Promoting student crossover to the Newtonian world

R. R. Hake

Physics Department, Indiana University, Bloomington, Indiana 47405

(Received 21 July 1986; accepted for publication 30 December 1986)

A six-week noncalculus-based introductory course was designed and taught with the intention of promoting students' conceptual understanding of Newtonian mechanics. Primary emphasis was placed on (1) laboratories structured to induce Socratic dialogue; (2) lectures stressing a qualitative approach to problem solving, and contrasting Newtonian and students' non-Newtonian concepts of motion; (3) videotapes from *The Mechanical Universe* series. That the course was effective in promoting student crossover to the Newtonian world was suggested by student performance on pre- and post-course mechanics exams.

I. INTRODUCTION

As is well known, 1-5 improvement in science instruction is badly needed. Newtonian mechanics is perhaps the most extreme example of the failure of science teaching at the high school and beginning college level, 6-22 evidently because (1) Newton's laws violate common-sense interpretation of everyday experience, 6-22 and (2) understanding of the laws requires relatively advanced thinking processes that some^{1,3,22d,23} associate, at least partially, with the Piagetian²⁴ "formal operational" level.²⁵ Progress toward a solution of this extreme-case problem would be a hopeful sign for eventual improvement of science instruction generally. Halloun and Hestenes^{22a} (henceforth H²) recently demonstrated that introductory-course mechanics instruction based on conventional lecture-discussion methods produced rather small differences in pre- and post-course performance on a concept-oriented mechanics exam^{22a} designed by them to distinguish Newtonian from non-Newtonian thinkers. They concluded that conventional mechanics instruction "has little effect on the student's basic knowledge state," consistent with the views of Arons, and with mounting evidence at Indiana²⁶ and other^{6-15,17-21} universities. H² also concluded that "basic knowledge gain under conventional instruction is essentially independent of the professor."

In the light of the above research, ^{1-3,6-25} we recently attempted to design and instruct a 6-week, noncalculus-based course in introductory physics so as to promote student crossover to the Newtonian world. In the present article we describe the nature of the course and the students, the instructional techniques employed, and the preand post-course tests that suggest a degree of success for the present methods.

II. NATURE OF COURSE AND STUDENTS

Indiana University is rather typical of large state-assisted universities. It currently enrolls about 33 000 students on the main campus at Bloomington. To be admitted, Indiana residents "should have demonstrated above average achievement in a strong college preparatory curriculum, should rank in the upper half of their high school class, and should have attained an SAT total score above 850, or comparable ACT score."

Our pedagogical testing ground was the General Physics I course, P201, a noncalculus-based introductory course for science (but not physics) majors. (There is no engineering school at Indiana University.) According to the

course catalog, P201 topics are "Newtonian mechanics, wave motion, heat and thermodynamics." The prerequisites are "M126 or high-school equivalent." M126 is the math course "Trigonometric Functions," which in turn has the prerequisite M125 ("Pre-Calculus Mathematics") whose prerequisite is one year of high-school algebra. P201 is a 5-credit-hour course that, in a standard semester, normally consists of (a) large class-size (100-250 students) lectures (2.5 h/week) by professors; (b) smaller class-size (30-50 students) discussions (0.83 h/week) devoted to problem solving and led by graduate-student associate instructors ("AI's"); (c) rather standard introductorycourse laboratories (about 24 students each) of 1.9 h/week that emphasize data taking, error analysis, report writing. and "verifying" various principles and laws. 27 The labs are conducted by AI's who are supervised by a staff laboratory coordinator.

The present test course was the summer-session version of P201, which retains the total number of full-semester (14 class week) instructional hours but compresses the course into only 6 weeks. This is accomplished by increasing the number of hours per week roughly in the ratio 14/ 6 = 2.3: (a) lectures, 6.25 h/week, (b) discussions, 1.5 h/ week; (c) labs, 4 h/week. In the summer session the educational advantages of a smaller lecture section (in the present case 69 students started and 53 finished), and (for some students) concentration on a one-course curriculum, are probably more than offset by the disadvantage of the very rapid pace. The course was taught with two discussion sections (two AI's) and three lab sections (two AI's). The four AI's were relatively experienced and were urged to study some of the relevant literature. 1-25 A rather complete nine-page course "Information Sheet"26 was distributed to students at the start of the course.

We selected the well-known text by Sears, Zemansky, and Young. 28 Eighteen chapters (1–12; 14–19) of the text were assigned, thus "covering" Newtonian mechanics (3 weeks); elasticity, periodic motion, fluid statics (1 week); temperature, heat, thermodynamics (2 weeks). (We omitted the normally "covered" kinetic theory, mechanical waves, vibration, and acoustics.) Thus about three chapters per week were assigned, along with about 30 end-of-chapter problems per week, nine of which were submitted for grading. We tried to enforce fairly high grading standards with automatic point deductions for problem solutions with deficiencies such as "no sketch," missing or erroneous units, or physically absurd answers. Detailed solutions in the approved manner 28,29 were posted and made available for photocopying for all assigned problems

© 1987 American Association of Physics Teachers

878

Table. I. Some characteristics of the 53 test-course students.

