Lessons From the Physics-Education Reform Effort

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• Abstract
• Introduction
• Survey Summary
• Fourteen Lessons

ABSTRACT
Several years ago I reported a survey (Hake 1998a,b,c) of pre/post test data for 62 introductory physics courses enrolling a total of 6542 students. The present article provides a summary of that survey and presents fourteen lessons from the physics-education reform effort that may assist the general upgrading of education and science literacy.

KEY WORDS: physics education, education reform, education research, interactive engagement, science literacy, cognitive science.

I. INTRODUCTION

For over three decades, physics-education researchers repeatedly showed that Traditional (T) introductory physics courses with passive-student lectures, recipe labs, and algorithmic problem exams were of limited value in enhancing conceptual understanding of the subject (McDermott & Redish 1999). Unfortunately, this work was largely ignored by the physics and education communities until Halloun & Hestenes (HH) (1985a,b) devised the “Mechanics Diagnostic” (MD) test of conceptual understanding of Newtonian mechanics. Among the virtues of the MD, and the subsequent “Force Concept Inventory” (FCI) (Hestenes et al. 1992, Halloun et al. 1995) tests, are (a) the multiple-choice format facilitates relatively easy administration of the tests to thousands of students, (b) the questions probe for conceptual understanding of basic concepts of Newtonian mechanics in a way that is understandable to the novice who has never taken a physics course (and thus can be given as an introductory-course pre-test), while at the same time rigorous enough for the initiate. A typical HH-type question is as follows (an actual HH question is avoided to help preserve the confidentiality of the test):

1 Submitted on 3/25/01 to Conservation Ecology < http://www.consecol.org/Journal/ >, a “peer-reviewed journal of integrative science and fundamental policy research.”
A student in a lab holds a brick of weight \( W \) in her outstretched horizontal palm and lifts the brick vertically upward at a constant speed. While the brick is moving vertically upward at a constant speed, the magnitude of the force on the brick by the student’s hand is:

A. constant in time and zero.
B. constant in time, greater than zero, but less than \( W \).
C. constant in time and \( W \).
D. constant in time and greater than \( W \).
E. decreasing in time but always greater than \( W \).

Note that the responses include as distractors not only “D,” the common Aristotelian misconception that “motion requires a net force,” but also other less common student misconceptions “A” and “E” that might not be known to traditional teachers. Unfortunately, too few teachers “shut up and listen to their students” so as to find out what they are thinking (Arons 1981). The distractors are based on my years of listening to students as they worked through the experiments in Socratic Dialogue Inducing Lab #1 “Newton’s First and Third Laws” (Hake 2001a). For actual HH questions the distractors were usually gleaned through careful qualitative research involving interviews with students and the analysis of their oral and written responses to mechanics questions.

Using the MD, Halloun & Hestenes (1985a,b) published a careful study using massive pre- and post-course testing of students in both calculus and non-calculus-based introductory physics courses at Arizona State University, and concluded that: (1) “. . . . the student’s initial qualitative, common-sense beliefs about motion and . . . .(its) . . . . causes have a large effect on performance in physics, but conventional instruction induces only a small change in those beliefs.” (2) Considering the wide differences in the teaching styles of the four professors . . . . (involved in the study) . . . . the basic knowledge gain under conventional instruction is essentially independent of the professor.” These outcomes were consistent with work done prior to the HH study as recently reviewed by McDermott & Redish (1999).

The HH results stimulated a flurry of research and development aimed at improving introductory mechanics courses. Most of the courses so generated sought to promote conceptual understanding through use of pedagogical methods published by physics-education researchers (see, e.g., Physical Science Resource Center 2001, Galileo Project 2001, UMd-PERG 2001a). These methods are usually based on the insights of cognitive science (Gardner 1985; Mestre & Touger 1989; Redish 1994; Bruer 1994, 1997; Bransford et al. 1999; Donovan et al. 1999) and/or outstanding classroom teachers (e.g., Karplus 1977; Minstrell 1989; Arons 1990; McDermott 1991, 1993; Fuller 1993; Reif 1995; Wells et al. 1995; Zollman 1996; Laws 1997). Although the methods differ in detail, they all attempt to guide students to construct their understandings by heads-on (always) and hands-on (usually) activities that yield immediate feedback through discussion with peers and/or instructors [Interactive Engagement (IE)], so as to finally arrive at the viewpoint of the professional physicist.
The survey summarized below documents some of the successes and failures of courses employing IE methods, may assist a much needed further improvement in introductory mechanics instruction in the light of practical experience, and may serve as a model for promoting educational reform in other disciplines. [Since the summary omits some important aspects, serious education scholars are urged to consult the original sources (Hake 1998 a,b,c).] I then present fourteen somewhat subjective lessons from my own interpretation of the physics-education reform effort with the hope that they may assist the general upgrading of education and science literacy.

2. SURVEY SUMMARY

Starting in 1992, I requested that pre/post-FCI data and post-test Mechanics Baseline (a problem-solving test due to Hestenes & Wells, 1992) data be sent to me. Since instructors are more likely to report higher-gain courses, the detector is biased in favor of those courses, but can still answer a crucial research question: Can the use of Interactive Engagement (IE) methods increase the effectiveness of introductory mechanics courses well beyond that obtained by traditional methods?

The Data

Figure 1 shows data from the survey (Hake 1998a,b,c) of 62 introductory physics courses enrolling a total 6542 students. The data are derived from pre/post scores of the MD and FCI tests indicated above, recognized for high validity and consistent reliability (Beichner 1994, Slavin 1992). Average pre/post test scores, standard deviations, instructional methods, materials used, institutions, and instructors for each of the survey courses are tabulated and referenced in Hake, 1998b. The latter paper also gives case histories for the seven IE courses whose effectiveness as gauged by pre-to-post test gains was close to those of T courses, advice for implementing IE methods, and suggestions for further research. Various criticisms of the survey (and physics-education research generally) are countered by Hake, 1998c.

