

The Case for Classroom Clickers – A Response to Bugeja * † †

Richard Hake <rrhake@earthlink.net>

Indiana University, Emeritus <<http://www.physics.indiana.edu/~hake>>

Michael Bugeja in an article “Classroom Clickers and the Cost of Technology” states that clickers at Iowa State have been pushed by commercial interests in way that subverts rather than enhances education, a complaint that deserves to be taken seriously by universities. But Bugeja then goes on to imply that clickers (a) were introduced into education by manufacturers, thus ignoring their academic pedigree, and (b) are nearly useless in education, ignoring the evidence for their effectiveness. Perhaps the most dramatic such evidence has been provided by Eric Mazur, who increased the class average *normalized* learning gain <g> on a standardized test of conceptual understanding of Newtonian mechanics by a factor of about two when he switched from traditional passive-student lectures to clicker-assisted “Peer Instruction.” In addition, clickers: (a) have contributed to the spread of the PI approach by providing a relatively easy and attractive bridge from traditional passive-student lectures to greater interactivity, (b) allow instructors to obtain real-time student feedback in histogram form thus “making students' thinking visible and promoting critical listening, evaluation, and argumentation in the class,” (c) archive student responses so as to improve questions and contribute to education research. From a broader perspective, clickers may contribute to the spread of “interactive engagement” methods shown to be relative effective in introductory physics instruction - i.e., methods designed to promote conceptual understanding through the active engagement of students in heads-on (always) and hands-on (usually) activities that yield *immediate feedback* through discussion with peers and/or instructors.

I. Bugeja’s Clicker Complaint

Michael Bugeja (2008a), director of the Greenlee School of Journalism and Communication at Iowa State University, in a recent *Chronicle of Higher Education* article titled “Classroom Clickers and the Cost of Technology,” exposed a dark side of clicker usage. Bugeja wrote:

Last spring I received an e-mail message from my university's Center for Excellence in Learning and Teaching that read like an advertisement: “If you are thinking of ordering personal response system units, or clickers, for your class next fall, be sure to attend the upcoming CELT session, Using TurningPoint Clickers to Engage Students in the Classroom.” In this case. . . . the center was helping a company by providing workshops and promotion for a device resembling a television remote control.

Bugeja stated that at Iowa State commercial vendors whose goal is profit, not pedagogy, have bypassed the standard competitive bidding process and pitched clickers directly to professors, relying on IT departments to assume costs and on centers of teaching excellence to provide training in workshops and promotion in posters, e-mail blasts, and new-product releases. Similar problems have arisen at the University of Missouri [Gunderson & Wilson (2004)].

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‡ All URL’s are hot-linked; accessed on 15 December 2008. Tiny URL’s courtesy <<http://tinyurl.com/create.php>>.

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Bugeja has emphasized a negative aspect to the commercialization of clickers that should concern universities. However, Bugeja's history of clickers ignores their academic pedigree, and his implication that clickers are next to useless ignores the extensive evidence for their effectiveness.

II. The History of Classroom Clickers

Bugeja states that clickers were developed in Hollywood to test audience response to their products, then commercialized by businesses to gauge audience response to presentations, then introduced by *manufacturers* into education.

But my reading of the history of classroom clickers is somewhat different. As far as I know, the late physicist H. Richard Crane was the inventor of classroom clickers and it was he, *not* "manufacturers," who first introduced clickers to education. In awarding Crane the Oersted Medal in recognition of his notable contributions to the teaching of physics – see Jossem (2007) and Crane (1977) -, Janet Guernsey (1977) wrote:

In spite of his responsibilities of service and leadership on many committees Dick Crane has found the time to indulge his gift for invention. At one time he devised an electronic instant grader by which students in a large class could answer questions put to them by an instructor "yes," "no," or "abstain," by pushing the appropriate button on their chairs. . . . [Crane (1961)]. . . . This device was not long in pointing out that the questions asked by some instructors were of poor quality, indeed, and it was promptly dubbed the "instructor rater."

In his historical review, clicker pioneer Louis Abrahamson (2006) cites the early classroom clicker implementation by physicist Ralph Littauer, first at Stanford in 1966 and then at Cornell about 1968 [Littauer (1972)], but overlooks Crane (1961) at Michigan.

III. Evidence for Educational Effectiveness of Clickers

Bugeja wrote:

. . . I am still wary of clickers, and I asked professors in my unit if they were using them. Jay Newell, who teaches advertising, consulted with his student advisory committee about using clickers in his large class. The students were against clickers, he observed: "One said that she and her friends would slow down lectures by inputting incorrect answers to poll questions. Another said that it was not unusual to have one student bring multiple clickers as a favor to friends in classes in which clicker responses were used to award credit."

Bugeja also quotes clicker naysayer, Ira David Socol <<http://tinyurl.com/6p2blm>> of Michigan State, as follows:

The idea of wasting money on a device no more sophisticated pedagogically than raising your hand drives me nuts, whether it is students' money or the university's. Cellphones can perform the same tasks as clickers with more interactivity and less inefficiency.

On his blog post "Who's Behind the Curtain?" Socol (2008) elaborates his anti-clicker stance, calling clickers "coercive technology" and "instant anachronisms."

If the above denigration of the educational effectiveness of clickers by Bugeja, Socol, and Newell's Student Advisory Committee (NSAC) is valid, then one wonders why clickers are relatively popular. Abrahamson (2006) wrote:

Today, at almost every university in the USA, somewhere a faculty member in at least one discipline is using a response system in their teaching. This is a phenomenon that has mushroomed to its present stage, mainly within the past three years, from a mere handful of pioneering educators a decade ago.