1. CLASS: No.		Freshman 2		Sophomore 8		Junior 21			Senior 20				Graduate 2		
2. MAJOR Biology No. 18	Medical sciences 10	Chemist	ту	Psychology 3		Engineerin (visitors)			Geolo 2	ogy E	ducation 2	English 2	Business 2	Environmental science	
, ,		Medical school 15		Dental school 4		Physical therapy Medical Technology Sports medicine 5		Optometry school 2			Other graduate schools 21				
4. GRADE THOUGHT NEEDED IN P201: No.				A 30						B 20		No Response			
5. PREPARATION INDEX (P): No.				High 10					Average 14			Low 29			
6. FINAL COURSE GRAD)E	A		В		<u>-</u>	С		D				F	GPA (weighted	
No.	A + (4)	A (4) 5	A - (3.7) 6	B + (3.3)	B (3.0) 6	B — (2.7) 7	C + (2.3)	C (2.0) 14	C – (1.7) 6	D+ (1.3) 0	D (1.0) 3	D – (0.7)	F (0) 0	average) 2.66	

after their due dates. The final course grade was determined by two 75-min exams (30%), one 150-min comprehensive final exam (30%), a laboratory grade (20%), and a homework grade (20%). Lack of time and personnel forced the exclusive use of multiple-choice tests. The average final course grade was 2.66 (row 6, Table I). The average P201 course grade for classes in the years 1980–85 is 2.49, about midway between C + and B -

At the start of the course we required students to complete an "Academic Background Questionnaire." Information thus generated on the 53 students who completed the course is shown in rows 1-4 of Table I. Also shown in rows 5 and 6 are distributions of the "Preparation Index" (Sec. IV), and the final course grades. In addition, student responses indicated that 74% had completed a high-school physics course, 51% had completed a high-school calculus course, and (somewhat surprisingly) 91% had completed a university calculus course. Forty-two percent of the present class were female.

III. INSTRUCTIONAL INNOVATIONS

A. Socratic dialogue inducing (SDI) labs

Two SDI labs on Newton's laws,²⁶ each of 4-h length, were conducted during the first 2 weeks of the present course. (During the next 3 weeks the class reverted to the standard introductory-course labs.) The SDI labs are in some ways similar to those employed previously with apparent success at the Universities of Washington, ^{13,14,31} Massachusetts,^{7b} and Nebraska,¹⁵ and at Indiana University.²⁶ They are more-or-less in the spirit of the Piagetian school ^{15,23,24} and recent similar standpoints of the "cognitive sciences." The SDI labs emphasize hands-on experience with simple concrete mechanics experiments and are designed to promote concept formation through "disequilibration," ^{15,23,24} discussion, and Socratic dialogue. ^{1,31} Many of the experiments have been selected from the literature ⁶⁻²¹ as those for which common sense understanding is contrary to the Newtonian viewpoint.

Each of the two SDI lab write-ups is about 24 pages long and provides blank quadrille-ruled spaces for student sketches and answers. The write-ups force active student involvement and thinking by requiring or inducing them to

- (1) Write down operational definitions^{28,31,33} of terms used in mechanics: e.g., vertical, horizontal; displacement; average velocity and acceleration; time interval; instant of time; "clock-reading"; instantaneous quantities: position, velocity, and acceleration.
- (2) Perform (sometimes predict and then perform) simple hands-on experiments (see Appendix) involving a BODY at rest or in motion.
- (3) Draw diagrams, usually at sequential instants of $time^{29}$ ("snapshot sketches at various 'clockreadings'"), showing (a) color-coded vectors to indicate "ALL the forces acting ON the BODY" and (to facilitate understanding of Newton's-Third-Law action-reaction couples) labeled as $F_{\text{on A by B}}$ (where A is the BODY and B is some other interacting body); (b) color-coded velocity and acceleration vectors "if they exist." It is insisted that students always draw vectors with tails on the BODY.
- (4) As the experiments proceed, discuss with other students and then write down answers to questions (see Appendix) that probe for reasoning skills and basic conceptual understanding of Newton's laws. The question format is such as to require rather complete explanations, justifications, and/or sketches and not simply yes-or-no answers.
- (5) If stumped or confused on any of the above (after serious effort and discussions with other students) engage in Socratic dialog with an instructor.

