220. **Isis Cumulative Bibliography 1966–1975,** Vol. 1. **Personalities and Institutions,** edited by John Neu (Mansell/Merrimack Book Service, Salem, NH, 1980). (A)

221. **Resources for the History of Physics,** edited by Stephen G. Brush (University Press of New England, Hanover, NH, 1972). The first part of this book is largely superseded by the present Resource Letter, except for a list of films; the second part is a "Guide to Original Works of Historical Importance and their Translations into Other Languages." (A)

222. **The History of Modern Science: A Guide to the Second Scientific Revolution, 1800–1950,** Stephen G. Brush (Iowa State University, Ames, 1987). Includes suggested readings, synopses and bibliographies for several topics in the history of modern physics. (I)

223. **The Biographical Dictionary of Scientists: Physicists,** edited by David Abbot (Blond Educational, London, 1984). (E)

224. **"The historical investigation of science in North America,"** Frederick Gregory, Z. Allg. Wiss. **16,** 151–166 (1985). Includes discussion of recent trends, books, list of research centers, and degree programs. (A)

Student understanding in mechanics: A large population survey

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There has recently been a considerable growth in research probing student understanding in mechanics. Questions based on four such research probes were included in the end-of-high-school physics examination undertaken by some 5500 students. The results obtained give an indication of the extent to which various interpretations of some physical situations are held in a whole population. The possibilities of using research probes as a basis for assessment questions are also illustrated.

I. INTRODUCTION

Concern with the nature and development of understanding in physics learners has been evident in many articles in this Journal in recent years. One growing dimension of this concern has been the consideration of the beliefs about natural phenomena that students bring to physics classes. These student beliefs have been described by a variety of labels: preconceptions, alternative frameworks, misconceptions, naive theories. Investigations of student beliefs have been common in the content area of classical mechanics (e.g., Champagne *et al.*,[1] Clement,[2] Trowbridge and McDermott,[3] and Whitaker[4]) but have also explored a wide range of other topics. Interpretative reviews of this area are now available, both in the area of mechanics (e.g., Gunstone and Watts[5] and McDermott[6]) and for science more generally (e.g., Driver and Erickson[7]).

As a consequence of this research, we can now confidently assert a number of propositions relating to the learning of a variety of introductory physics topics: (i) students very frequently have beliefs about/ways of interpreting physical phenomena that develop before they experience formal study of physics; (ii) these beliefs/ways of interpreting often differ in significant ways from those that students are expected to learn in physics; (iii) the beliefs relating to a particular phenomenon show consistency across diverse samples of students; (iv) the beliefs are remarkably resistant to change by exposure to traditional instructional methods.[8] The fourth of these propositions is a particularly significant one from the point of view of physics teaching. Part of the support for the proposition comes from the observation that students can often achieve success on standard end-of-course tests, while still retaining their preinstruction beliefs. For example students may well use $g = 9.8$ throughout a test, but continue to interpret the real-world phenomena around them via a belief that "heavier objects fall faster because they are heavier." Successful application of Newton's Laws to standard dynamics problems is often accompanied by a retention of the view that, in the real world, motion implies a force. It seems clear that the sort of understanding recently argued to be crucial in introductory physics courses by Arons[9] and Hewitt[10] is not possible in these cases.

The present article considers data about some student beliefs in mechanics that have been obtained from the end-of-high-school examination in physics in the state of Victoria. There are two purposes in this presentation. First, these data give a picture of the extent of particular beliefs in a whole population of students (with some reservations, as discussed below). Second, the data provide an illustration of the possibility of using existing research studies to generate assessment questions which probe student beliefs.

II. THE CONTEXT OF THE DATA COLLECTION

High schools in the state of Victoria take students from years 7–12. Virtually all schools teach general science courses to all students in the first 4 years of high school. The curriculum becomes more specialized in years 11 and 12. In these final 2 years, the subject of physics is undertaken by a minority of students, as one of six subjects in year 11 and one of five subjects in year 12. Physics is usually taken only by those students choosing a specialist mathematics and science course in years 11 and 12. A simple guide to the content covered in this 2-year course is given by the fact that it has evolved from the Physical Sciences Study Committee (PSSC) course. The mechanics content of the present course is roughly that covered by PSSC.

