Is It Time for a Science Counterpart of the Benezet–Berman Mathematics Teaching Experiment of the 1930's?

Sanjoy Mahajan,[1] University of Cambridge ⟨http://www.inference.phy.cam.ac.uk/sanjoy⟩
Richard R. Hake,[2] Indiana University ⟨http://www.physics.indiana.edu/~hake⟩

Based on an invited poster presented at the *Physics Education Research Conference 2000: Teacher Education* ⟨http://www.sci.ccny.cuny.edu/~rstein/perc2000.htm⟩

Abstract. Should teachers concentrate on critical thinking, estimation, measurement, and graphing rather than college-clone algorithmic physics in grades K–12?[3] Thus far physics education research offers little substantive guidance. Mathematics education research addressed the mathematics analogue of this question in the 1930's. Students in Manchester, New Hampshire were not subjected to arithmetic algorithms until grade 6. In earlier grades they read, invented, and discussed stories and problems; estimated lengths, heights, and areas; and enjoyed finding and interpreting numbers relevant to their lives. In grade 6, with 4 months of formal training, they caught up to the regular students in algorithmic ability, and were far ahead in general numeracy and in the verbal, semantic, and problem solving skills they had practiced for the five years before. Assessment was both *qualitative* – e.g., asking 8th grade students to relate in their own words why it is 'that if you have two fractions with the same numerator, the one with the smaller denominator is the larger'; and *quantitative* – e.g., administration of standardized arithmetic examinations to test and control groups in the 6th grade. Is it time for a science counterpart of the Benezet/Berman Manchester experiment of the 1930's?

1 Rote learning: Opium for the mind

Traditionally taught science and mathematics teach little except obedience. Here are examples for the skeptical. This gem is discussed by Alan Schoenfeld (1987):

> One of the problems on the NAEP [National Assessment of Educational Progress] secondary mathematics exam, which was administered to a stratified sample of 45,000 students nationwide, was the following: An army bus holds 36 soldiers. If 1128 soldiers are being bused to their training site, how many buses are needed?
>
> Seventy percent of the students who took the exam set up the correct long division and performed it correctly. However, the following are the answers those students gave to the question of 'how many buses are needed?': 29% said...31 remainder 12; 18% said...31; 23% said...32, which is correct. (30% did not do the computation correctly).
>
> It's frightening enough that fewer than one-fourth of the students got the right answer. More frightening is that *almost one out of three students said that the number of buses needed is '31 remainder 12'*. [emphasis added]

---

[1] Supported by the Gatsby Charitable Foundation.

[2] Partially supported by NSF Grant DUE/MDR-9253965

[3] For non-US readers: Children begin kindergarten (grade K) roughly at age 5 and finish the highest grade (12) roughly at age 18.

Mathematics has no meaning for most students; it is a sequence of mysterious steps, which the clever or obedient quickly master to score high on examinations. More disturbing than mindless mathematics are examples showing that students are not bothered by nonsense. An example from Schoenfeld (1991) shows the trouble:

> In his dissertation research, Kurt Reusser …(Reusser 1988)… asked 97 first and second grade students the following question: 'There are 26 sheep and 10 goats on a ship. How old is the captain?' Seventy-six of the 97 students 'solved' the problem, providing a numerical answer by adding 26 and 10.

School aggravates the problem. Into sets of problems worked by school children, Radatz (cited in Schoenfeld (1989)) inserted non-problems such as the following (in its entirety!):

> Mr. Lorenz and 3 colleagues started at Bielefeld at 9 a.m. and drove the 360 km to Frankfurt, with a rest stop of 30 minutes.

The percentage of students who answer such non-problems *increases consistently from kindergarten through 6th grade*. The more time students spend in rote learning, the more brain-dead they become.

The problem is international. One of the authors (SM) gave this problem to a sample of physics majors at the University of Cambridge:

> Two people are on opposite sides of a rotating merry-go-round. One throws a ball to the other. In which frame of reference is the path of the ball straight when viewed from above? Choices: (a) the earth, (b) the merry-go-round, (c) both, or (d) neither.