For survey classification and analysis purposes I operationally defined:

a. Interactive Engagement (IE) methods as those designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors, all as judged by their literature descriptions;

b. IE courses as those reported by instructors to make substantial use of IE methods;

c. Traditional (T) courses as those reported by instructors to make little or no use of IE methods, relying primarily on passive-student lectures, recipe labs, and algorithmic-problem exams.
Fig. 1. The %<Gain> vs %<Pretest> score for 62 courses enrolling a total of 6542 students. Here %<Gain> = %<posttest> – %<pretest>, where the angle brackets "<...>" indicate an average over all students in the course. Points for high school (HS), college (COLL), and university (UNIV) courses are shown in green for Interactive Engagement (IE), and in red for Traditional (T) courses. The straight negative-slope lines are lines of constant average normalized gain <g>. The two dashed purple lines show that most IE courses achieved <g>'s between 0.34 and 0.69. The definition of <g>, and its justification as an index of course effectiveness, is discussed in the text. The average of <g>'s for the 48 IE courses is <<g>>_{48IE} = 0.48 ± 0.14 (standard deviation) while the average of <g>'s for the 14 T courses is <<g>>_{14T} = 0.23 ± 0.04 (sd). Here the double angle brackets "<<...>>" indicate an average of averages.
A histogram of the data of Fig. 1 is shown in Fig. 2.

![Histogram of the average normalized gain $<g>$](image)

**Fig. 2.** Histogram of the average normalized gain $<g>$: red bars show the fraction of 14 Traditional (T) courses (2108 students) and green bars show the fraction of 48 Interactive Engagement (IE) courses (4458 students), both within bins of width $<g> = 0.04$, centered on the $<g>$ values shown. (From Hake 1998a.)

**Average Normalized Gain**

To understand the graphical interpretation of the average normalized gain $<g>$ of Figs. 1 and 2, consider the point [$\%<\text{pretest}> = 44\%$, $\%<\text{Gain}> = 19\%$] at the tip of the white arrowhead in Fig. 1. This point has an abscissa (100\% - 44\%) = 56\% and ordinate 19\%. The absolute value of the slope $s$ of the purple dashed line connecting this point to the lower right vertex of the graph is $|s| = 19\%/56\% = 0.34$. This absolute slope $|s| = <\text{Gain}>/(100\% - <\text{pretest}>)$ = $<\text{Gain}>/$(maximum possible $<\text{Gain}>$) = $<\text{Gain}>/ <\text{Gain}>_{\text{max}}$ is taken to be an index of that course’s effectiveness (as justified below – see Conclusion “A”), and is called the average normalized gain $<g>$ for that particular course. Thus, all courses with points close to the purple dashed line are judged to be of about equal average effectiveness, regardless of their average pretest scores. A similar calculation for the point [$\%<\text{pretest}> = 32\%$, $<\text{Gain}> = 47\%$] at the tip of the blue arrowhead, yields $<g> = 0.69$. The maximum of value of $<g>$ occurs when the $<\text{Gain}>$ is equal to $<\text{Gain}>_{\text{max}}$ and is therefore 1.00, as shown in Fig. 1.
Popular Interactive Engagement Methods

For the 48 interactive-engagement courses of Figs. 1 & 2, the ranking in terms of number of IE courses using each of the more popular methods follows. [See the paragraph below the listing for an explanation of the abbreviations within the “{…}” ].

1. Collaborative Peer Instruction (Johnson et al. 1991; Heller et al. 1992a,b): 48 (all courses) {CA}.


5. Active Learning Problem Sets or Overview Case Studies (Van Heuvelen 1991a,b; 1995): 17 courses {CA}; information on these materials is online at <http://www.physics.ohio-state.edu/~physedu/>.

6. Physics-education-research based text (referenced in Hake 1998b, Table II) or no text: 13 courses.


The notations within the curly brackets “{ . . .}” follow Heller (1999) in loosely associating the methods with “learning theories” from cognitive science. Here “DT” stands for “Developmental Theory,” originating with Piaget (Inhelder & Piaget 1958, Gardner 1985); and “CA” stands for “Cognitive Apprenticeship” (Collins et al. 1989, Brown et al. 1989). All the methods (save #6) recognize the important role of social interactions in learning (Vygotsky 1978, Lave & Wenger 1991, Dewey 1997). It should be emphasized that the above rankings are by popularity within the survey, and have no necessary connection with the effectiveness of the methods relative to one another. In fact, it is quite possible that some of the less popular methods used in some survey courses, as listed by Hake (1998b), could be more effective in terms of promoting student understanding than any of the above popular strategies.
Conclusions of the Survey

The conclusions of the survey (Hake 1998 a,b,c; 1999a) may be summarized as follows:

A. The average normalized gain $<g>$ affords a consistent analysis of pre/post test data on conceptual understanding over diverse student populations in high schools, colleges, and universities. The correlation of the average normalized gain $<g>$ with ($<\text{pretest}>$) for the 62 courses of Fig. 1 (Hake 1998a) is a very low +0.02. This constitutes an experimental justification for the use of $<g>$ as a comparative measure of course effectiveness over diverse student populations with widely varying average pretest scores. In contrast, the average posttest score ($<\text{postest}>$) and the average actual gain ($<\text{Gain}>$) are less suitable for comparing course effectiveness over diverse groups since their correlation with ($<\text{pretest}>$) is significant. The correlation of

\[
(\%<\text{posttest}>) \text{ with } (\%<\text{pretest}>) \text{ is } +0.55, \text{ and the correlation of } \\
(\%<\text{Gain}>) \text{ with } (\%<\text{pretest}>) \text{ is } -0.49,
\]

both of which correlations would be anticipated. Note that in the absence of instruction, a high positive correlation of ($<\text{posttest}>$) with ($<\text{pretest}>$) would be expected. The successful use of the normalized gain for the analysis of pre/post test data in this and other physics-education research (see “Is it Scientific Research” below), calls into question the common dour appraisals of pre/post test designs (Cook & Campbell 1979, Cronbach & Furby 1970).

B. Fourteen Traditional (T) courses (2084 students) of the survey yielded $<g>_{14T} = 0.23 \pm 0.04sd$. Considering the elemental nature of the MD/FCI questions (many physics teachers regard them as too easy to be used on examinations) and the definition $<g> = \%<\text{Gain}>/ \%<\text{Gain}>_{\text{max}}$, this suggests that traditional (T) courses fail to convey much basic conceptual understanding of Newtonian mechanics to the average student.