In physics, as with the majority of current year 12 subjects, students sit for a single, statewide examination at the end of year 12. This examination is set and marked external to the school. It contributes 70% of the student's final grade for the physics course. (The remaining 30% is derived from school-based assessment of optional physics units selected by the school.) The combined final grading in all subjects undertaken by a student in year 12 is used for selection into tertiary courses. Hence a subset of those students undertaking the physics examination at the end of year 12 comprise the Victorian component of the first-year physics population in tertiary institutions in this state.

The physics examination currently contains 80 questions, each worth a single mark. Questions are all either multiple choice or short problems (numerical or symbolic). Only the answer to each question is recorded on an answer sheet for correction. That is, none of the working used to derive an answer is presented on the answer sheet. Because of this format, questions calling for a verbal, graphical, or diagram response are written in multiple choice format. The paper is set by a panel who generate approximately twice the number of items required. These are tested, and both the results of the trials and coverage of course objectives and content are used to select the final paper. The resulting paper has for many years been, in terms of test statistics, an excellent example of this form of assessment; e.g., for the eight years (1977–1984) that the examination has been 80 items in length, the reliability of the exam, as assessed by the Kuder–Richardson formula 20, has varied between 0.92 and 0.95.[11]

In the 1983 examination, a number of mechanics questions were based on probes of student thinking which have been used in studies of student beliefs in physics. Inspection of the answer sheets of the 5534 students who sat for the exam generated the data discussed below.

Table I. Responses to rocket problem ($n = 5534$).

Answer	n	%
A	673	12.2
B	1201	21.7
C	479	8.7
D	527	9.5
E	2171	39.2
F	467	8.4
Other[a]	9	0.2
No ans.	7	0.1
Correct first section (D + E + F)		57.1
Correct second section (B + E)		60.9

[a] Other answers included dual answers, e.g., "A and E," and answers other than A–F, e.g., "4," the number of the question on the examination.

III. RESULTS

The questions are considered in the order in which they appeared in the examination paper. All were explicitly derived from research about student thinking. The questions involved appear in the Appendix to this article.

A. The rocket problem (see Question A in the Appendix)

This question is a multiple choice form of one used by Clement.[12] In its original form, the question was essentially as shown here, but open ended. The multiple choice form combines the two basic features found by Clement for student beliefs about the first section of the rocket's path (straight line or parabola), and the three basic features for the second section (continuance of path from first part reversion to horizontal, partial reversion to horizontal).

Results are shown in Table I. It can be seen that 57% correctly answered the first part of the question (path between Q and R) and 61% correctly answered the second part (path after R). Clement's data showed: for 150 prephysics engineering students, 11% correct on first part and 38% correct on second; for 37 engineering students after two semesters of physics, 35% correct on first part and 65% correct on second.

B. The pendulum problem (see Question B in the Appendix)

This question is also a multiple choice form of an open-ended question used by Clement.[13] The same situation has been used by others in the consideration of student beliefs.[14] Again, distractors have been generated on the basis of knowledge of student beliefs about the situation. For these sorts of situations the overwhelmingly common misconception is that a force must act in the direction of motion, hence alternative D. Alternatives A and C (which include a sort of "centrifugal" force) were seen as likely to be far less popular.

Results are shown in Table II. As expected almost all of the incorrect responses involve a force in the direction of motion, and most of them were the correct answer with a

Table II. Responses to pendulum problem ($n = 5534$).

Answer	n	%
A	66	1.2
B	4369	78.9
C	104	1.9
D	986	17.8
Other[a]	9	0.2
No ans.	···	···

[a] Of the other answers, seven were "B and C," one was "9," the number of the question on the exam, and one was uninterpretable.

force in the direction of motion added (alternative D). These results are broadly similar to those found by Viennot[15] with 60 first-year university students enrolled in a science degree. She used open-ended questions that asked for the resultant force acting on a pendulum bob at a number of positions. For the position similar to that in Question B, and with a velocity vector also shown so as to indicate that motion was towards the extreme displacement of the bob, 28% indicated that the resultant force was in a direction broadly similar to the direction of motion.