Only 58% of physics majors answered correctly; of whom only 40% were sure of their answer. The success rate did not increase with more years of studying physics. It seems that even very talented physics students depend on rote learning.[4]

2 Benezet's (1935a, 1935b, 1936) curriculum

Etta Berman, a teacher who worked under Benezet as a K-12 teacher in Manchester, and researched the Benezet method for her master's thesis (Berman 1935), reports an interview in which Benezet commented with characteristic pungency:

> We have been chloroforming children's reasoning powers. We have been drilling them in formulae and tables to the detriment of their reasoning ability. (Berman 1935, p. 45)

Berman summarized Benezet's views as:

> … greater intellectual powers can be secured by warding off material which makes for mental stunting and substituting in its place content in which the children find enjoyment, as well as things common to their understanding, experience, and environment.
>
> … formal arithmetic drilled before the child's reasoning powers are developed is one of the underlying causes for stunted reasoning powers. (Berman 1935, p. 46)

In two sentences Benezet described his method:

> Teachers were told to soft-pedal the mechanical arithmetical drills and to concentrate on reasoning, estimation, and on self-expression. They were asked to give the children a great number of books to read, and to encourage oral English in telling the story of these books. (Berman 1935, p. 46)

Students learnt mathematics *in context*.[5] First-graders meet small numbers:

---

[4] More details of the questions and answers are on the web at ⟨http://www.inference.phy.cam.ac.uk/sanjoy⟩.

[5] A warning to those thinking of trying the method or of criticizing it for avoiding all arithmetic: 'Some teachers, new in the experiment, have steered clear of all arithmetic but Mr. Benezet's idea is really to teach any arithmetic as the need comes up but not on the plane of formal drill.' (Berman 1935, p. 48)

> This instruction is not concentrated into any particular period or time but comes in incidentally in connection with assignments of the reading lesson or with reference to certain pages of the text.

Second graders make friends with larger numbers (their readers are longer):

> If any book used in this grade contains an index, the children are taught what it means and how to find the pages referred to. Children will naturally pick up counting in the course of games which they play.

The principle of learning in context continues through the entire curriculum. A short summary of each year's curriculum is in Table 1; detailed descriptions are in (Benezet 1935b).

Table 1. *Benezet's curriculum.*

Grade	*Mathematics ideas*
1	Numbers < 100; comparison: more, less, higher, lower
2	Telling time (hours and half-hours) page numbers; using an index.
3	Bigger numbers: license plates, house numbers.
4	Inch, foot, yard. Estimating lengths. Square inch, square foot.
5B	Counting by 5's, 10's, 2's, 4's, and 3's (mentally), leading to those multiplication tables. Estimation games; always writing estimate before checking. Fractions by pictures.
5A	Multiplication table.
6	Formal arithmetic, but *estimate first* then check.
7	Lots of mental arithmetic without reference to paper or blackboard.
8B	More mental arithmetic.
8A	Reasons for processes. Explaining how to attack problems.

3 Assessment

Benezet combined qualitative and quantitative assessment, the better to convince people who accept one or other kind of evidence.

As a qualitative assessment, he asked students questions that appear ridiculously easy:

> The distance from Boston to Portland [Maine] by water is 120 miles. Three steamers leave Boston, simultaneously, for Portland. One makes the trip in 10 hours, one in 12, and one in 15. How long will it be before all 3 reach Portland? (Benezet 1936)

In the regularly taught 9th grade, 6 out of the 29 students (!) got it right. In the experimental 2nd grade, all students got it right. Benezet does not say what answer the regularly taught 9th-grade students gave, but the example of sheep and goats suggests that it was probably 37.

Benezet also asked students to explain their thinking:

> I was trying to get the children to tell me, in their own words, that if you have two fractions with the same numerator, the one with the smaller denominator is the larger.

From the regularly taught 8th grade, he got: 'The smaller number in fractions is always the larger', and 'The denominator that is smallest is the largest.'