C. Forty-eight Interactive Engagement (IE) courses (4458 students) of the survey yielded $<g>_{48IE} = 0.48 \pm 0.14sd$. The $<g>_{48IE}$ is over twice that of $<g>_{14T}$, and is almost two sd’s of $<g>_{48IE}$ above that of the T courses, reminiscent of differences seen in comparing instruction delivered to students in large groups with one-on-one instruction (Bloom 1984). This suggests that IE courses can be much more effective than T courses in enhancing conceptual understanding. Although it was not possible in this survey to randomly assign students from a single large homogeneous population to the T and IE courses, the T and IE data are all drawn from the same institutions and the same generic introductory program regimes (Hake 1998b). Thus it seems very unlikely that the nearly-two-sd difference between $<g>$’s for the IE and T courses could be accounted for by differences in the student populations.
An alert critic of an early draft [and more recently Becker (2001) – see below] have pointed out that the <<g>> difference might be due in part to the apparent smaller average enrollment for IE courses (4458/48 = 93) than for T courses (2084/14 = 149). However such calculation of average class size is invalid because in several cases (Hake, 1998a,b) classes of fairly homogeneous instruction and student population were combined into one “course” whose <g> was calculated as a number-of-student-weighted average of the <g>'s of the individual classes. A correct calculation yields an average class enrollment of 4458/63 = 71 for IE classes and 2084/34 = 61 for T classes, so the average class sizes are quite similar.

D. A detailed analysis of random and systematic errors has been carried out (Hake 1998a) but will not be repeated here. It was concluded that “it is extremely unlikely that random or systematic error plays a significant role in the nearly two-standard deviation difference in the <<g>>’s of T and IE courses.”

E. Conclusions “A” and “C” are bolstered by an analysis of the Fig. 1 data in terms of the “effect size” <d> (Hake 1999a). The effect size is commonly used in meta-analyses (Cohen 1988, Hunt 1997), and strongly recommended by many psychologists (B. Thompson 1996, 1998, 2000), and biologists (Johnson 1999, Anderson et al. 2000, W.L. Thompson 2001) as the preferred alternative to the usual t-tests and p values associated with null-hypothesis testing. (See also Anderson 1998.) Here <d> is defined as the ratio of the actual average gain (%<posttest> - %<pretest>) to the average of the standard deviations (sd’s). I obtain an average effect size <d> = 0.88 for 9 T courses (1620 students), and an average <d> = 2.18 for 24 IE courses (1843 students) for which sd’s are available. The latter can be compared with: (1) the similar <d> = 1.91 reported by Zeilik, Schau, Mattern (1998) for a single IE introductory astronomy course (N = 221) given in Spring 1995 at the University of New Mexico, and (2) the much smaller average <d> = 0.51 obtained in a meta-analysis of small-group learning by Springer et al. (1999). In the Springer study, as for much research reported in the educational literature, (a) in many cases there was no pretesting to disclose initial knowledge states of the test or control groups, (b) the quality of the “achievement tests” was not critically examined (were they of the plug-in-regurgitation type so common in introductory physics courses?). I think that the Springer et al. meta-analysis probably understates the effectiveness of small-group learning in advancing conceptual understanding and problem-solving ability.

As in “C” above, the critic of an early draft pointed out that <d> difference might be due in part to the apparent smaller average enrollment for IE courses (1843/24 = 77) than for T courses (1620/9 = 169). However such calculation of average class size is invalid for the reason given in “C.” A correct calculation of average class size indicates an average class enrollment of 1843/39 = 47 for IE classes and 1620/31 = 52 for T classes, so the average class enrollments are quite similar.
F. Considering the elemental nature of the MD/FCI tests, **current IE methods and their implementation need to be improved, since none of the IE courses achieves \( g \) greater than 0.69.** In fact, as can be seen in Figs. 1, seven of the IE courses (717 students) achieved \( g \)’s close to those of the T courses. Case histories of the seven low-\( g \) courses (Hake 1998b) suggest that implementation problems occurred that might be mitigated by:

1. apprenticeship education of instructors new to IE methods,
2. emphasis on the nature of science and learning throughout the course,
3. careful attention to motivational factors and the provision of grade incentives for taking IE_activities seriously,
4. recognition of and positive intervention for potential low-gain students,
5. administration of exams in which a substantial number of the questions probe the degree of conceptual understanding induced by the IE methods,
6. use of IE methods in all components of a course and tight integration of those components.

Personal experience with the Indiana IE courses and communications with most of the IE instructors in the survey suggest that similar implementation difficulties probably occurred to a greater or lesser extent in all the IE courses and are probably partially responsible for the wide spread in the \( g \)’s, apparent for IE courses in Figs. 1 & 2.

G. I have plotted (Hake 1998a) average post-course scores on the problem-solving Mechanics Baseline test (Hestenes & Wells, 1992) [available for 30 (3259 students) of the 62 courses of the survey] vs those on the conceptual FCI. There is a very strong positive correlation \( r = + 0.91 \) of the MB and FCI scores. This correlation and the comparison of IE and T courses at the same institution (Hake 1998a) imply that **IE methods enhance problem-solving ability.**
Criticisms of the Survey.

Early criticisms of the survey have been countered in Hake 1998c. Becker (2001) has recently raised other objections:

1. “The amount of variability around a mean test score for a class of 20 students versus a mean of 200 students cannot be expected to be the same. Estimation of a standard error for sample of 62 . . . (courses) . . . , where each of the 62 receives an equal weight ignores this heterogeneity.” But only the standard deviations (sd’s) of the g’s for the 48 IE and 14T courses were given (not the standard errors). For example, I give \( g_{48IE} = 0.48 \pm 0.14 \) (sd). The spread (sd) in g values for the IE courses is large, 29% of \( g_{48IE} \). In the error analysis (Hake 1998a), I adduce evidence that the large spread in the IE distribution is due to random errors plus other factors: e.g., course to course variations in the systematic errors and in the effectiveness of the pedagogy and/or implementation. In my opinion, attempts to take into account only the heterogeneity due to course enrollment would add little to the analysis. The crucial point, seemingly ignored by Becker, is that the difference \( g_{48IE} - g_{14T} \) is almost two sd’s of \( g_{48IE} \), and therefore large in comparison to the spread in the data; more technically, the “effect size” is large as emphasized in “C” and “E” above.