C. The pulley problem (see Question C in the Appendix)

In this case the question is taken from research done with first-year university physics students by Gunstone and White.[16] In that research, the demonstration described in Question C in the Appendix was actually performed. The apparatus used comprised a bicycle wheel (shown to be able to turn freely) mounted on a stand, an 18-liter plastic bucket of sand, and a large piece of wooden fence post. After the wood had been pulled down, it was held at the lower position while subjects wrote their prediction as to what would happen when the block was released. Similar open-ended questions asked for reasons for the prediction, the observation made when the wood was released, and for a reconciliation between prediction and observation if appropriate.

In the generation of the question for the year 12 examination, a more conventional apparatus was used in the description of the situation. The multiple choice question took common incorrect predictions and explanations from the original research as distractors. The performance of the year 12 population on this question is shown in Table III.

Table III. Responses to pulley problem ($n = 5534$).

Answer	n	%
A	995	18.0
B	2532	45.8
C	556	10.0
D	1436	25.9
Other[a]	4	0.1
No ans.	11	0.2

[a] All four other answers were "C and D."

Table IV. Responses to bouncing ball problem ($n = 5534$).

Response	n	%	Mean score on remaining 79 questions for group giving this response (sample, $n = 1020$)
A	1258	22.7	41.3
B	1400	25.3	37.4
C	1549	28.0	48.5
D	1303	23.5	39.8
Other[a]	13	0.2	34.0
No ans.	11	0.2	35.4

[a] Other responses included dual responses, e.g., "A and D," the number of the question on the paper, and one uninterpretable.

In the initial use of this situation, Gunstone and White[16] had 466 open-ended responses from their sample of first-year university physics students. Of these, 253 (54%) predicted that the wood would not move. A small number of these indicated a belief that movement would occur if less friction were present. The huge majority of other responses predicted that the wood would return to its initial position (204, 44%). By far the most common reason given in support of that prediction involved the use of equilibrium (alternative D in the question.

D. The bouncing ball problem (see Question D in the Appendix)

This question is taken from work by Warren.[17] Unfortunately, in reporting the use of an open-ended form of this question, he gives no substantive detail of the nature of answers given by university students. He does, however, indicate that the response that the force exerted on the ball by the table is equal to mg is "common."

In this case then, the multiple choice question used could not incorporate distractors based directly on knowledge of student interpretations of the same situation. Instead, distractors were based on more general considerations of student beliefs. Distractor B was based on an understanding of some of the student beliefs related to elastic and inelastic collisions, while A and D involved common conceptual problems with Newton's third Law. Results are shown in Table IV.

Since broadly similar proportions selected each of the alternatives, an initial reaction to these data may be that there was widespread guessing involved in answering the question. However, this seems most unlikely given the additional information contained in Table IV. This shows that, for a random sample of about 20% of the population, the mean score on the remaining 79 questions of those who selected the correct response was between seven and nine marks higher than the mean score obtained by students selecting each of the other alternatives. Put another way, the point biserial correlation between score on this question and score on the remainder of the examination was 0.30. That is, students correctly answering this question were likely to perform better on the paper as a whole. This would not be the case for random guessing responses.

IV. DISCUSSION

Two purposes underlie the reporting of these data: indicating the extent of various beliefs about situations in a whole population and illustrating the use of probes of student thinking as a source of assessment questions. The two purposes are discussed in turn.

There are two good reasons for believing that these results give an underestimate of the extent of various beliefs in this population. First, the format of the examination required that the correct answer was placed in front of students. Given the context in which this was happening (70% of course mark being derived from this single examination), it would clearly be unwise to assert that all who gave the correct answer would accept the validity of that answer. Some authors[18] have pointed to examples of students using a physics analysis to solve a problem in a physics context (such as this examination) while interpreting the same phenomenon in the everyday world via a different belief. That is, to consider the pendulum question described in this paper by way of example, it is very likely that some unknown proportion of students correctly answering about the forces on the pendulum will still be interpreting real-world phenomena in terms of "a force is needed in the direction of motion to keep something moving."