Etta Berman, in her Masters thesis (1935) on the Benezet experiment, used numerous quantitative assessments:

- verbal: antonyms, synonyms, alphabet, analogies, anagrams

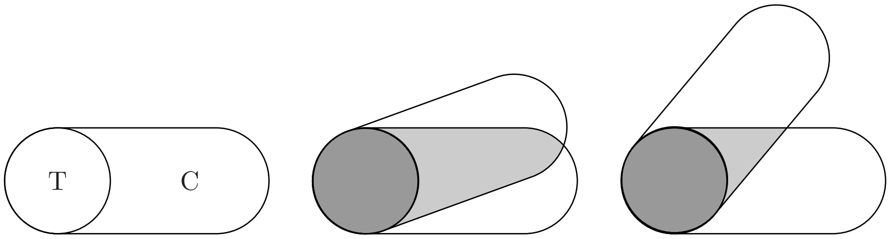
- mathematical: word problems, single- and multidigit addition and multiplication; subtraction, addition, multiplication, and division of fractions; long division
- everyday knowledge: 'common sense'; typical prices (e.g. of gasoline and coal), interest rates, and discounts

In formal arithmetic, the experimental students caught up to the regular ones in only 4 months during the 6th grade. As Berman concluded with academic understatement: 'The results of this study cast doubt upon whether we are justified in devoting five years to the drilling of formal arithmetic' (Berman 1935, p. 40). The experimental students instead got years of extra practice in reading, writing, and thinking:

> In one [traditionally taught] fourth grade I could not find a single child who would admit that he had committed the sin of reading. I did not have a single volunteer, and when I tried to draft them, the children stood up, shook their heads, and sat down again. In the four experimental fourth grades the children fairly fought for a chance to tell me what they had been reading. The hour closed, in each case, with a dozen hands waving in the air and little faces crestfallen, because we had not gotten around to hear what they had to tell. (Benezet 1935a)

4 Teaching for transfer

The examples of the army buses and of the steamers going to Portland show that traditionally taught students cannot use their knowledge except in rote, classroom problems. In traditional mathematics teaching, the applications are similar to one another, so the ideas common to all the applications include much besides the essentials. Thus the student cannot easily abstract the essential, transferable ideas (Figure 1). For an idea to transfer, students must apply it in widely differing contexts. Bransford, Brown, and Cocking (1999, ch. 3) give a valuable discussion of transfer; see especially the references on how 'contrasting cases' enhance transfer (p. 48). By having students read stories, poems, and adventures, by having them read geography and history, and by having them invent their own stories, Benezet introduced students to a vast diversity of mathematical applications. In this rich environment, students learnt mathematical skills useful well beyond the classroom.



(a) (b) (c)

Figure 1. *Why 'knowledge' from traditional mathematics teaching does not transfer. (a) Ideas used in an application, showing contingent, contextual ideas (C) and essential ideas (T), the ones of general use that you would like students to transfer automatically to other contexts. (b) Traditional course with two applications. The contexts are similar, so the intersection of the two applications (shaded area) includes much more than the essentials of the transferable ideas (darker shaded area). (c) Teaching for transfer. Here the contexts are diverse, so the intersection is mostly the essentials of the ideas.*

5 Mathematical proficiency

In a recent National Research Council report, *Adding It Up: Helping Children Learn Mathematics*, Kilpatrick et al. (2001) advise revamping P–8 (ages 3–12) mathematics education so that all students attain 'mathematical proficiency':

- *conceptual understanding:* comprehension of mathematical concepts, operations, and relations
- *procedural fluency:* skill in carrying out procedures flexibly, accurately, efficiently, and appropriately
- *strategic competence:* ability to formulate, represent, and solve mathematical problems
- *adaptive reasoning:* capacity for logical thought, reflection, explanation, and justification
- *productive disposition:* habitual inclination to see mathematics as sensible, useful, and worthwhile, coupled with a belief in diligence and one's own efficacy

According to committee chair Jeremy Kilpatrick (as quoted by Mervis 2001): 'We want to move past the . . . ['Math Wars']. . . debate over skills versus understanding. It's not one or the other. The point is that both are needed, and more, to learn and understand mathematics.'