One can get some idea of the popularity of response systems in *education* by googling first “collaborative learning” (as a calibration) and then the ***bold italicized*** alternate terms for clickers below (with the quotes “.....” but without the square brackets [.....]) to obtain the following “hit list” (all hit numbers are prefaced by Google with the word “about”) in descending order of hits as of 9 Dec 2008):

“Collaborative Learning”	1,030,000
Clickers.....	787,000
<i>[Clickers education]</i>	<i>643,000</i>
“Audience Response Systems”.....	104,000
<i>[“Audience Response Systems” Education].....</i>	<i>72,700</i>
“Group Decision Support Systems”.....	33,900
<i>[“Group Decision Support Systems” Education]...<i></i></i>	<i>10,400</i>
“Personal Response Systems”	22,300
<i>[“Personal Response Systems” Education].....</i>	<i>14,100</i>
<i>“Classroom Response Systems”</i>	<i>10,900</i>
<i>“Classroom Communication Systems”</i>	<i>1,620</i>
“Group Process Support Systems”	246
<i>[“Group Process Support Systems” Education].....</i>	<i>102</i>

If clickers were as educationally marginal as Bugeja, Socal, and the NSAC suggest, then one might expect many of the above hits to carry negative appraisals [as for the “Ford Edsel” (59,700 Google Hits)], but quick scans of the first few non-commercial hits in each of the above ***black italicized*** categories show primarily positive commentary. In addition, “Google Trends” <<http://google.com/trends>> can be used to examine *search frequencies*. For example, if one types in [“collaborative learning”, clickers] (with the quotes “.....” but without the square brackets [.....]), for the United States and for the year 2008, then the bar graphs show that “clickers” are far more searched for than “collaborative learning” - by about factors of two in Georgia to four in clicker-crazed California.

How is it that so many faculty, including respected academics such as physicists Eric Mazur (1997) and Nobelist Leon Lederman [Burnstein & Lederman (2001, 2003, 207)]; biologists Gordon Uno (1985) and William Wood (2004); chemist Arthur Ellis [Ellis et al. (2000)]; and cognitive scientists Bransford et al. (2000a,b) and Jeremy Roschelle & Roy Pea (2002) do not seem to share the insights of Bugeja, Socal, and the NSAC regarding the futility of clicker usage?

Could it be that clickers, if properly used, could actually provide a cost-effective way of enhancing student learning?

Responding to Bugeja, clicker expert Derek Bruff (2008a), assistant director of the Vanderbilt Center for Teaching, rose to the defense of clickers in his blog post “The Costs and Benefits of Clickers.” Bruff wrote:

I agree with some of Bugeja's (2008a) takeaways from his institution's experiences with clicker vendors. He argues that students should be involved in decisions about instructional technology, that chief information officers should be consulted by departments making such decisions, that faculty adopting technologies should be aware of not-so-obvious costs of using these technologies, and that administrators should be prudent when conducting cost-benefit analyses of new instructional technologies.

Those are all very sensible points. However, I see some problems in the ways Bugeja uses clickers as an example in support of these points. The fundamental weakness of the essay is that Bugeja seems to be doing a cost-benefit analysis on clickers without paying much attention to the benefits portion of that analysis. As well-referenced as the cost portion of his analysis is. . . . [Bugeja (2008c)]. . . , *he fails to consider any of the research looking into the impact of teaching with clickers on student learning. . . .* [My italics.]

Perhaps the most dramatic example of the effective use of clickers; is provided by Eric Mazur and his group at Harvard, who use clickers in a pedagogical method called “Peer Instruction” - see e.g., Mazur (1997), Crouch & Mazur (2001), Lorenzo et al. (2006), Rosenberg et al. (2006), Crouch et al. (2007), and Lasry et al. (submitted)

In sharp contrast to most educational research on the effectiveness of clickers [for reviews see e.g., Bruff (2008b), Caldwell (2007), Hake (2007a), Banks (2006)], the relative effectiveness of “Peer Instruction” (PI) in enhancing student learning has been convincingly demonstrated by pre-post testing using valid and consistently reliable tests of conceptual understanding such as the *Force Concept Inventory* (FCI) [Hestenes et al. (1992)], developed through arduous qualitative and quantitative research by disciplinary experts, see e.g., the landmark work of Halloun & Hestenes (1985a,b).

Table 1 of Crouch & Mazur (2001) shows the following progression in the class average *normalized* pre-to-posttest gain $\langle g \rangle$ where $\langle g \rangle = (\% \text{post} - \% \text{pre}) / (100\% - \% \text{pre}) = (\text{actual gain}) / (\text{maximum possible gain})$ on the FCI [the rationale for - and history of - the half-century-old “normalized gain” is discussed by Hake (2008b)]:

1991 - Using the traditional passive-student lecture method Mazur's class achieved $\langle g \rangle = 0.25$, about average for the 14 traditional passive student lecture courses surveyed in Hake (1998a,b).

1992 - After switching to PI, Mazur's class achieved $\langle g \rangle = 0.49$, about average for the 48 “interactive engagement” courses surveyed in Hake (1998a,b).

1997 - After further experience and augmentations from “Just In Time Teaching” [Novak et al. (1999)] and the McDermott Group's “Tutorials” [McDermott et al. (1998)], Mazur's class achieved $\langle g \rangle = 0.74$, exceeding the highest $\langle g \rangle = 0.69$ in the courses surveyed in Hake (1998a,b).

That PI is also relatively effective at institutions less selective than Harvard has been shown by Fagen et al. (2002) and by Lasry et al. (2008).