During each lab session most students appeared to exert considerable effort to understand the material and there was much discussion among students. Student behavior was consistent with Piagetian ideas 15,23,24 that people feel uneasy about disequilibrating experiences and spontaneously seek to reorganize their understanding. The two or three instructors present at each session were almost continually occupied in discussions with students, either individually or in groups of 2–4. These instructor–student discussions were more-or-less Socratic, depending on the skills, knowledge, and experience of the instructors. Ideally, the Socratic method would involve questioning students in such a way that they would be led to express their ideas and figure things out for themselves. In practice, our lab instructors often fell short of this ideal, but improved with

time. We recommend that at least one experienced Socratic dialogist (preferably the professor) be present at lab sessions to act as a second and role model for less experienced instructors. It is, of course, essential that the instructors themselves have a thorough understanding of Newtonian mechanics and preferably some familiarity with the pertinent instructional literature. 1-25

Students were required to hand in their filled-in lab write-ups at the end of the lab period. Instructors reviewed and annotated the reports but it was decided at the end of the first week's lab sessions that it would be counterproductive for lab AI's to assign lab report grades. Any student whose work indicated substantial confusion on a lab section was requested to repeat that section at the next lab period. A lab grade for the two SDI labs was derived from a lab exam that comprised the first half of the first 75-min exam given at the start of the third week. The lab exam also counted for 50% of the first exam grade. Student awareness (after the first week) that a lab exam grade would count for 17.5% of the final course grade may have reinforced any spontaneous disequilibrium-reorganization effort to understand the lab material.

B. Quasi-Gutenberg³⁴ lectures

About 70% of the lecture time was devoted to

- (1) problem solving that emphasized initial qualitative analysis^{1,29} and vector diagramming, ^{28;29;31a,e} both similar to those required in the SDI labs;
- (2) contrasting Newtonian concepts with students' non-Newtonian (pre-Aristotelian, Aristotelian, medieval, or simply muddled) ideas on motion;
- (3) posing and then attempting to induce class discussion of qualitative, conceptually oriented questions;
- (4) demonstrations (sometimes associated with problem solutions):
- (5) showing videotapes from the *Mechanical Universe* series (see below).

Thus no concerted effort was made to paraphrase or interpret the text. On the other hand, students were held responsible for text material as regarded homework problems and exams. In principle, the Gutenberg lecture method facilitates such strategy because it "recognizes the invention of the printing press" and attempts to induce students to study the text on their own. In practice we were forced to retreat to a quasi-Gutenberg mode because students seemed to spend all their time working on the nine hand-in problems per week and to neglect study of text sections not directly relevant to immediate grades on homework or labs until just before the exams.

C. The Mechanical Universe videotapes³⁵

We showed 14 of the half-hour videotapes in *The Mechanical Universe* series. In our judgment, these tapes were particularly effective in placing Newtonian mechanics in a historical perspective; dramatizing the historical overthrow of Aristotelian and medieval ideas; illustrating the diverse nature of scientists and the scientific endeavor; stimulating student interest and enthusiasm; and, through excellent animation, illustrating the time dimension of certain mechanics concepts. The companion text (Ref. 35) was placed on library reserve for the course but was not extensively utilized by students. Both the SDI labs and the lectures made frequent references to material that had been

presented by means of the tapes. The Mechanical Universe's overt calculus orientation was a refreshing reinforcement of the class text's covert calculus emphasis and bolstered our efforts to explain instantaneous quantities: position, velocity, acceleration.

IV. PRE- AND POST-COURSE TESTS

At the start of the present course we required all students to take pre-course mathematics and mechanics tests. The mathematics exam covered only pre-calculus mathematics, primarily algebra and trigonometry. Although both tests were nearly identical to those given by H² at Arizona State ^{22a,c} (henceforth referred to as "H² tests"), there was a difference in administration of the exams. At Arizona State both the exams were taken by students in one 50-min session (students started on the mechanics exam, which was collected after 30 min). ^{22c} At Indiana the tests were given on separate days and students were allowed a full hour for each exam.

As a measure of the effort that would be required on the part of the students and instructors (and following Ref. 22a,c), we utilized pre-course scores on H^2 tests to define a preparation index P:

```
P(\max 64) = S_{\text{mech}} + S_{\text{math}},

S_{\text{mech}} \pmod{36} = \text{correct responses on mechanics exam},

S_{\text{math}} \pmod{28} = \text{correct responses on math exam},

with P's grouped as
```

```
"High" when P \geqslant 40,

"Average" when 30 < P < 40,

"Low" when P \leqslant 30.
```

The pre-course math and mechanics scores, as well as P's, were posted by student ID numbers shortly after the exams. Students with "low" P's [55% of the class (Table I, row 5)] were urged to work especially hard and those with low scores on the math test were advised to brush up on algebra and trigonometry.

At both Arizona State and Indiana the H² mechanics test was given (without warning) as part of the final exam. Here again, the Arizona State exam was collected after 30 min,^{22c} whereas at Indiana students were given a full hour for the exam (most of them finished well before this and proceeded to the second part of the final exam).