2. “Unfortunately, the gap closing outcome measure g is algebraically related to the starting position of the student as reflected in the pretest: g falls as the pretest score rises, for maximum score \( \geq \) posttest score \( \geq \) pretest score.” This assertion is based on Becker’s partial differentiation \( \frac{\partial g}{\partial y} = \frac{(x – Q)/(Q – y)^2}{x} \), in agreement with Hake, 1998a, footnote 45. Here Q is the number of questions on the exam, y and x are the number of correct responses on the pretest and posttest, respectively, and \( g = (x – y)/(Q – y) \). But Becker’s differentiation, while mathematically correct, has little physical significance because for a single student x is not, in general, independent of y; and for a single class the average \( x \) is not independent of the average \( y \). In fact, as indicated above, for the 62 courses of the survey, correlation of the average posttest score \( x \) with the average pretest score \( y \) is +0.55, while the correlation of average normalized gain \( g \) with \( y \) is a very low +0.02. [As an aside, Becker relates g to the “Tobit model” (named after economics Nobel laureate James Tobin) and implies that economist Frank Ghery (1972) was the first to propose use of g, evidently unaware (as was I) that g was earlier used by psychologists Hovland et al. (1949).]

3. “When studies ignore the class size . . . (see my counter to this in “C” above under “Conclusions of the Survey”) . . . and sample selection issues, readers should question the study’s findings regardless of the sample size or diversity in explanatory values. . . . Hake does not give us any indication of beginning versus ending enrollments, which is critical information if one wants to address the consequences of attrition.” Becker is either unaware or has chosen to ignore ref. 17a (the same as Hake 1998b) of Hake (1998a). The data Tables Ia,b,c of Hake 1998b clearly indicate
which courses were and which were not analyzed with "matched" data, i.e., data in which only posttest scores of students who had also taken the pretest were included in the average posttest score. In a majority of courses matched data were used. Tables Ia,b,c show no obvious dependence of \( g \) on whether or not the data were matched. In footnote “c” of that table, I estimate, from my experience with the pre/post testing of 1263 students at Indiana University, "that the error in the normalized gain is probably less than 5% for classes with 20 – 50 students and less that 2% for classes with more than 50 students.” Saul (1998) on page 117 states "... I found that the matched and unmatched results ... from his extensive pre/post FCI studies ... are not significantly different.”

4. “... there is relatively strong inferential evidence ... [evidently from Almer et al. (1998) and Chizmar & Ostrosky (1999)] ... supporting the hypothesis that periodic use of variants of the one-minute paper (wherein an instructor stops class and asks each student to write down what he or she thought was the key point and what still needed clarification at the end of a class period) increases student learning. Similar support could not be found for other methods...” (My italics.) In Becker’s econocentric view, all quantitative educational research, including that done over the past 30 years in physics (Redish & McDermott 1998), has evidently been in vain, save for two isolated recent studies by economists on the one-minute paper! Becker’s “11-point set of criteria that all inferential studies can be expected to address in varying degrees of detail” omits what to most physical scientists is the most crucial criterion: the extent to which the conclusions are independently verified by other investigators under other circumstances so as to contribute to a community map. (See “Is it Scientific Research” below.)

As an aside, my own experience with minute papers (Hake 1998b, ref. 58 and Table IIc) is that they can constitute a significant but relatively minor segment of effective interactive engagement. Becker continues the usual literature misattribution of minute papers to Wilson (1986) [and indirectly to CAT champions Angelo and Cross (1993)] rather than to Berkeley physicist Charles Schwartz. Becker is evidently either unaware or chooses to ignore ref. 58 of Hake, 1998b. (See also the footnote at the reference to Davis et al. 1983 in Hake 2000d.)
Is it Scientific Research?

There has been a long standing debate over whether or not education research is or should be “scientific” (Lagemann 2000, Mayer 2000, Phillips & Burbules 2000, Phillips 2000, Eisner 1997, Dewey 1929). In my opinion, substantive education research must be “scientific.” My biased prediction (Hake 2000b) is that for physics-education research, and possibly even education research generally: (a) the bloody “paradigm wars” (Gage 1989) will have ceased by the year 2009, with, in Gage’s words, a “productive rapprochement of the paradigms,” (b) some will follow paths of pragmatism or Popper’s “piecemeal social engineering” to this paradigm peace, as suggested by Gage, but (c) most will enter onto this “sunlit plain” from the path marked “scientific method” as practiced by most research physicists:

1. **EMPIRICAL:** Systematic investigation ...... (by quantitative, qualitative, or any other means) .......... of nature to find reproducible patterns in the structure of things and the ways they change (processes).

2. **THEORETICAL:** Construction and analysis of models representing patterns of nature. (Hestenes 1999).

3. Continual interaction, exchange, evaluation, and criticism so as to build a . . . . community map (Redish 1999).

For the presently discussed research, the latter feature is demonstrated by the fact that FCI normalized gain results for IE and T courses that are consistent with those of (Hake 1998a,b,c) have now been obtained by physics-education research groups at the Univ. of Maryland (Redish et al. 1997, Saul 1998, Redish & Steinberg 1999, Redish 1999); Univ. of Montana (Francis et al. 1998); Rensselaer and Tufts (Cummings et al. 1999); North Carolina State Univ. (Beichner et al. 1999); and Hogskolan Dalarna - Sweden (Bernhard 1999). Thus in physics education research, just as in traditional physics research, it is possible to perform quantitative experiments that can be reproduced (or refuted) by other investigators and thus contribute to the construction of a “community map.”
III. FOURTEEN LESSONS FROM THE PHYSICS-EDUCATION REFORM EFFORT

The lessons (L) below are derived from my own interpretation of the physics-education reform movement and are therefore somewhat subjective and incomplete. They are meant to stimulate discussion rather than present any definitive final analysis.

L1. The use of IE strategies can increase the effectiveness of conceptually difficult courses well beyond that obtained with traditional methods.

Education research in biology (Hake 1999b,c), chemistry (Herron & Nurrenbern 1999), and engineering (Felder et al. 2000a,b), although neither as extensive nor as systematic as that in physics (McDermott & Redish 1999, Redish 1999), is consistent with the latter in suggesting that in conceptually difficult areas, interactive engagement methods are more effective than traditional passive-student methods in enhancing students’ understanding. I see no reason to doubt that such is not also the case in other science and even non-science areas.

L2. The use of interactive-engagement and/or high-tech methods, by themselves, does not insure superior student learning.