The rigorously demonstrated effectiveness of clicker-assisted PI relative to traditional pedagogy by the Harvard group for a wide range of institutions, teachers, and student populations would seem to call into question the dour appraisals of educational clicker usage by Bugeja (2008a), Socal (2008), and the NSAC.

In addition, positive contributions of clicker-assisted pedagogy to student learning have also been reported by:

- a. Other physicists, e.g.: Dufresne et al. (1996), Mestre et al. (1997), Massen et al. (1998), Reay et al. (2005, 2008), Beatty et al. (2006), Burnstein & Lederman (2001, 2003, 2007); see also Bruff's physics-astronomy bibliography at <<http://tinyurl.com/5ndzvt>>.
- b. Educators in many other disciplines, see, e.g.: the reviews by Banks (2006); Caldwell (2007); and Bruff (2007, 2008b, 2009). Bruff's (2008b) bibliography lists clicker references for the following disciplines: Biological Sciences, Business and Management, Chemistry, Communications, Computer Science, Earth Sciences, Economics, Engineering, English, Law, Library Science & Information Literacy, Mathematics & Statistics, Medical Professions (Non-Nursing), Nursing, Philosophy, Physics & Astronomy, Political Science, & Psychology.
- c. Cognitive Scientists, see, e.g., "Theorizing the Networked Classroom" [Penuel et al. (2004)]; "Classroom response and communication systems: Research review and theory" [Roschelle et al. (2004)]; "A walk on the WILD side: How wireless handhelds may change computer-supported collaborative learning" [Roschelle & Pea (2002), WILD = Wireless Internet Learning Devices]; *How people learn: brain, mind, experience, and school* [Bransford et al. (2000a)] and "When computer technologies meet the learning sciences: Issues and opportunities" [Bransford et al. (2000b)].

Bransford et al. (2000a, page 182), in discussing the early clicker system Classtalk [Abrahamson (1998, 1999, 2006), Better Education (2008)] wrote [my insert at ". . . [insert]. . . .":

[Classtalk is] an interactive learning environment in the lectures: students work collaboratively on conceptual questions, and the histogram of students' answers is used as a visual springboard for classwide discussions when students defend the reasoning they used to arrive at their answers. This technology makes students' thinking visible and promotes critical listening, evaluation, and argumentation in the class. The teacher is a coach, providing scaffolding where needed, tailoring "mini-lectures" to clear up points of confusion, or, if things are going well, simply moderating the discussion and allowing students to figure out things and reach consensus on their own. The technology is also a natural mechanism to support formative assessment. . . . [in the sense used by Black & Wiliam (1998) and Shavelson (2008) as assessment done "on the fly" by teachers so as to immediately adapt their teaching to meet student needs - as in the method of the *historical* Socrates [Hake (2007b)] - and not in the sense of the "Joint Committee on Standards for Educational Evaluation" [JCSEE (1994)] as assessment to improve a course as it is being developed]. . . . , providing both the teacher and students with feedback on how well the class is grasping the concepts under study. The approach accommodates a wider variety of learning styles than is possible by lectures and helps to foster a community of learners focused on common objectives and goals.

Thus clickers may allow a cost-effective Socratic approach [Hake (1992, 2008a), Abrahamson (1998, 1999)] to instruction in large-enrollment "lecture" sections, but this advantage has been generally deemphasized in the literature, possibly because of the gross misunderstanding of the Socratic Method by many academics (Hake 2007b).

IV. Clickers vs Flashcards

Returning to Socal's claim that cellphones can replace clickers, a less expensive alternative to clickers is low-tech flashcards as used by Meltzer & Manivannan (1996, 2002). Nathaniel Lasry (2008), in "Clickers or Flashcards: Is There Really a Difference?" *directly* compared the difference in student learning for clicker vs flashcard usage by measuring pre-to-post test gains on the FCI in courses he taught using Mazur's (1997) "Peer Instruction" method. Lasry concluded (my *italics*, my insert at ". . . .[insert]. . . ."):

Clickers are usually used in the classroom to enhance *teaching* and *learning*. From a *teaching* perspective, clickers have a number of very practical advantages: they allow instructors to get precise real-time feedback and store students' responses to Concep-Tests. Furthermore, using clickers draws attention to Peer Instruction (PI) and requires instructors to shift their focus toward conceptual instruction. *From a learning perspective, using PI with clickers does not provide any [statistically]. . . significant learning advantage over low-tech flashcards.* PI is an approach that engages students and challenges them to commit to a point of view that they can defend. *The pedagogy is not the technology by itself.*

The only other comparison of clickers and flashcard of which I'm aware is that of Stowell & Nelson (2007). According to Bruff's (2008b) discussion of that paper:

The clicker group appeared to answer in-class questions more honestly than the response card and hand-raising groups. This was the authors' conclusion after noting that the percent of questions answered correctly using clickers more closely mirrored the percent of questions answered correctly on the post-lecture quiz. (There was a 22% drop in accuracy from during-lecture to post-lecture for clickers versus a 38% drop for hand-raising and 40% drop for response cards.)

However, since Stowell & Nelson - like most education researchers - failed to measure student learning gains from start to finish of the course, their comparison of clickers to flashcards complements rather than conflicts with Lasry's conclusions that student learning gains are about the same for those two methods as used in "Peer Instruction."

The flashcard/clicker equivalence in promoting student learning seems to be yet another case where it's the *pedagogy* rather than the *technology* that's important. Steve Ehrmann, director of the Flashlight Program <<http://www.tltgroup.org/flashlightP.htm>> [in the commentary section following Groveman's (2008) charge that clickers were "edtechtainment - pedagogy by gimmickry"] put it well:

The clickers don't "cause" the learning, any more than the paper in a physics textbook or the blackboard behind the faculty member "cause" learning. But like them, clickers are a powerful tool in the proper circumstances and in the right hands.