Table II shows the pre- and post-course H²-test results at Arizona State^{22a} and at Indiana University. Since these institutions are rather similar large state universities 22a and have similar admissions requirements^{22a} it would seem that average math exam performance of students entering the noncalculus-based physics courses should be similar. We suspect that the 18% better performance of Indiana students on the pre-course math test (Table II, column 3) may reflect only the longer time they were given (and appeared to need) for completion of the exam, although their relatively advanced [see Sec. II (91% had taken a university calculus course) | mathematics backgrounds may also have played a role.³⁷ On the other hand, the qualitative nature of the mechanics exam was such that one would not expect the longer time given Indiana students (which they did not appear to need) to be very important, consistent with the fact that the pre-course mechanics scores differ by only 4% (Table II, column 6).

Table II (columns 6 and 9) shows an improvement of average H² mechanics test scores from 41% for the pre-

Table II. Pre- and post-course mechanics and mathematics test results for noncalculus-based introductory physics courses.

Institution (1)		Pre-course math test			Pre-course mecl	nanics t	Post-course mechanics test			
	Number of students (2)	$Mean \equiv M$ $[(M/28) \times 100]$ (3)	SD ^c (4)	KR ^d (5)	Mean $\equiv M$ [$(M/36) \times 100$] (6)	SD ^c (7)	KR ^d (8)	$ \text{Mean} \equiv M \\ [(M/36) \times 100] \\ (9) $	SD ^c (10)	KR ^d (11)
Indiana Univ.ª	53	15.47 (55%)	4.66	0.75	14.81 (41%)	5.32	0.77	26.23 (73%)	4.64	0.81
Arizona State ^b	82	10.48 (37%)	4.58		13.48 (37%)	5.00		19.00 (53%)	5.16	

^a Present work, math test same as Ref. 22a. Mech. test same as Ref. 22a except for minor corrections and clarifications (Ref. 22c, Ref. 26).

course exam to 73% for the post-course exam. The latter grade is 20% higher than the corresponding score of non-calculus-based-course students at Arizona State who took a "conventional" introductory lecture-discussion course with (for most students^{22a}) concurrent labs, presumably of the standard introductory course type. It might be objected that the present relatively superior performance on the post-course H² mechanics test is an artifact stemming from a tendency of present SDI labs to "teach" the H² test. We think that such "test-teaching" might account for correct answers on five of the H² test^{22a} questions (1,3,8,16,21) but would not account for the entire average gain of 11.4 questions (Table II, columns 6 and 9).

In a recent study similar to the present work, H² (Ref. 22c) observed an improvement of average scores on the H² mechanics test from 48% for the pre-course exam to 75% for the post-course exam for one test group "TG3." The latter was comprised of calculus-based-course students in a full standard-semester course who received "modeling instuction" in lectures conducted by Hestenes and "paradigm problem" instruction in discussons by Halloun. The discussions were expanded from the usual 1 h week to 3 h/week for the half-semester devoted to particle mechanics, and also included "a systematic effort to eliminate common-sense misconceptions." Thus it would appear that there are at least several ways to enhance student understanding of mechanics over that achieved in conventional instruction.

V. CONCLUSIONS

We have described a rapid-pace, noncalculus-based, introductory physics course with various innovations in labs and lectures designed to promote student understanding of mechanics. Pre- and post-course mechanics exam scores suggest that student crossover to the Newtonian world has been significantly enhanced over that which occurs for conventional instruction.

More work is required to better establish that the present innovations are actually effective, to test them in standard large-enrollment full-semester courses, to assess their relative importance in contributing to student understanding, and to further improve their value. Experiments more rigorously controlled than the present are, of course, desirable. In order to reduce possible "test-teaching" effects, it might be advisable to have pre- and post-course exams de-

vised and administered independently of the teaching staff. Student Interviews^{7-9,11-13,19b,22b} before and after the course could provide useful information to supplement and check written examination results. It would be worthwhile to gauge knowledge retention by exams and/or interviews administered a year or so after the course. "Peer perspective" studies, 39 might yield some valuable insights. In a recent such program at Indiana University, 40 10 nonphysical-scientist professors (Folklore, Psychology, English, Classics, Economics, Music, Fine Arts, etc.) took P201 with the presently discussed innovations for three standard-semester weeks. Their pre- and post- course H² test averages (46.4% and 71.4%) suggested a reasonable knowledge enhancement, considering their relatively small time input. Many of the professors said that the SDI labs and the Mechanical Universe videotapes contributed substantially to their learning.

We suspect that SDI labs were an important positive factor in the present course design. Among their advantages are (1) they are generally well received and popular⁴¹ with students; (2) laboratory equipment needs and expense are minimal; (3) they are adaptable to a wide range of student populations, including those of large enrollment university courses in introductory physics; (4) their conceptual and verbal orientation should appeal to nonscience and/or nonmathematically oriented students; (5) they should serve to promote cognitive development^{23-25,32}; (6) they provide excellent pedagogic training grounds for graduate-student instructors and faculty who may, after posing a question, discover undreamed-of learning problems by shutting up and listening to students^{1,24,31}: (7) they diminish the impersonality of large-enrollment university courses and afford some degree of individual student attention; (8) they effectively supplement and reinforce textbook, lecture, and discussion material. It may eventually be possible to program computers⁴² to assist in some phases of Socratic-dialog-type promotion of Newtonian thinking, but the present experience suggests that input from instructors with extensive mechanics SDI-lab experience would be required.