As previously indicated, the data of Fig. 1 show that seven of the IE courses (717 students) achieved $g$’s close to those of the T courses. Five of those made extensive use of high-tech microcomputer-based labs (Thornton and Sokoloff 1990, 1998). Case histories of the seven low-$g$ courses (Hake 1998b) suggest that implementation problems occurred. Another example of the apparent failure of IE/high-tech methods has been described by Cummings et al. (1999). They considered a standard physics Studio Course at Rensselaer in which group work and computer use had been introduced as components of in-class instruction, the classrooms appeared to be interactive, and students seemed to be engaged in their own learning. Their measurement of $g$’s using the FCI and the Force Motion Concept Evaluation (Thornton & Sokoloff 1998) yielded values close to those characteristic of T courses (Hake 1998a,b,c). Cummings et al. suggest that the low $g$ of the standard Rensselaer studio course may have been due to the fact that “the activities used in the studio classroom are predominately ‘traditional’ activities adapted to fit the studio environment and incorporate the use of computers.” Thus the apparent “interactivity” was a product of traditional methods (supported by high technology), not published IE methods developed by physics-education researchers or outstanding teachers, as for the survey courses. This explanation is consistent with the fact that Cummings et al. measured $g$’s in the 0.35 – 0.45 range for Rensselaer Studio courses using physics-education research methods: (a) Interactive Lecture Demonstrations (Thornton & Sokoloff (1998), and (b) Cooperative Group Problem Solving (Heller et al. 1992a,b).
It should be emphasized that while high technology, by itself, is no panacea, it can be very advantageous when it promotes interactive engagement, as in computerized classroom communication systems (see, e.g., Mazur, 1997), *properly implemented* microcomputer-based labs (Thornton and Sokoloff 1990), and *Just-In-Time Teaching* (Novak et al. 1998, 1999).

L3. **Teachers who possess both content knowledge and “pedagogical content knowledge” are more apt to deliver effective instruction.**

“Pedagogical content knowledge” is evidently a term due to Shulman (1986, 1987), but its importance has long been well known to effective classroom teachers. The difference between content knowledge and “pedagogical content knowledge,” can be illustrated by consideration of the HH-type question given in the Introduction. *Content knowledge* informs the teacher that, according to Newton’s First Law, while the brick is moving vertically upward at a constant speed in the inertial reference frame of the lab, the magnitude of the force on the brick by the student’s hand is constant in time and of magnitude $W$, so that the *net force* on the brick is zero. On the other hand, *pedagogical content knowledge* would inform the teacher that students may think that e.g.: (a) since a net force is required to produce motion, the force on the brick by the student’s hand is constant in time and greater than $W$; or (b) since the weight of the brick diminishes as it moves upward away from the Earth, the force on the brick by the student’s hand decreases in time but is always greater than $W$; or (c) no force is exerted on the brick by the student’s hand because as the students hand moves up the brick must simply move up to stay out of the hand’s way. In addition, pedagogical content knowledge provides a hard-won toolkit of strategies (see, e.g., the list of “Popular IE Methods” in Sec. 2 above) for guiding the student away from these misconceptions and towards the Newtonian interpretation. In my opinion, the need for teachers to possess pedagogical content knowledge is strikingly confirmed by the marked differences in normalized gains $<g>$ for traditional and IE-oriented physics teachers (Hake 1998a). Unfortunately, such knowledge may take many years to acquire (Wells et al. 1995).

L4. **Faculty tend to overestimate the effectiveness of their own instructional efforts and thus tend to see little need for educational reform.**


L5. **Such complacency can sometimes be countered by the administration of high-quality standardized tests of understanding and by “video snooping.”**

a. Harvard’s Eric Mazur (1997) was very satisfied with his introductory-course teaching - he received very positive student evaluations and his students did reasonably well on “difficult” exam problems. Thus it came as a shock when his students fared hardly better on the “simple” FCI than
on their “difficult” midterm exam. As a result, Mazur developed and implemented his interactive-engagement “Peer Instruction” method as a replacement for his previous traditional passive-student lectures. This change resulted in much higher $g$’s on the FCI as shown by comparison of the red and green triangular points with average pretest scores in the vicinity of 70% in Fig. 1.

b. Like Mazur, most Harvard faculty members are proud of their undergraduate science courses. However, the videotape Private Universe (Schneps & Sadler 1985) shows Harvard graduating seniors being asked “What causes the seasons?” Most of them confidently explain that the seasons are caused by yearly changes in the distance between the Sun and the Earth! Similarly most MIT faculty regard their courses as very effective preparation for the difficult engineering problems that will confront their elite graduates in professional life. However the videotape “Simple Minds” (Shapiro et al. 1997) shows MIT graduating seniors having great trouble getting a flashlight bulb to light, given one bulb, one battery, and one piece of wire.

L6. High-quality standardized tests of the cognitive and affective impact of courses are essential for gauging the relative effectiveness of non-traditional educational methods.

As indicated in the introduction, so great is the inertia of the educational establishment (see L13) that three decades of physics-education research demonstrating the futility of the passive-student lecture in introductory courses were ignored until high-quality standardized tests that could easily be administered to thousands of students became available. These tests are yielding increasingly convincing evidence that interactive engagement methods enhance conceptual understanding and problem solving abilities far more than do traditional methods. Such tests may also indicate implementation problems in IE courses (Hake 1998b) and differences in the effectiveness of various IE methods (Saul 1998, Redish 1999). As far as I know, disciplines other than physics and astronomy (Adams et al. 2000; Zeilik et al. 1997, 1998, 1999) have yet to develop any such tests and therefore cannot effectively gauge either the need for or the efficacy of their reform efforts. In my opinion, all disciplines should consider the construction of high-quality standardized tests of essential introductory course concepts.