V. What Causes Higher Order Learning?

What *does* cause higher-order learning? My survey [Hake (1998a,b; 2002)] of 62 introductory physics courses in high schools, colleges, and universities indicated about a two-standard deviation superiority of average normalized gains $\langle g \rangle$ on the *Force Concept Inventory* [Hestenes et al. (1992)] of “interactive engagement” methods over traditional passive-student lecture methods. This result and confirmatory results shown in about 25 other physics-education research papers as listed in Hake (2008a) strongly suggests that the key to relatively effective introductory physics education (and probably the enhancement of students' understanding of difficult concept in other subjects):

(a) IS primarily – “interactive engagement,” i.e., promotion of conceptual understanding through the active engagement of students in heads-on (always) and hands-on (usually) activities that yield *immediate feedback* through discussion with peers and/or instructors; and

(b) IS NOT primarily the e.g., technology involved; nature of the institution; student or peer evaluation ratings of the instructors; grade level or scientific reasoning ability of the students [although this *can* be a factor as shown by Coletta & Phillips (2005) and Coletta et al. (2007a,b)]; or the - particular type of "interactive engagement" - e.g., (a) the “Peer Instruction” of the Mazur group; (b) the collaborative peer instruction of Johnson, Johnson, & Smith; Slavin; and Heller, Keith, & Anderson; (c) the “Modeling” method of Halloun & Hestenes; (d) the “Active Learning Problem Sets or Overview Case Studies of Van Heuvelen, or (e) the Socratic Dialogue Inducing Laboratories of Hake - for references to the above methods see Hake (2002).

BUT WAIT! Judging from their articles I suspect that Socal (2008) and Groveman (2008) would object that higher-level learning cannot be measured by multiple-choice tests such as the *Force Concept Inventory*. But psychometricians Wilson & Bertenthal (2005) think differently. They wrote (p. 94):

Performance assessment is an approach that offers great potential for assessing complex thinking and learning abilities, but multiple choice items also have their strengths. For example, although many people recognize that multiple-choice items are an efficient and effective way of determining how well students have acquired basic content knowledge, many do not recognize that they can also be used to measure complex cognitive processes. For example, the *Force Concept Inventory* . . . [Hestenes, Wells, & Swackhamer (1992)] . . . is an assessment that uses multiple-choice items to tap into higher-level cognitive processes.

The superiority of "interactive engagement" methods in promoting conceptual understanding and higher-order learning is probably related to the “enhanced synapse addition and modification” induced by those methods. Cognitive scientists Bransford et al. (2000a, page 118) state:

“ . . . synapse addition and modification are lifelong processes, driven by experience. In essence, the quality of information to which one is exposed and the amount of information one acquires is reflected throughout life in the structure of the brain. This process is probably not the only way that information is stored in the brain, but it is a very important way that provides insight into how people learn.”

See also “Can Neuroscience Benefit Classroom Instruction?” [Hake (2006)] and “Are Concepts Instantiated in Brain Synapses?” Hake (2007d)

VI. Lessons Relevant to Bugeja's Essay

Bugeja takes the moral of his essay to be (my *italics*):

Institutions have *much to learn from students about the cost and effectiveness of technology*. Chief information officers need to be consulted before departments invest in expensive for-profit consumer technologies. Professors need to realize that technology comes at a price, even when advertised as “free.” Finally, administrators need to double their efforts at cost containment, demanding assessment before investment, especially in schemes that bypass mandated accountability standards. Otherwise business as usual will continue to disenfranchise our students, who will hold their debt-ridden futures in their clicking hands.

In my opinion, other important lessons relevant to Bugeja's essay are:

1. Pedagogy is not the technology itself [consistent with Hake (1998a,b) and Lasry 2008)];
2. Administrators should demand assessment before investment [*consistent* with Bugeja (2008a)], but [*contrary* to Bugeja] should NOT rely on the *opinions of students* to assess the cognitive (as opposed to the affective) impact of instructional methods. Instead administrators should encourage a bottom up reform of the effectiveness of higher education by standing aside and encouraging faculty to gauge the extent of student learning in their courses by means of *formative* pre/post testing with valid and consistently reliable tests devised by disciplinary experts [Hake (2005; 2008b,c)].

References [Tiny URL's courtesy <<http://tinyurl.com/create.php>>.]

Abrahamson A.L. 1998. "An Overview of Teaching and Learning Research with Classroom Communication Systems (CCSs)," presented at the *Samos International Conference on the Teaching of Mathematics*, Village of Pythagorion, Samos, Greece, July, online at <<http://www.bedu.com/Publications/Samos.html>>.

Abrahamson A.L. 1999. "Teaching with a Classroom Communication System - What it Involves and Why it Works," Mini-Course presented at the VII Taller Internacional *Nuevas Tendencias en la Enseñanza de la Física*, Benemerita Universidad Autonoma de Puebla, Puebla, Mexico, May 27-30; online at <<http://www.bedu.com/Publications/PueblaFinal2.pdf>> (108 kB).

Abrahamson A.L. 2006. "A Brief History of Networked Classrooms: Effects, Cases, Pedagogy, and Implications," in Banks (2006).

Banks, D., ed. 2006. *Audience Response Systems in Higher Education: Applications and Cases*. Information Sciences Publishing, publishers information at

<<http://www.igi-pub.com/books/details.asp?id=5556>> including the Table Of Contents, Book Excerpt, Preface, Reviews & Testimonials, and the Author's/Editor's Bio. The publisher states:

Taking advantage of user-friendly technology, Audience Response Systems (ARS) facilitate greater interaction with participants engaged in a variety of group activities. Each participant has an input device that permits them to express a view in complete anonymity, and the composite view of the total group appears on a public screen. ARS can then be used to support summative and formative activities with groups ranging in size from as small as five through to large groups of several hundred. The data can be used to help the facilitator adjust the pace of teaching to match the requirements of the learners, gauge understanding, or trigger discussion and debate.