Berman's (1935) study suggests that Benezet's 8th-grade students possessed far greater mathematical proficiency in the above sense than did regularly taught students. Perhaps the Math Wars can end in a Treaty of Benezet, in the spirit of *Adding It Up*, and acceptable to both sides, e.g., to the 'Mathematically Correct' ⟨http://mathematicallycorrect.com⟩ and the 'Mathematically Sane' ⟨http://mathematicallysane.com⟩.

The requirements for mathematical proficiency given by Kilpatrick et al. (2001) are consistent with Benezet's curriculum (Table 1); they complement the Benezet/Swartz physics topics (Tables 2 and 3); and they mesh with the features of science literacy listed by Arons (1990).

6 Physics

A physics counterpart of the Benezet experiment could include a huge variety of ideas. In Table 2 we sketch a possible curriculum.

Qualitative assessment could include estimation problems:

- How many miles must I run to burn off the calories from a candy bar?
- How high can animals jump as a function of size?
- Why are hummingbirds so tiny?
- Estimate for your country the fractional change in the average miles per gallon (or km/liter) of gasoline used by automobiles if the speed limit is changed from 55 mph (or 88 km/hr) to 75 mph (or 120 km/hr).

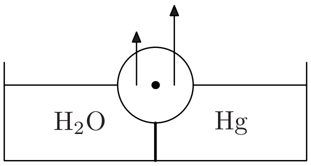
High-school students could try to find flaws in perpetual-motion machines. Here are two such machines:

1. *Bouncing.* A ball bounces elastically off a wall (in one dimension): It strikes and rebounds with velocity V and energy is conserved. In a reference frame that moves with the initial velocity of the ball, the ball before the bounce has velocity 0; and after the bounce, velocity $2V$. In this frame, energy is not conserved. Are you worried?

Table 2. *A possible physics curriculum.*

Grade	*Physics and mathematics ideas*
1–8	Benezet's mathematics program as a basis. Add *physical quantities* to it: angles, volumes, weight (mass), force (estimating only), density as students learn division, energy, power. All quantities are related to everyday experience: density of rocks, volume of houses, power required in climbing stairs or cycling, power in the falling water at Niagara Falls. Proportional reasoning and scaling: 'If you double the side of a cube, what happens to the volume?' Use scaling throughout, starting in grade 4, with the introduction of square measure, and emphasize it especially in grade 8.
9-11	Gravitation, motion of planets by hand simulation to develop a tick-by-tick model of how Newton's second law works. Dimensions, units, dimensional analysis to guess formulae. Springs, waves, sound, music, pressure. Matter is made of atoms. This order would fit with a physics-first curriculum (Livanis 2001) as suggested by Leon Lederman (1999).
12	Begin exact calculations, including conservation laws.

2. *Buoyancy.*



> The figure shows a cross-section of a long trough, showing a cylinder free to rotate about the spindle at its center, but not free to move off axis. The mercury and water are kept from mixing by an impermeable membrane. The upward arrows show the buoyant forces on each half of the cylinder, with the mercury's contribution greater than the water's by a factor of 13 (the density ratio). So the spindle should rotate and, by symmetry, keep rotating. Perpetual motion?

After completing Table 2, we stumbled across an editorial by Cliff Swartz (1993). Swartz suggests topics (Table 3) for K–12 science education that seem compatible with the physics and mathematics ideas of Table 2. His description of how to chose the important topics reminds us of Benezet:

> Here are some samples of my proposed standards for physics topics. . . The theme is that. . . all physics standards K–12 should emphasize the quantitative. . . I mean dealing with the size of things, relating numbers to measurable and measured magnitudes, necessarily therefore paying attention to significant figures and knowing how to do order-of-magnitude, zeroing-in calculations. . . my elementary-school science standards involve only topics and experiences that are literally tangible. The change to abstraction should be proceed only during junior high, in general to be introduced only after concrete examples. . . The National Committee, NSTA, AAAS, Albert Shanker, and everyone else is making lists of standards. Physics teachers should produce their own list before some power from on high congeals a new federal dogma in our name.