The lengthy and arduous process of constructing valid and reliable multiple choice tests has been discussed by Halloun & Hestenes (1985a), Hestenes et al. (1992), Beichner (1994), Aubrecht (1991), and McKeachie (1999). In my opinion such hard-won Diagnostic Tests that cover important parts of common introductory courses are national assets whose confidentiality should be as well protected as the MCAT (Medical College Admission Test). Otherwise the test questions may migrate to student files and thereby undermine education research that relies upon the validity of such tests. Suggestions for both administering Diagnostic Tests and reporting their results so as to preserve confidentiality and enhance assessment value have been given by Hake (2001b).
Regarding tests of affective impact, administration of the “Maryland Physics Expectations” (MPEX) survey to 1500 students in introductory calculus-based physics courses in six colleges and universities . . . (showed) . . . “a large gap between the expectations of experts and novices and . . . a tendency for student expectations to deteriorate rather than improve as a result of introductory calculus-based physics” (Redish et al. 1998). Here the term “expectations” is used to mean a combination of students’ epistemological beliefs about learning and understanding physics and students’ expectations about their physics course (Elby 1999). The Arizona State University “Views About Sciences Survey” (VASS) (Halloun & Hestenes 1998, Halloun 1997) - available for physics, chemistry, biology and mathematics at <http://modeling.la.asu.edu/R&E/Research.html> - indicates that students have views about physics that (a) often diverge from physicists’ views; (b) can be grouped into four distinct profiles: expert, high transitional, low transitional, and folk; (c) are similar in college and high school; and (d) correlate significantly with physics achievement. It may well be that students’ attitudes and understanding of science and education are irreversibly imprinted in the early years. If so, corrective measures await a badly needed drastic improvement in K-12 education (Hake 2000c,d; Mahajan & Hake 2000; Benezet 1935/36) – see L10.

L7. Education Research and Development (R&D) by disciplinary experts (DE’s), and of the same quality and nature as traditional science/engineering R&D, is needed to develop potentially effective educational methods within each discipline. But the DE’s should take advantage of the insights of (a) DE’s doing education R&D in other disciplines, (b) cognitive scientists, (c) faculty and graduates of education schools, and (d) classroom teachers.

Redish (1999) has marshaled the arguments for the involvement of physicists in physics departments – not just faculty of education schools - in physics-education research. Similar arguments apply more generally to other disciplines: (a) physicists have good access to physics courses and students on which to test new curricula, (b) physicists and their departments directly benefit from physics education research, (c) education schools have limited funds for disciplinary education research, (d) understanding what’s going on in physics classes requires deep rethinking of physics and the cognitive psychology of understanding physics. One might add that the researchers themselves must be excellent physics teachers with both content and “pedagogical content” knowledge (see L3) of a depth unlikely to be found among non-physicists.

The education of disciplinary experts in education research requires Ph.D. programs at least as rigorous as those for experts in traditional research. The programs should include, in addition to the standard disciplinary graduate courses, some exposure to: the history and philosophy of education, computer science, statistics, political science, social science, economics, engineering - see L11, and, most importantly, cognitive science (i.e., philosophy, psychology, artificial intelligence, linguistics, anthropology, and neuroscience). The breadth of knowledge required for effective education research is
similar to that required in ecological research (Holling 1997). In the U.S. there are now about a dozen Ph.D. programs in physics education within physics departments and about half that number of interdisciplinary programs between physics and education or cognitive psychology (Physical Science Resource Center 2001, UMd-PERG 2001b.). In my opinion, all scientific disciplines should consider offering Ph.D. programs in education research.

But how can disciplinary education researchers, and for that matter, university faculty generally, take advantage of the insights of: disciplinary experts doing education R&D in other disciplines; cognitive scientists; faculty and graduates of education schools; and classroom teachers? In my opinion, even despite the rigid departmental separation of disciplines in most research universities, the web has the potential to dramatically enhance cooperation and interchange among these groups (Hake, 1999c, 2000e). Certainly the success of Conservation Ecology <http://www.consecol.org/Journal/> testifies to the value of the web in promoting interdisciplinary effort. A starting point might be the construction of web guides for various disciplines similar to REDCUBE <http://www.physics.indiana.edu/~redcube> (Hake 1999b), which provides a point of entry into the vast literature and web resources relevant to REsearch, Development, and Change in Undergraduate Biology Education. The 9/8/99 version contains 47 biology-educator profiles; 446 references (including 124 relevant to general science-education reform); and 490 hot-linked URL’s on (a) Biology Associations, (b) Biology Teachers’ Web Sites, (c) Scientific Societies and Projects (not confined to Biology), (d) Higher Education, (e) Cognitive Science and Psychology, (f) U.S. Government, and (g) Searches and Directories.

Regarding the value of tapping into cognitive science, J.J. Duderstadt (2000), president emeritus of the University of Michigan - Ann Arbor writes: “Few faculty members have any awareness of the expanding knowledge about learning from psychology and cognitive science. Almost no one in the academy has mastered or used this knowledge base. One of my colleagues observed that if doctors used science the way college teachers do, they would still be trying to heal with leeches.” (My italics.)

L8. The development of effective educational methods within each discipline requires a redesign process of continuous long-term classroom use, feedback, assessment, research analysis, and revision.

Wilson and Davis (1994) suggest that the “redesign process,” used so successfully to advance technology in aviation, railroads, automobiles, and computers can be adapted to K-12 education reform through “System Redesign Schools.” Redesign processes in the reform of introductory undergraduate physics education have been undertaken and described by McDermott (1991) and by Hake (1998a). In my opinion “redesign” at both the K-12 and undergraduate levels can be greatly assisted by the promising Scholarship of Teaching & Learning movement (Carnegie Academy 2000) inspired by Boyer (1990) and the Boyer Commission (1998).
L9. Although non-traditional interactive-engagement methods appear to be much more effective than traditional methods, there is need for more research to develop better strategies for the enhancement of student learning.

On a test as elemental as the FCI it would seem that reasonably effective courses should yield $g$’s above 0.8, but thus far none much above 0.7 have, to my knowledge, been reported. This and the poor showing on the pre/post MPEX test of student understanding of the nature of science and education (Redish et al. 1998) indicates that more work needs to be done to improve IE methods. It would appear that understanding of science might be improved by students’ apprenticeship research experiences (Collins et al. 1989, Brown et al. 1989), and enrollment in courses featuring interactive engagement among students and disciplinary experts from different fields, all in the same classroom at the same time (Benbasat & Gass 2001).

In my opinion, more support should be given by universities, foundations, and governments to the development of a science of education spearheaded by disciplinary education researchers working in concert with cognitive scientists and education specialists. In the words of cognitive psychologists Anderson et al. (1998): “The time has come to abandon philosophies of education and turn to a science of education . . . . If progress is to be made to a more scientific approach, traditional philosophies . . . (such as radical constructivism) . . . will be found to be like the doctrines of folk medicine. They contain some elements of truth and some elements of misinformation . . . . Only when a science of education develops that sorts truth from fancy - as it is beginning to develop now will dramatic improvements in educational practice be seen.” (My italics.)