Amazon.com information at <<http://tinyurl.com/698pv8>>. Note the "Look Inside" feature. A searchable Google preview is online at <<http://tinyurl.com/5u8rc5>>.

Beatty, I.D., W.J. Gerace, W.J. Leonard, and R.J. Dufresne. 2006. "Designing effective questions for classroom response system teaching," *Am. J. Phys.* **74**(1): 31-39; online at <<http://srri.umass.edu/files/beatty-2006deq.pdf>> (892 kB).

Better Education, Inc. website at <<http://www.bedu.com>> :

We invented *Classtalk* - the classroom communication system, which we designed, prototyped, and researched with the help of National Science Foundation grants. Subsequently as we made & sold *Classtalk* systems, we realized that we would never have enough capital to do the job properly. So, in 1997 we signed an agreement with Texas Instruments (TI) to help develop better systems.

Bransford, J.D., A.L. Brown, R.R. Cocking, eds. 2000a. *How people learn: brain, mind, experience, and school*. Nat. Acad. Press; online at <<http://tinyurl.com/apbgf>>.

Bransford, J., S. Brophy, & S. Williams. 2000b. "When computer technologies meet the learning sciences: Issues and opportunities," *Journal of Applied Developmental Psychology* **21**(1): 59-84; abstract online at <<http://tinyurl.com/6mzgrm>>.

Bruff, D. 2007. "Clickers: a Classroom Innovation: Motivate and assess students with classroom response systems. Clickers, a new instructional tool, improve classroom dynamics and provide useful information on how students learn," National Education Association, *Higher Education Advocate Online*, October; online at <<http://www2.nea.org/he/advo07/advo1007/front.html>>.

Bruff, D. 2008a. "The Costs and Benefits of Clickers," in Bruff's Blog "Teaching with Classroom Response Systems," 3 December; online at <<http://derekbruff.com/teachingwithcrs/?p=39>>. As of 15 December 2008, this blog entry contained an extensive comments section in which Bruff, Bugeja, Socal, Stowell, and Hassall debated the issues.

Bruff, D. 2008b. "Classroom Response Systems ('clickers') Bibliography," Vanderbilt Center for Teaching; online at <<http://tinyurl.com/5ndzvt>>. "Most of the articles present some form of research on the effectiveness or impact of CRSs on student learning. The first group of articles are not discipline-specific; the later articles are grouped by discipline." See also Bruff's (2007) essay "Clickers: a Classroom Innovation" and his forthcoming book *Teaching with Classroom Response Systems: Creating Active Learning Environments* [Bruff (2009)].

Bruff, D. 2008c. "Article: Stowell & Nelson (2007)" in Bruff's Blog "Teaching with Classroom Response Systems," 16 July; online at <<http://derekbruff.com/teachingwithcrs/?p=6>>.

Bruff, D. 2009. *Teaching with Classroom Response Systems: Creating Active Learning Environments*. Jossey-Bass. Amazon.com information at <<http://tinyurl.com/5otp9r>>. See also the description in Bruff's Blog at <http://derekbruff.com/teachingwithcrs/?page_id=36>.

Bugeja, M. 2005. *Interpersonal Divide: The Search for Community in a Technological Age*. Oxford University Press. Amazon.com information at <<http://tinyurl.com/5nq25q>>. See also the book's website at <<http://www.interpersonal-divide.org/>>.

Bugeja, M. 2008a. "Classroom Clickers and the Cost of Technology," *Chronicle of Higher Education* **55**(15), Page A31, 5 December; online at <<http://chronicle.com/free/v55/i15/15a03101.htm>>. I thank Michael Scriven for alerting me to this essay. For a previous report in a similar vein see Bugeja (2008b). For Bugeja's dim view of the "technological age" see Bugeja (2005). For a brighter view see e.g., Nielsen (2008).

Bugeja, M. 2008b. "Could You Be a Hoopla-dite? Too many colleges fail to hold technology to academic standards of cost analysis and assessment," *Chronicle of Higher Education*, 12 September; online at <<http://chronicle.com/jobs/news/2008/09/2008091201c.htm>>.

Bugeja, M. 2008c "FACT CHECK: "Classroom Clickers and the Cost of Technology," online at <<http://www.interpersonal-divide.org/clickers.pdf>> (28 kB)

Burnstein, R.A. & L.M. Lederman. 2001. "Using wireless keypads in lecture classes," *Phys. Teach.* **39**(1): 8-11; online to subscribers at <<http://ojps.aip.org/dbt/dbt.jsp?KEY=PHTEAH&Volume=39&Issue=1>>. In April 2007 Burnstein informed me that the references on keypad systems in this article are outdated.

Burnstein, R.A. & L.M. Lederman. 2003. "Comparison of Different Commercial Wireless Keypad Systems," *Phys. Teach.* **41**(5): 272-275; online to subscribers at <<http://ojps.aip.org/dbt/dbt.jsp?KEY=PHTEAH&Volume=41&Issue=5>>. In April 2007 Burnstein informed me that the references on keypad systems in this article are outdated.

Burnstein, R.A. & L.M. Lederman. 2007. "Wireless Keypads - A New Classroom Technology Using Enhanced Multiple Choice Questions," *Physics Education* **24**(3); online at <http://physics.unipune.ernet.in/~phyed/24.3/24.3_Burnstein.pdf> (96 kB). *Physics Education* <<http://physics.unipune.ernet.in/~phyed/>> "is a peer reviewed online journal that deals with education in physics at the level of secondary school, undergraduate, and postgraduate studies." The two preceding URL's were both dead on 15 Dec 2008, but they may revive.