ACKNOWLEDGMENTS

We wish to thank D. Hestenes for providing us with the mathematics pretest used at Arizona State and for preprints of Ref. 22c,d. We have benefited from correspon-

^b Ref. 22a. These data are for professor "E's" class, the only class for which post-course mechanics exam scores were available in the noncalculus-based courses tabulated in Table I of Ref. 22a.

SD = Standard deviation.

^d KR ≡ Kuder-Richardson reliability coefficient (Ref. 36).

dence with A. B. Arons, A. Bork, L. C. McDermott, and R. J. Whitaker; and from suggestions by R. D. Bent, R. G. Fuller, A. Hendry, W. Krejci, F. M. Lurie, S. Tobias, and G. E. Walker. The Funky Winkerbean cartoon strip (Appendix) appears by permission of News America Syndicate, copyright 1985.

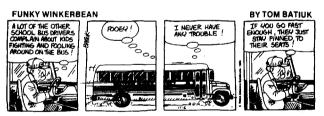
APPENDIX

The nature of a few of the SDI lab exercises and questions is indicated below in a very abbreviated outline form. The apparent triviality of some of the exercises and questions is deceptive, since for brevity we do NOT explicitly include the instructions which require (a) time-sequential vector diagramming for most excercises as indicated in Sec. III A3 (marked by asterisk) and (b) thoughtful explanations, justifications, and/or sketches for the questions (not simply yes-or-no answers).

A common attitude⁴³ of physics faculty towards exercises of the present type is that they are too elementary and nonanalytical to be worthwhile beyong the grade- or high-school level. However, the bulk of current research, as well as the present experiment, contradicts this view. Grave student difficulties for all these exercises were apparent in the present work and have been reported for

- (a) Ex. (1) by university students, ^{31c}
- (b) Ex. (4b), (5c), (13a) by university physics honor students, 17
- (c) Ex. (5d), (6c), (13b) by university students who had and had not taken physics courses, 9,10
 - (d) Ex. (12) and (13a) by university students,⁶
- (e) Ex. (10) and (13a) by pre- and post-mechanics course university engineering students,⁷
- (f) Ex. (8a) by university calculus-based-physics-course students, ^{12a}
 - (g) Ex. (6b) by university students, ¹³
- (h) Ex. (1), (4-6), (10), (13) by univesity physics majors and engineering students and by high-school physics teachers, ^{31c}
- (i) Ex. (13a) by university physics students and some physics professors!^{2b}
- 1. Operationally define "vertical" and "horizontal."
 - a. How would you tell "up" from "down," a crow from a crocus?⁴⁴
- 2. Hold two permanent magnets close together but not touching.*
 - a. Do you think noncontact (action-at-a-distance) forces exist?
- 3. Hold a 1-kg mass stationary in the palm of your hand.*
- 4. Hold a 1-kg mass in the palm of your hand and move it a. vertically upwards with an increasing velocity,*
 - b. horizontally across the room with a constant velocity.*
 - (1) Is the mass in equilibrium?
 - (2) Is there a horizontal force vector acting on the mass?
 - (3) Is the force exerted on the mass by your hand equal and opposite to the force exerted on the mass by the Earth?
 - (This illustrates Newton's _____Law.)
 - (4) Is the force exerted on the mass by the Earth equal and opposite to the force exerted on the Earth by the mass?
 - (This illustrates Newton's ____ Law.)

- (5) Is the force exerted on the mass by your hand equal and opposite to the force exerted on your hand by the mass?
 - (This illustrates Newton's ____Law.
- 5. Take a wooden block and
 - a. Place it at rest on a table.*
 - b. Give the block a tap (impulsive force) in a horizontal direction so that it slides on the table. While the block is sliding but not in contact with your hand*:
 - (1) Is the *NET* vector force exerted on the block by the table equal and opposite to the force exerted on the block by the Earth?
 - c. Push the block across the table with a nearly constant horizontal velocity v. During this motion*:
 - (1) Is there a *NET* horizontal force acting on the block?
 - d. Give the block a push so that it slides across the table and is projected horizontally into the air; while in the air*:
 - (1) Is there a horizontal force vector acting on the block?
 - (2) Is there a vertical force vector acting on the block?
- 6. Take a 5-25-kg dry-ice block and place it on an approximately 1×2 m glass surface. 45
 - a. Repeat 5a,b.*
 - b. Predict the path and then give the block a tap (impulsive force) in a direction *perpendicular* to its direction of motion as it slides on the glass.*
 - c. Predict the path and then release the block after moving it along a curved path.
- d. Predict and then determine the motion of the block after being hitched to a flea (if a flea is unavailable show the PSSC videotape "A Million to One" 146).
- 7. A Funky Winkerbean cartoon strip shows a set-jawed old codger driving a school bus. He says "Fooey, I never have any trouble" (with kids). "If you go fast enough they just stay pinned to their seats."*
 - a. Is there a horizontal force vector on the kid?
 - b. Is the kid pinned to her seat?
 - c. How might a bus driver pin a kid to her seat by control of the bus motion?