The imperative for educational improvement has been set forth by the National Research Council (1997): “The education that many students receive in science, mathematics, and technology is not adequate for a world that is being transformed by scientific and technological advances. People have to be familiar with the basic concepts of science, mathematics, engineering, and technology to think critically about the world and to make informed decisions about personal and societal issues. Literacy in these fields is essential also for an appreciation of the rapid expansion of human knowledge – surely one of the great adventures of the 20th century.”

Wilson and Barsky (1998) see the need “for a launch of a research and development initiative in education, paralleling existing national research initiatives related to AIDS or global climate change . . . . Today we have to think of education as demanding in multiple dimensions: as a science, as a design challenge, and as a performing art while still being an imperative for life in a democracy. Handed down traditions are no longer enough.” See also <http://www.physics.ohio-state.edu/~redesign/>.
The House Committee on Science (1998) states that: “Currently, the U.S. spends approximately $300 billion a year on education and less than 30 million, 0.01% of the overall education budget, on education research. At a time when technology promises to revolutionize both teaching and learning, this miniscule investment suggests a feeble long-term commitment to improving our educational system.”

However, it should be emphasized that the development of better strategies for the enhancement of student learning will not improve the educational system unless (a) university and K-12 teachers (see L10) are educated to effectively implement those strategies, and (b) research universities start to think of education in terms of student learning rather than the delivery of instruction (see L12h).

L10. **A major problem for undergraduate education is the inadequate preparation of incoming students, in part due to the inadequate university education of K-12 teachers.**

According to the National Research Council (1999), the Third International Mathematics and Sciences Survey (TIMSS) indicates that: “U.S. students’ worst showing was in population 3 . . . . (final year of secondary School. . . . corresponding to U.S. high school seniors). . . . In the assessment of general mathematics and science knowledge, U.S. high school seniors scored near the bottom of the participating nations. In the assessments of advanced mathematics and physics given to a subset of students who had studied those topics, no nations had significantly lower mean scores than the United States. The TIMSS results indicate that a considerably smaller percentage of U.S. students meet high performance standards than do students in other countries.” Consistent with the foregoing, I have observed (Hake 2000d) that FCI pretest averages for students entering the introductory physics course at Indiana University are quite low (30% - 45%) and about the same regardless of whether or not the students are graduates of high-school physics classes.

But it’s not just a matter of physics floundering. According to Epstein (1997-98): “While it is now well known that large numbers of students arrive at college with large educational and cognitive deficits many faculty and administrative colleagues are not aware that many students lost all sense of meaning or understanding in elementary school……In large numbers our students …… [at Bloomfield College (New Jersey) and Lehman (CUNY)]……cannot order a set of fractions and decimals and cannot place them on a number line. Many do not comprehend division by a fraction and have no concrete comprehension of the process of division itself. Reading rulers where there are other than 10 subdivisions, basic operational meaning of area and volume, are pervasive difficulties. Most cannot deal with proportional reasoning nor any sort of problem that has to be translated from English. Our diagnostic test, which has now been given at more than a dozen institutions shows that there are such students everywhere . . . . .[even Wellesley (Epstein 1999)].
Kati Haycock (1999), director of the American Association of Higher Education’s (AAHE’s) Education Trust < http://www.edtrust.org/> hits the nail on the head: “Higher education…. (unlike Governors and CEO’s) ….. has been left out of the loop and off the hook …. (in the effort to improve America’s public schools since release of A Nation at Risk in 1983)…. Present neither at the policy tables where improvement strategies are formulated nor on the ground where they are being put into place, most college and university leaders remain blithely ignorant of the roles their institutions play in helping K-12 schools get better - and the roles they currently play in maintaining the status quo …. How are we going to get our students to meet high standards if higher education continues to produce teachers who don’t even meet those same standards?  How are we going to get our high school students to work hard to meet new, higher standards if most colleges and universities will continue to admit them regardless of whether or not they even crack a book in high school?” (My italics.)

According to the NSF Advisory Committee (1996): “Many faculty in SME&T. . . . (Science, Math, Engineering, and Technology) . . . . at the post-secondary level continue to blame the schools for sending underprepared students to them. But, increasingly, the higher education community has come to recognize the fact that teachers and principals in the K-12 system are all people who have been educated at the undergraduate level, mostly in situations in which SME&T programs have not taken seriously enough their vital part of the responsibility for the quality of America’s teachers.” (My italics.) See also NSF Advisory Committee (1998).

Fortunately, despite the general failure of pre-service teacher education, several programs have been established over the past few years to enhance the pedagogical skills and content knowledge of in-service physics teachers. For a hot-linked list of 25 such programs see Hake (2000d).

The recent Glenn Commission (2000) proposals may be a step in the right direction. The commission requests 5 billion dollars in the first year to initiate (my italics):

a. establishment of an ongoing system to improve the quality of mathematics and science teaching in grades K–12,

b. significant increase in the number of mathematics and science teachers with improved quality of their preparation,

c. improvement of the working environment and so as to make the teaching profession more attractive for K–12 mathematics and science teachers.
L11. Interdisciplinary cooperation of instructors, departments, institutions, and professional organizations is required for synthesis, integration, and change in the entire chaotic educational system.

Although more research to develop better strategies for the enhancement of student learning (L9) is required, that by itself will not reform the entire chaotic educational system, as has been emphasized by Tobias (1992a,b; 2000), Sarason (1990, 1996), Hilborn (1997), and Wilson & Davis (1994). In my opinion, an engineering approach to the improvement of education (Felder 2000a,b) seems to be required. Bordogna (1997) conveys the essence of engineering as “integrating all knowledge for some purpose. . . . The engineer must be able to work across many different disciplines and fields - and make the connections that will lead to deeper insights, more creative solutions, and getting things done. In a poetic sense, paraphrasing the words of Italo Calvino (1988), the engineer must be adept at correlating exactitude with chaos to bring visions into focus.” (My italics). It would appear that “engineering” as seen by Bordogna is similar to “integrative science” as seen by Holling (1998).

L12. Various institutional and political factors, including the culture of research universities, slow educational reform.