The second reason for believing that the data are an underestimate of the extent of beliefs about situations is a more obvious one: some of the specific situations may have been familiar to some students. The views of learning underpining the questions presented here (as discussed in the Introduction to this paper) have been presented in Victoria at in-service physics teacher meetings and in science teacher journals since 1979. The possibility of familiarity is particularly strong for the pulley problem. (Question C in Appendix.) This situation has been used on a number of occasions in in-service meetings, with the apparatus involved in the original research study (bicycle wheel, bucket of sand, block of wood). In the six months following the exam, a considerable number of high school physics teachers approached the author to express sentiments of the form: "I know where that question came from; I've taught my students that; all of them will have got that question correct." So frequently did this happen that one is left with the absurd notion that, if these teachers were correct, *all* other students must have got the question wrong. (This suggests something is wrong with the strategy of just telling students the physics explanation of a phenomenon, an issue returned to briefly later in this article.)

Even though these data are then very likely an underestimate of the extent of particular beliefs in a whole population, it is clear that some beliefs are quite common. In presenting the above results, brief comparisons were made with results obtained from the use of very similar questions with research samples. These results were broadly consistent with the whole population data, which is the focus of the present article. This suggests any attempt to explain the results of previously reported studies of student beliefs in terms of the sample involved are clearly unreasonable.

In this population, 40% have interpreted the second section of the rocket problem in terms of a previous motion somehow reestablishing itself (see Table I). This, taken in conjunction with the approximately 20% indicating a force in the direction of motion for the pendulum (see Table II), might suggest a label such as "an impetus view of motion." However, there are dangers to be recognized in the use of such labels, as Lythcott[19] has recently argued. In brief, these dangers revolve around the fact that students rarely have a consistent interpretation across all possible phenomena. Their explanations are very likely to be influenced by the particular context in which the explanation is offered. For example, the situation described in Question C, the pulley problem, is one that has students thinking from some form of "intuition," or so-called "common sense" (words often used by students themselves in this case) more frequently than does a situation such as the pendulum problem, Question B.

The second purpose in presenting these data, as foreshadowed above, is the illustration of the use of probes of student thinking as a source of assessment questions. The examples contained here all represent the use of research on student beliefs to generate multiple choice distractors, as suggested by Iona.[20] The reviews referred to in the Introduction to this paper are a helpful source of particular beliefs likely to be appropriate distractors.

Of course, assessment questions do not have to be of the form required in the context described here. Each of the four questions described above could have been asked in open-ended form, or the multiple choice form used here could have been followed in each case by a seond question asking students to "explain your answer." In contexts other than the present one, questions such as C, the pulley problem, can be given with the actual demonstration being performed in the test. In this way, written predictions, explanations of predictions, and observations can all be asked for.

V. A BRIEF CONCLUDING COMMENT ABOUT INSTRUCTION

Accounts of research that probes student thinking about physical phenomena frequently, and most appropriately, conclude by drawing inferences for physics instruction.[21] The same general set of inferences could well be drawn here: teacher telling does not equate with student learning; student beliefs in physics can provide useful guidelines for the nature and sequencing of instruction; introductory physics involves difficult and abstract concepts, the understanding of which takes time; traditional forms of assessment often do not probe the nature of understanding; and so on.

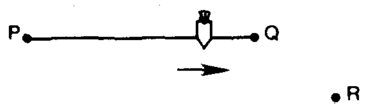
As suggested in the above discussion, there is even a strong suggestion here that students having been told about a specific situation (the pulley question) did not result in them interpreting that situation in the way their teachers expected.

Assessment is a significant issue in these problems. If our course assessments do not reward the level of understanding which is the focus for research of this *genre*, then it is hardly surprising if students do not seek that understanding. The nature of course assessment is often the most obvious source of student knowledge of course objectives. If our course objectives include understanding, so should our assessment.