8. Take positions as shown in Fig. 1. When the weakly pushed block #1 is about one-quarter of the way across the table, strong student B pushes his/her block #2 so that it passes block #1.

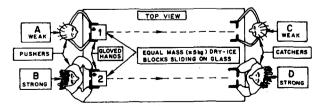


Fig. 1. Students pushing and then catching dry-ice blocks as explained in the text. [This and all other sketches in SDI-lab write-ups are *free-hand* drawings designed to illustrate sketching technique (unknown to most students).]

- a. Considering only the motion of the blocks when they are *NOT* in contact with the students hands, would you predict that for this motion the velocities of the two blocks are ever equal?
- b. Do the above experiment.*
- 9. Take positions as in Fig. 1. Both students apply forces starting at t=0 which are constant in time over the same short time span, the only difference being that strong student B applies the larger force. Consider the motion of the blocks over the time interval Δt from t=0 until just before block #2 makes contact with student D's hands.*
 - a. Are the velocities of the two blocks equal for any clockreading within the above specified time interval Δt ? (Graph v vs t.)
 - b. Are the accelerations of the two blocks equal for any clockreading within the above specified time interval (Graph a vs t).
- 10. Throw a ball vertically upward so that it rises to a point near the ceiling and then falls to the floor.*
- 11. Throw a ball across the room in an arc.*
- 12. Juggle six balls simultaneously. Draw F, v, and a vectors for all balls at an instant in time when none of the balls is in contact with your hands.
- 13. Set a steel pendulum bob in motion.
 - a. Show time-sequence F, v, and a diagrams for the motion from the top of its path on one side of the swing to the top of its path on the other side of the swing.
 - b. For the above motion, predict the path and then arrange to release the bob from its constraint when the bob is moving upward and is midway between the bottom and top of its path.
- 14. Simultaneously release a light sheet of paper and a heavy steel ball from the same height above the floor with the
 - a. plane of paper horizontal.*
 - (1) Do your observations support Aristotle's contention that heavier bodies fall faster than light bodies?
 - (2) Is the above experiment in error?
 - b. paper sheet crumpled into a ball.*
 - (1) How would you explain the nearly simultaneous impact of the paper and steel balls with the floor to an Aristotelian friend?
- ¹A. B. Arons, Am. J. Phys. **41**, 769 (1973); **42**, 157 (1974).
- ²F. Reif, (a) Science **184**, 537 (1974); (b) Phys. Today **39**, 48 (Nov. 1986).
- ³D. Hestenes, Phys. Teach. 17, 235 (1979).
- ⁴National Commission on Excellence in Education, "A nation at risk: the imperative for educational reform" (U.S. Department of Education, Washington, D.C., April 1983) reviewed in Phys. Today 36, 44 (June 1983) and by G. T. Seaborg, Science 221, 219 (1983).
- ⁵Report of the National Science Board Task Committee on Undergraduate Science and Engineering Education, reported in Science 232, 153 (1986) and in Phys. Today 39, 65 (June 1986). ... "the deterioration of collegiate science, mathematics, and engineering education is a grave long-term threat to the nation's scientific and technological capacity, its industrial and economic competitiveness, and the strength of its national defense."
- ⁶L. Viennot (a) Eur. J. Sci. Educ. 1, 205 (1979); (b) Am. J.Phys. **53**, 432 (1985).
- ⁷J. Clement, (a) Am. J. Phys. **50**, 66 (1982); (b) Seven laboratories (Univ. of Massachusetts, 1978, unpublished).
- ⁸A. A. DiSessa, Cognitive Sci. 6, 37 (1982).
- ⁹M. McCloskey, Sci. Am. 248, 122 (April 1983).