Caldwell, J.E. 2007. "Clickers in the Large Classroom: Current Research and Best-Practice Tips," *CBE Life Sci Educ* **6**(1): 9-20; online at <<http://www.lifescied.org/cgi/content/full/6/1/9>>.

Coletta, V.P. and J.A. Phillips. 2005. "Interpreting FCI Scores: Normalized Gain, Preinstruction Scores, & Scientific Reasoning Ability," *Am. J. Phys.* **73**(12): 1172-1182; online to subscribers at <<http://tinyurl.com/e5k7m>>.

Coletta, V.P., J.A. Phillips, & J.J. Steinert. 2007a. "Why You Should Measure Your Students' Reasoning Ability," *Phys. Teach.* **45**(4): 235-238; online to subscribers at <<http://tinyurl.com/2gn9aa>>.

Coletta, V.P., J.A. Phillips, & J.J. Steinert. 2007b. "Interpreting Force Concept Inventory scores: Normalized gain and SAT scores," *Phys. Rev. ST Phys. Educ. Res.* **3**, 010106, Issue 1 - June; free online at <<http://prst-per.aps.org/abstract/PRSTPER/v3/i1/e010106>>.

Crane, H.R. 1961. "An experiment toward establishing communication from audience to lecturer," *IRE Transactions on Education* **4**: 162-166; an abstract is online at <http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=4322216>.

Crane, H.R. 1977. "Response of the Oersted Medalist," *Am. J. Phys.* **45**(7): 599-601; online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=AJPIAS&Volume=45&Issue=7>>.

Crouch, C.H. & E. Mazur. 2001. "Peer Instruction: Ten years of experience and results," *Am. J. Phys.* **69**(9): 970-977; online at <<http://tinyurl.com/sbys4>>.

Crouch, C.H., J. Watkins, A. Fagen, and E. Mazur. 2007. "Peer Instruction: Engaging students one-on-one, all at once" in *Reviews in Physics Education Research*, edited by E.F. Redish and P. Cooney; online at <<http://tinyurl.com/5vcke5>>.

Dufresne, R.J., W.J. Gerace, W.J. Leonard, J.P. Mestre, & L. Wenk. 1996. "Classtalk: A Classroom Communication System for Active Learning," *Journal of Computing in Higher Education* **7**: 3-47; online at <<http://www.bedu.com/Publications/UMASS.pdf>> (336 kB).

Ellis, A.B., A. Cappellari, G.C. Lisensky, J.K. Lorenz, K. Meeker, D. Moore, K. Campbell, J. Billmann, and K. Rickert. 2000. ConcepTests; online at <<http://tinyurl.com/5jslzk>>.

Black, P. & D. Wiliam. 1998. "Inside the Black Box: Raising Standards Through Classroom Assessment," *Phi Delta Kappan* **80**(2): 139-144, 146-148; online at <<http://www.pdkintl.org/kappan/kbla9810.htm>>.

- Fagen, A.P., C.H. Crou, & E. Mazur. 2002. "Peer Instruction: Results from a Range of Classrooms," *Phys. Teach.* **40**: 206-209; online at <<http://tinyurl.com/sbys4>>.
- Groveman, A. 2008. "Clickers, Pedagogy and Edtechtainment," *Inside Higher Ed*, 30 June; online at <<http://www.insidehighered.com:80/views/2008/06/19/groveman>>. For more positive *Inside Higher Ed* reports on clickers see Guess (2007) and Jaschik (2008).
- Guess, A. 2007. "Keeping Clickers in the Classroom." *Inside Higher Ed*, 18 July; online at <<http://insidehighered.com/news/2008/07/18/clickers>>.
- Gunderson, M. & G. Wilson. 2004. "Introducing Student Response Systems at MU," online at <<http://etatmo.missouri.edu/toolbox/doonline/StudentResponseSystems.pdf>> (48 kB).
- Gurnsey, J.B. 1977. "H. Richard Crane: Oersted Medalist for 1976," *Am. J. Phys.* **45**(6): 507; online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=AJPIAS&Volume=45&Issue=6>> (1977).
- Hake, R.R. 1992. "Socratic pedagogy in the introductory physics lab," *Phys. Teach.* **30**: 546-552; updated version (4/27/98) at <<http://www.physics.indiana.edu/~sdi/SocPed1.pdf>> (88 kB).
- Hake, R.R. 1998a. "Interactive-engagement vs traditional methods: A six thousand- student survey of mechanics test data for introductory physics courses," *Am. J. Phys.* **66**(1): 64-74; online at <<http://tinyurl.com/3xuyqe>> (84 kB).
- Hake, R.R. 1998b. "Interactive-engagement methods in introductory mechanics courses," online at <<http://tinyurl.com/2tg5d9>> (108 kB) - a crucial companion paper to Hake (1998a).
- Hake, R.R. 2002. "Lessons from the physics education reform effort," *Ecology and Society* **5**(2): 28; online at <<http://www.ecologyandsociety.org/vol5/iss2/art28/>>. *Ecology and Society* (formerly *Conservation Ecology*) is a free online "peer-reviewed journal of integrative science and fundamental policy research with about 11,000 subscribers in about 108 countries." For an update on six of the lessons on "interactive engagement" see Hake (2007c).
- Hake, R. R. 2005. "The Physics Education Reform Effort: A Possible Model for Higher Education?" online at <<http://www.physics.indiana.edu/~hake/NTLF42.pdf>> (100 kB). This is a slightly edited version of an article that was (a) published in the *National Teaching and Learning Forum* **15**(1), December, online to subscribers at <<http://www.ntlf.com/FTPSite/issues/v15n1/physics.htm>>, and (b) disseminated by the *Tomorrow's Professor* list <<http://ctl.stanford.edu/Tomprof/postings.html>> as Msg. 698 on 14 Feb 2006.
- Hake, R.R. 2006. "Can Neuroscience Benefit Classroom Instruction?" online at <<http://listserv.nd.edu/cgi-bin/wa?A2=ind0610&L=pod&P=R6888&I=-3>>. Post of 12 Oct 2006 to POD and other discussion lists.
- Hake, R.R. 2007a. "Re: Review article on electronic instructional polling?" online at <<http://listserv.nd.edu/cgi-bin/wa?A2=ind0706&L=pod&P=R9979&I=-3>>. Post of 16 Jun 2007 17:04:56 -0700 to POD and other discussion lists.

