fairly constant proportion of neutral responses.

[35] Sheila Tobias, *They're Not Dumb, They're Different: Stalking the Second Tier* (Research Corp., Tucson, AZ, 1990).

[36] This response is particularly dangerous because it is both easier for the faculty and less challenging for the student. This is analogous to the story told about the economic system in the former Soviet Union: ''The workers pretended to work, and the government pretended to pay them, and everyone was satisfied.''