- ¹⁰M. McCloskey, A. Caramuzza, and B. Green, Science 210, 1139 (1980).
- ¹¹A. B. Champagne, L. E. Klopfer, and J. H. Anderson, Am. J. Phys. 48, 1074 (1980).
- ¹²D. E. Trowbridge and L. C. McDermott, (a) Am. J. Phys. 48, 1020 (1980); (b) Am. J. Phys. 49, 242 (1981).
- ¹³L. C. McDermott, Phys. Today 37, 24 (July 1984).
- ¹⁴M. Rosenquist and L. C. McDermott, laboratory module 2 "Kinematics" with instructor's guide (3rd trial edition, Univ. of Washington, 1982).
- ¹⁵R. G. Fuller, Phys. Today 35, 43 (Sept. 1982); Piagetian Programs in Higher Education, edited by R. G. Fuller (ADAPT, Univ. of Nebraska-Lincoln, 1982).
- ¹⁶J. Minstrel, (a) Phys. Teach. 20, 10 (1982); (b) in 1984 Association for the Education of Teachers Yearbook, edited by C. W. Anderson (1984).
- ¹⁷P. C. Peters, Am. J. Phys. 50, 501 (1982).
- ¹⁸R. J. Whitaker, Am. J. Phys. **51**, 352 (1983).
- ¹⁹B. Y. White, (a) Cognitive Instruct. 1, 69 (1984); (b) Cognitive Sci. 7, 41 (1983).
- ²⁰L. B. Resnick, Science **220**, 477 (1983).
- ²¹P. W. Hewson, Am. J. Phys. **53**, 684 (1985).
- ²²I. A. Halloun and D. Hestenes, (a) Am. J. Phys. 53, 1043 (1985); (b)
 53, 1056 (1985); (c) 55, 455 (1987); (d) D. Hestenes, 55, 440 (1987).
- ²³See, e.g., J. W. McKinnon and J. W. Renner, Am. J. Phys. 39, 1047 (1971); A. B. Arons and R. Karplus, Am. J. Phys. 44, 396 (1976); E. L. Chiappetta, Sci. Ed. 60, 253 (1976); W. T. Griffith, Am. J. Phys. 53, 839 (1985)
- ²⁴B. Inhelder and J. Piaget, The Growth of Logical Thinking from Childhood to Adolescence (Basic, New York, 1958); J. H. Flavell The Developmental Psychology of Jean Piaget (Van Nostrand, Princeton, 1963).
 For a recent assessment see H. Gardner, Frames of Mind (Basic, New York, 1985).
- ²⁵According to Piaget, the "formal operational" level is characterized by the ability to form theories, consider "that which is not," isolate and control variables, and use proportional reasoning and propositional logic. Piaget's early research suggested that most people become "formal operational" thinkers by the age of 15 or 16 but Chiappetta's review (Ref. 23) of more recent research led him to conclude that "most adolescents and young adults (over 85% of this population) in the United States do not appear to be at the formal operational level of intellectual development."
- ²⁶R. R. Hake (unpublished, available upon request).
- ²⁷For recent discussion regarding introductory physics laboratories see e.g., F. Reif and M. St. John, Am. J. Phys. 47, 950 (1979); W. S. Toothacker, Am. J. Phys. 51, 516 (1983); J. G. Potter and J. Burns, Am. J. Phys. 52, 12 (1984).
- ²⁸F. W. Sears, M. W. Zemansky, and H. D. Young, *College Physics* (Addison-Wesley, Reading, MA, 1985), 6th ed.
- ²⁹F. Reif, Phys. Tech. **19**, 310 (1981); F. Reif and J. I. Heller, Educat. Psychol. **17**, 102 (1982); J. I. Heller and F. Reif, Cognitive Instruct. **1**, 177 (1984).
- ³⁰For recent views on multiple choice tests see CON: A. Bork, Am. J. Phys. **52**, 873 (1984); R. N. Varney, *ibid*. **52**, 1069 (1984); T. R. Sandin, *ibid*, **53**, 299 (1985). PRO: B. L. Scott, *ibid*. **53**, 1035 (1985); M. Zeilik, *ibid*. **53**, 393 (1985); M. Iona, *ibid*, **54**, 295 (1986).
- 31A. B. Arons, (a) Am. J. Phys. 44, 843 (1976); (b) The Various Language (with Teacher's Handbook) (Oxford, New York, 1977); (c) Phys. Teach. 19, 166 (1981); (d) Liberal Education 71, 141 (1985); (e) Handbook of Introductory Physics Teaching (unpublished).
- ³²J. Larkin, Am. J. Phys. 49, 534 (1981); Refs. 2, 3, 20, 22d. H. Gardner, The Mind's New Science: A History of the Cognitive Revolution (Basic, New York, 1985), p. 7 regards "cognitive sciences" to be philosophy, psychology, artificial intelligence, linguistics, anthropology, and neuroscience.
- ³³G. Holton and S. G. Brush, *Introduction to Concepts and Theories in Physical Science* (Princeton U.P., Princeton, NJ, 1985), pp. 178-180.
- ³⁴R. Morrison, in *Undergraduate Education in Chemistry and Physics*, Proceedings of the Chicago Conferences on Liberal Education, No. 1, edited by M. R. Rice (Univ. of Chicago, 1986), p. 50.
- 35R. P. Olenick, T. M. Apostol, and D. L. Goodstein, *The Mechanical Universe* (Cambridge U.P., London, 1985), preface.