Hake, R.R. 2007b. "The Socratic Method of the Historical Socrates, Plato's Socrates, and the Law School Socrates," online at <<http://tinyurl.com/60d097>>. Post of 21 June to AERA-L and various other discussion lists.

Hake, R.R. 2007c. "Six Lessons From the Physics Education Reform Effort," *Latin American Journal of Physics Education* **1**(1), September; online at <<http://journal.lapen.org.mx/sep07/HAKE%20Final.pdf>> (124 kB).

Hake, R.R. 2007d. "Are Concepts Instantiated in Brain Synapses?" online at <<http://listserv.nd.edu/cgi-bin/wa?A2=ind0706&L=pod&P=R10342&I=-3>>. Post of 17 Jun 2007 to POD and other discussion lists.

Hake, R.R. 2008a. "Design-Based Research in Physics Education Research: A Review," in *Handbook of Design Research Methods in Education: Innovations in Science, Technology, Engineering, and Mathematics Learning and Teaching* [Kelly, Lesh, & Baek (2008)] - publisher's information at <<http://tinyurl.com/4eazqs>>; a pre-publication version of Hake's chapter is online at <<http://www.physics.indiana.edu/~hake/DBR-Physics3.pdf>> (1.1 MB).

Hake, R.R. 2008b. "Should We Measure Change? Yes!" online at <<http://www.physics.indiana.edu/~hake/MeasChangeS.pdf>> (2.5 MB), and as ref. 43 at <<http://www.physics.indiana.edu/~hake>>. To appear as a chapter in an AEA Monograph *Evaluation of Teaching and Student Learning in Higher Education* [Hake, in preparation].

Hake, R.R. 2008c. "Can Distance and Classroom Learning Be Increased?" *IJ-SoTL* **2**(1), January; online at <<http://tinyurl.com/2t5sro>>. The *International Journal of Scholarship of Teaching and Learning* (IJ-SoTL) <<http://www.georgiasouthern.edu/ijsofl/>> "is an open, peer reviewed, international electronic journal containing articles, essays, and discussions about the scholarship of teaching and learning (SoTL) and its applications in higher/tertiary education today."

Halloun, I. & D. Hestenes. 1985a. "The initial knowledge state of college physics students." *Am. J. Phys.* **53**: 1043-1055; online at <<http://modeling.asu.edu/R&E/Research.html>>. The print version contains the *Mechanics Diagnostic* test, precursor to the *Force Concept Inventory* [Hestenes et al. (1992)].

Halloun, I. & D. Hestenes. 1985b. "Common sense concepts about motion," *Am. J. Phys.* **53**: 1056-1065; online at <<http://modeling.asu.edu/R&E/Research.html>>.

Hestenes, D., M. Wells, & G. Swackhamer. 1992. "Force Concept Inventory," *Phys. Teach.* **30**(3): 141-158; online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=PHTEAH&Volume=30&Issue=3>>. Also online, but without the test itself, at <<http://modeling.asu.edu/R&E/FCI.PDF>> (100kB). The 1995 revision of the FCI by Halloun, Hake, Mosca, & Hestenes is online (password protected) at the same URL, and is currently available in 16 languages: Chinese, Czech, English, Finnish, French, German, Greek, Italian, Malaysian, Persian, Portuguese, Russian, Spanish, Slovak, Swedish, & Turkish.