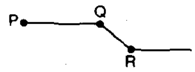
APPENDIX

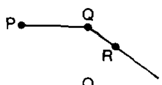
Question A: The rocket problem

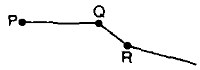
A rocket is drifting sideways from P to Q in outer space. It is not subject to any outside forces.

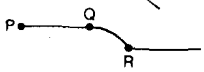


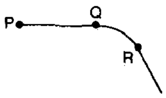
When the rocket reaches Q, its engine is fired to produce a constant thrust at right angles to PQ. The engine is turned off again when it reaches R. Which of the following (A, B, C, D, E, or F) best represents the path of the rocket?

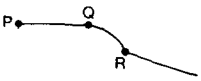
A


B


C


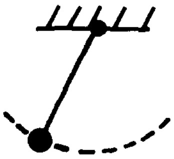
D


E


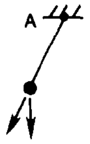
F


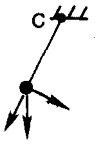
Question B: The pendulum problem

A pendulum bob is swinging from left to right.



When it is at the point shown, which of the diagrams below (A, B, C, or D) best represents the forces acting on the bob? Friction is negligible.





Question C: The pully problem

A teacher performs the following demonstration:
A sphere and a block are connected by a string placed over a pully. The two objects are at rest at the same level, as shown in Fig. 1.

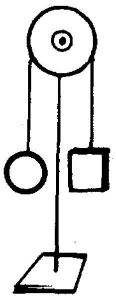


FIGURE 1

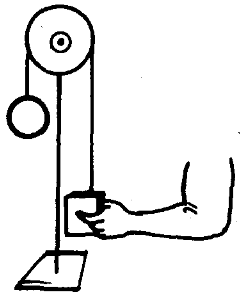


FIGURE 2

The block is now pulled down and held while in its new position, as shown in Fig. 2.

The teacher asks the class to predict what will happen in this real situation when the block is released, and to give a reason supporting and prediction.

Which of the following gives the best prediction and supporting reason?

(A) The block will move down because the gravitational force on the block will be greater at this lower level.
(B) The block will remain stationary because there will be no resultant force on the block.
(C) The block will move up and return to its original position because this will conserve potential energy.
(D) The block will move up and return to its original position because that was its equilibrium position.

Question D: The bouncing ball problem

A steel ball of mass m is dropped on to a steel-topped table from a height of 1 m. The ball is in contact with the table for 0.01 s and rebounds with only a very small loss of kinetic energy.

Which of the following statements best describes the average force exerted on the ball by the table during the collision?

(A) It equals the normal reaction force mg.
(B) It is slightly less than mg because the collision is not quite elastic.
(C) It is greater than mg.
(D) It is greater than the force exerted by the ball on the table, in order to make the ball rebound.

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[13] Reference 2, p. 67.

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[21] For example see Ref. 2, p. 70.

Bell's theorem: Does quantum mechanics contradict relativity?

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Special relativity demands a locality principle (no instantaneous action at a distance); locality implies Bell's theorem; quantum mechanics violates Bell's inequality, therefore, quantum mechanics contradicts relativity! Or so it would seem. It is shown, however, that the locality principle needed for Bell's theorem is stronger than the simple locality that is needed to satisfy the demands of relativity and that quantum mechanics satisfies the latter. The stronger locality principle is equivalent to the conjunction of simple locality and predictive completeness, and it is the latter principle that fails. The notion of predictive completeness is weaker than, and is implied by, the completeness criterion of Einstein, Podolsky, and Rosen. But the quantum mechanical state description is not only incomplete but incompletable, for any local complete state description would satisfy Bell's inequality and disagree with experiment.

I. INTRODUCTION

It is common knowledge that special relativity forbids instantaneous action at a distance and, more generally, that it forbids the propagation of energy or information at speeds exceeding the speed of light. This assertion has occasionally been subject to controversy, but after reviewing the relevant analysis in Sec. II, we shall conclude that in this