Among the institutional and political factors listed by Tobias (2000) as thwarting educational reform are (those most associated with the culture of research universities are indicated in italics):

a. Advanced Placement (AP) courses serve as a filter rather than a pump.

b. In-class and standardized tests (MCAT, SAT, GRE) drive the curriculum in a traditional direction.

c. Effectiveness of teaching has little effect on promotion/tenure decisions or on national departmental rankings.

d. High-school science courses are not required for college admission; many colleges require little or no science for graduation.

e. Clients for the sciences aren’t cultivated among those who do not wish to obtain PhD.’s.

f. Class sizes are too large.

To Tobias’s list I would add:

g. The failure of the K-12 system to incorporate physics – the most basic of the sciences and essential for any proper understanding of biology and chemistry – into all grades for all students (Hammer 1999, Neuschatz 1999, Lederman 1999, Livanis 2000). In the words of physics Nobelist Leon Lederman: “We have observed that 99 percent of our high schools teach biology in 9th (or 10th) grade, chemistry in 10th or 11th grade, and, for survivors, physics in 11th or 12th grade. This is alphabetically correct, but by any logical scientific or pedagogical criteria, the wrong order. . . . This reform . . . (“physics first”). . . . concentrates on installing a coherent, integrated science curriculum, which matches the standards of what high school
graduates should understand and be able to do . . . And wouldn’t it be a natural next step to invite the history teachers, the teachers of arts and literature, to help develop those connections of the fields of learning that the biologist E.O. Wilson (1998) calls ‘consilience’?

h. **The failure of research universities to:**

1. **Discharge their obligation to adequately educate prospective K-12 teachers**
   (Hake 2000c) – see L10.

2. **Think of education in terms of student learning rather than the delivery of instruction**
   (Barr & Tagg 1995). An emphasis on the learning paradigm may be encouraged by:
   
   a. the previously mentioned *Scholarship of Teaching & Learning* movement
      (Carnegie Academy 2000) inspired by Boyer (1990) and the Boyer Commission (1998);
   
   b. the National Academy for Academic Leadership
      <http://www.thenationalacademy.org/>, which strives to “educate academic decision makers to be leaders for sustained, integrated institutional change that significantly improves student learning;”
   
   c. threats from accrediting agencies such as ABET (Accreditation Board for Engineering and Technology <http://www.abet.org/>) with its emphasis on accountability for actual student learning (Van Heuvelen & Andre 2000, Heller (2000); and
   
   d. competition for transmission-mode lecture services from distance-education conglomerates (Marchese 1998).

3. **Effectively consider crucial multidisciplinary societal problems such as education.**
   In the words of Karl Pister (1996), former Chancellor of UC - Santa Cruz: “. . . we need to encourage innovative ways of looking at problems, moving away from the increasing specialization of academia to develop new interdisciplinary fields that can address complex real-world problems from new perspectives.”

i. **The failure of society to pay good K-12 teachers what they are worth.** Physicist Don Langenberg (1999), chancellor of the University System of Maryland and president of the National Association of System Heads <http://mdk16.usmd.edu/nash.html>, suggests that “on average, teacher’s salaries ought to be about 50% higher than they are now. Some teachers, including the very best, those who teach in shortage fields (e.g., math and science) and those who teach in the most challenging environments (e.g., inner cities) ought to have salaries about twice the current norm. . . . Simple arithmetic applied to publicly available data shows that the increased cost would be only 0.6% of the GDP, about one twentieth of what we pay for health care. I’d assert that if we can’t bring ourselves to pony up that amount, we will pay far more dearly in the long run.” (My italics.)
L13. The monumental inertia of the educational system may thwart long-term national reform.

The glacial inertia of the nearly immovable U.S. educational system is not well understood. A recent issue of *Daedalus* (1998) contains essays by researchers in education and by historians of more rapidly developing institutions such as power systems, communications, health care, and agriculture. The issue was intended to help answer a challenge posed by physics Nobelist Kenneth Wilson: “If other major American ‘systems’ have so effectively demonstrated the ability to change, why has the education ‘system’ been so singularly resistant to change? What might the lessons learned from other systems’ efforts to adapt and evolve have to teach us about bringing about change - successful change – in America’s schools?” As far as I know, no definitive answer has yet been forthcoming.

Clifford Swartz (1999), former editor of *The Physics Teacher* and long-time acerbic critic of physics-education research, wrote: “There is a variety of evidence, and claims of evidence, that each of the latest fads . . . (constructivism, ‘group’ and ‘peer’ instruction, ‘interaction’) . . . produces superior learning and happier students. In particular, students who interact with apparatus or lecture do better on the *Force Concept Inventory* exam (Hestenes et al. 1992). The evidence of Richard Hake’s (1998a) metastatistical study is so dramatic that the only surprising result is that many schools and colleges are still teaching in old-fashioned ways. Perhaps the interaction technique reduces coverage of topics, or perhaps the method requires new teaching skills that teachers find awkward. *At any rate the new methodology is not sweeping the nation.*” (My italics.)

New educational methodologies have from time to time swept the nation (e.g., “the new math,” PSSC (Physical Science Study Committee) physics, the Keller Plan (Personalized System of Instruction) but then faded from sight. History (Holton 1986; Arons 1993, 1997; Sarason 1990, 1996; Cuban 1999) suggests that the present educational reform effort may, like its predecessors, have little lasting impact. This would be most unfortunate, considering the current imperative to:

a. educate more effective science majors and science-trained professionals,

b. raise the appallingly low level of science literacy among the general population,

c. solve the monumental science-intensive problems (economic, social, political, and environmental) that beset us.
L14. “Education is not rocket science, it’s much harder.”
George Nelson, astronaut and astrophysicist, as quoted by Redish (1999).

My own belief, conditioned by 40 years of research in superconductivity and magnetism, 28 years in physics teaching, and 16 years in education research, is that effective education (both physics teaching and education research) is harder than solid-state physics. The latter is, of course, several orders of magnitude harder than rocket science. Nuclear physicist Joe Redish (1999) writes: “The principles of our first draft of a community map for physics education are different in character from the laws we would write down for a community map of the physical world. They are much less like mathematical theorems and much more like heuristics. This is not a surprise, since the phenomena we are discussing are more complex and at a much earlier stage of development.” Since education is a complex, early-stage, dynamic, non-linear, scientific/sociopolitical, high-stakes system, it might benefit from the expertise of conservation ecologists who are well used to dealing with such challenging systems. (Holling 1999).

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your responses will be hyperlinked to the article. To submit a comment, follow this link. To read comments already accepted, follow this link.

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30


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