- Jaschik, S. 2008. "Clicker U.," *Inside Higher Ed.*, 3 November; online at <<http://www.insidehighered.com:80/news/2008/11/03/clicker>>.
- Jossem, E.L. 2007. "Remembering Dick Crane," *Phys. Teach.* **4**(6): 330-331; online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=PHTEAH&Volume=45&Issue=6>>.
- Lasry, N., E. Mazur, & J. Watkins. 2008. "Peer Instruction: From Harvard to Community Colleges," *Am. J. Phys.* **76**(11): 1066-1069; online at <<http://tinyurl.com/sbys4>>.
- Lasry, N. 2008. "Clickers or Flashcards: Is There Really a Difference?" *Phys. Teach.* **46**(4): 242-244, online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=PHTEAH&Volume=46&Issue=4>>, also online to all at <<http://tinyurl.com/sbys4>>.
- Lasry, N., E. Mazur, J. Watkins, and D.M. Van Wieren. Submitted for publication, "Student Response Times to Conceptual Questions," online at <<http://tinyurl.com/6fnmrq>>.
- Littauer, R. 1972. "Instructional implications of a low-cost electronic student response system," *Educational Technology: Teacher and Technology Supplement* **12**(10): 69-71.
- Lorenzo, M., C.H Crouch, & E. Mazur. 2006. "Reducing the gender gap in the physics Classroom," *Am. J. Phys.* **74**(2), 118-122.); online at <<http://mazor-www.harvard.edu/publications.php?function=search&topic=9>>.
- Massen, C., J. Poulis, E. Robens, M. Gilbert. 1998. "Physics lecturing with audience paced feedback," *Am. J. Phys.* **66**(5): 439-441; online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=AJPIAS&Volume=66&Issue=5>>, and free to all at <<http://www.bedu.com/Publications/PhysLectAPF.pdf>> (24 kB).
- Mazur, E. 1997. *Peer instruction: A user's manual*. Prentice-Hall. A description is online at <http://mazor-www.harvard.edu/education/pi_manual.php>.
- McDermott L.C., P.S. Schaffer, and the University of Washington Physics Education Research Group. 1998. *Tutorials in Introductory Physics*. Prentice Hall. For information see <<http://www.phys.washington.edu/groups/peg/tut.html>>.
- Meltzer, D.E. & K. Manivannan. 1996. "Promoting interactivity in physics lecture classes," *Phys. Teach.* **34**: 72-76; online at <<http://tinyurl.com/2z8z6s>>. This is the precursor to the more recent Meltzer & Manivannan (2002).
- Meltzer D.E. & K. Manivannan. 2002. "Transforming the lecture-hall environment: The fully interactive physics lecture," *Am. J. Phys.* **70**: 639-654; online at <<http://www.physicseducation.net/docs/AJP-June-2002-Vol.-70--639-654.pdf>> (356 kB).

Mestre, J.P., W.J. Gerace, R.J. Dufresne, and W.J. Leonard. 1997. "Promoting active learning in large classes using a classroom communication system," pp. 1019-1036, in *"The Changing Role of Physics Departments in Modern Universities - Proceedings of the International Conference on Undergraduate Physics Education,"* E.F. Redish and J.S. Rigden, eds. American Institute of Physics.

Nielsen, M. 2008. "The Future of Science: Building a Better Collective Memory," *APS News*, **17**(10). The full version appears on Nielsen's blog at <<http://michaelnielsen.org/blog/?p=448>>. Note the extensive exchange of opinions following Nielsen's blog article.

Novak, G., E. Patterson, A. Gavrin, and W. Christian. 1999. *Just-in-Time Teaching: Blending Active Learning and Web Technology*. Prentice Hall. See also <<http://jittdl.physics.iupui.edu/jitt/>>.

Penuel, W.R., L. Abrahamson, & J. Roschelle. 2004. "Theorizing the Networked Classroom," online at <http://ctl.sri.com/publications/downloads/Theorizing_the_Networked_Classroom.pdf> (108 kB), in Banks (2006).

Reay, N.W., L. Bao, P. Li, R. Warnakulasooriya, and G. Baugh. 2005. "Toward the effective use of voting machines in physics lectures," *Am. J. Phys.* **73**(6): 554-558; online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=AJPIAS&Volume=73&Issue=6>>.

Reay, N.W., P. Li, , & L. Bao. 2008. "Testing a new voting machine methodology," *Am. J. Phys.* **76**(2): 171-178; online to subscribers at <<http://scitation.aip.org/dbt/dbt.jsp?KEY=AJPIAS&Volume=76&Issue=2>>.

Roschelle, J., W.R. Penuel, & L. Abrahamson. 2004. "Classroom response and communication systems: Research review and theory." Presented at the Annual Meeting of the American Educational Research Association, San Diego, CA, online at <http://ubiqcomputing.org/CATAALYST_AERA_Proposal.pdf> (204 kB).

Roschelle, J. & R. Pea. 2002. "A walk on the WILD side: How wireless handhelds may change computer-supported collaborative learning," *International Journal of Cognition and Technology* **1**(1): 145-168; online as a 944 kB pdf at <<http://tinyurl.com/6dtoep>>.

Rosenberg, J., M. Lorenzo, & E. Mazur. 2006. "Peer instruction: Making science engaging," in *Handbook of College Science Teaching*, (pp. 77-85), J.J. Mintzes and W.H. Leonard, eds., NSTA Press; online at <<http://tinyurl.com/5oxk2c>>.

Shavelson, R.J. 2008. "Formative Assessment," Guest Editor's Introduction, special issue of *Applied Measurement in Education*, in press; online at <<http://www.stanford.edu/dept/SUSE/SEAL/>>. Also free online at the same URL are five articles on formative assessment that appear in *Applied Measurement in Education* **21**(4) of 4 October; online to subscribers at <<http://tinyurl.com/5jxnwx>>.

Socol, I.D. 2008. "Who's Behind the Curtain?" Socol's Blog post, online at <<http://speedchange.blogspot.com/2008/12/whos-behind-curtain.html>>

Stowell, J.R., & J.M. Nelson. 2007. "Benefits of electronic audience response systems on student participation, learning, and emotion," *Teaching of Psychology* **34**(4): 253-258; abstract online at <<http://www.informaworld.com/smpp/content~content=a790482090~db=all>>. For Bruff's commentary on this article see Bruff (2008c).

Uno, G.E. 1984. "A Push-Button Electronic System to Promote Class Discussion," *American Biology Teacher* **46**(4), 229-232 (1984).

Wilson, M.R. & M.W. Bertenthal, eds. 2005. *Systems for State Science Assessment*. National Academy Press; online at <http://www.nap.edu/catalog.php?record_id=11312>.

Wood, W.B. 2004. "Clickers: A Teaching Gimmick that Works," *Developmental Cell* **7**: 796-798; online at <<http://www.colorado.edu/MCDB/MCDB6440/ClickersDevCellC.pdf>> (84 kB).