- component Courses (DISCOE)," Teaching and Learning, Indiana Univ., Jan. 1979 (available on request).
- ⁴²A. Bork, Phys. Today **34**, 24 (Sept. 1981); A. B. Arons, Science **224**, 1051 (1984).
- ⁴³This attitude generates its own negation. By refusing to engage in or support "remedial" instruction to promote cognitive development of undergraduates, who form the pool of precollege teachers, university faculty apply a "degenerative signal into" (an educational) "feedback loop" [Ref. 31a,d,e (Sec. 1.16)].
- ⁴⁴R. W. Wood, How to Tell the Birds from the Flowers (Paul Elder, San Francisco, 1907; Dodd, Mead, New York, 1917; Dover, New York, 1959), p. 2.
- ⁴⁵Adapted from Ref. 31e, pp. 3-13 to 3-15 (see also Ref. 13). A high inertia 50 lb (23 kg) block is more instructive, but high humidity with consequent vapor condensation on the glass may force use of lower-mass blocks.
- ⁴⁶Available from Central Scientific Company, 11222 Melrose Ave., Franklin Park, Illinois 60131-1364 [(312) 451-0150].

Teaching of transcendence in physics

Stanlev L. Jaki

Department of Physics, Seton Hall University, South Orange, New Jersey 07079

(Received 31 October 1986; accepted for publication 25 November 1986)

Efforts aimed at showing that modern physics points to a truly transcendental factor as the explanation of the universe should be welcomed by those who have urged the teaching of physics in a broad cultural context. Those efforts may profit from the following guidelines: avoid the antiontological basis of the Copenhagen interpretation of quantum mechanics; make much of the reality of the universe and its enormous degree of specificity as revealed by general relativity and the cosmic background radiation; exploit Gödel's incompleteness theorems against any grand unified theory proposed as if it were true *a priori* and necessarily; and realize that the design argument always presupposes the validity of the cosmological argument.

Of the three nouns in the title of this article, the word teaching may serve as the least controversial starting point. At any rate, the teaching of physics was the practical target of Dr. Pollard's article, which has already prompted a rejoinder in this Journal.²

Those who have urged the teaching of physics in its broader cultural context, of which religion is an integral part, should, for the sake of consistency alone, welcome Dr. Pollard's suggestion that physics be taught with reference to the transcendence transpiring through it. The transcendence Dr. Pollard had in mind was implied in his introductory reference to his serving with Dr. Berger of Rumors of Angels fame on the advisory board of the Center of Theological Inquiry in Princeton that was mistakenly referred to as the Center of Technological Inquiry. At the end of his article Dr. Pollard openly spoke of the transcendence that only an inference to a creator can evoke, a frankness befitting a Christian clergyman-physicist and the author of books dealing with the relation of physics to theology.

The strategy Dr. Pollard followed in his article may be

unwelcome not only for reasons relating to Weltanschauung, religious and philosophical, but also for reasons relating to teaching. His broader strategy is an account of the overriding importance that the statistical method achieved in physics since the time of Boltzmann. Dr. Pollard seems to overlook the fact that just because that method has generally been taken for a renunciation of causality. at least on the atomic level, the truth about causality and about the nature of physical reality did not thereby become the function of majority opinion, however overwhelming. Precisely because these questions are of fundamental importance in all human reasoning, the teaching about them in physics should remain very cautious. Otherwise, the physics teacher may simply indoctrinate his students in a particular climate of opinion. Worse, he would thereby promote a repetition of a pattern in the history of physics, namely, the befogging of the mental vision of physicists taking the prevailing climate of opinion for indisputable verity. The categorical assertion, on mechanistic grounds, of the existence of the ether by classical physicists³ may be

³⁶L. S. Feldt, in *Encyclopedia of Statistical Sciences* (Wiley, New York, 1982), Vol. 4, p. 417.

³⁷D. Hestenes (private communication).

³⁸In a recent study (Ref. 40), 323 students took a standard full semester P201 course with the present innovations, except that only a 53-student test-group fraction took the SDI labs (31% of lab time, 10% of total instructional time) while the remaining 270-student control group took only standard labs. Pre- and post-course H²-mechanics exam scores were test group (42.1%, 77.3%); control group (43.5%, 72.8%). A statistical t-test analysis indicates a probability p = 0.105 that the difference (77.3 – 72.8) is merely the result of chance.

³⁹S. Tobias, Phys. Today 38, 61 (June 1985); Change 18, 36 (March/April, 1986); in Ref. 34, p. 11; Phys. Teach. (in press).

⁴⁰S. Tobias and R. R. Hake, "Professors as physics students: What can they teach us?" (preprint, 1987).

⁴¹In addition to informal verbal comments to instructors, we obtained written responses and comments at the start of the fourth week of the course using a student evaluation method described by R. R. Hake and J. C. Swihart "Diagnostic Student Computerized Evaluation of Multi-