What is the relationship of the Benezet/Swartz material in Tables 2 and 3 to the physical-science portion of the National Science Education Standards (National Research Council 1996a) shown in

Table 3. *Possible topics for K–12 suggested by Swartz (1993).*

Grade	*Physics and mathematics topics*
1–6	Use standard measuring tools.
	Students measure their foot lengths, then organize and interpret a class distribution graph.
	Students time their pulses, plot a distribution of class results, and make comparisons with results of before and after physical exercise.
	Select the needed apparatus and make all the measurements, calculations, and graphs to determine who runs faster in their class, tall kids or short kids.
7–9	Use standard measuring tools.
	Use wire, battery, and bulb with the right tools and connectors to make the bulb light.
	With a convex lens as a magnifier, produce both real and virtual images.
	Measure the volume and mass of an object and calculate its density.
	Measure work input and output of a simple machine.
	Use echoes to measure the speed of sound.
10–12	Use standard measuring tools.
	Given the mass of a pollutant in a quantity of water, calculate the degree of pollution in parts per million.
	Organize the history of the universe on a power-of-ten map.
	Characterize the electromagnetic spectrum in terms of wavelengths, frequencies, and photon energies, doing necessary calculations and examples to illustrate each regime.
	Use Archimedes' principle to explain how a boat floats.

Table 4? The Benezetian items in Tables 2 and 3 are concrete examples of general categories in Table 4. In our view, Tables 1 and 2 may give teachers a clearer idea of possible nuts and bolts for a worthwhile K–12 science and mathematics education.

After considering Benezet's articles, the late Arnold Arons (2000) wrote to us:

> I have looked at the Benezet papers, and I find the story congenial. The importance of cultivating the use of English cannot be exaggerated. I have been pointing to this myself since the '50's, and am delighted to find such explicit agreement. I can only point out that my own advocacy has had no more lasting effect than Benezet's. You will find some of my views of this aspect in my 1959 paper . . . (Arons 1959). . . on the Amherst course. . . . *It is worth noting that what Benezet was doing 70 years ago could now be done even more effectively because of the existence of excellent science and social studies curricula. . . (Arons 1993, 1997, 1998). . . that would provide rich opportunity for invoking and applying just the kind of thinking, reasoning, and interpretation that Benezet was advocating and for which he had to invent his own illustrations.* [emphasis added]

Consistent with Arons's emphasis, Appendices I and II provide post-1930's resources and references, respectively, that may assist a Benezetian overhaul of K–12 science education. Many of the listed items are taken from Hake (2000a), which has even more resources and references.

Table 4. *Physical science portion of the National Science Education Standards (National Research Council 1996a, Table 6.2, p. 106).*

Grade	*Physical science standards*
K–4	Properties of objects and materials.
	Position and motion of objects.
	Light, heat, electricity, and magnetism.
5–8	Properties and changes of properties in matter
	Motions and forces
	Transfer of energy
9–12	Structure of atoms
	Structure and properties of matter
	Chemical reactions
	Motions and forces
	Conservation of energy and increase in disorder
	Interactions of energy and matter

Quantitative assessment could include various ‘Classroom Assessment Techniques’ (NISE 2001) and diagnostic tests of conceptual understanding (Hake 2001b, NCSU 2001). Unfortunately, there are, as far as we know, few research-based diagnostic tests for the measurement of science understanding in grades K–10.

7 So what?

Sixty years ago, in a small New England mill town, a creative superintendent made mathematics meaningful for students. Students today still leave traditional mathematics and science classes with almost no conceptual understanding of the subjects and little ability to solve real-world problems. For too long the pioneering experiment of Benezet has been ignored by the education community.

We hope the reader will forgive the length of following quotation, which describes teaching that we all can admire. Berman attended a demonstration lesson in which Benezet taught one of the experimental classrooms:

> . . . the children were on their feet every chance they could possibly get to tell all they knew. They were free to think and, indeed, made the most of every opportunity. One could see mental expansion in actual operation, and also observe satisfactions register, when accredited with right answers or worthwhile opinions[,] for every second brought something to challenge their interests, and which they had to reach high to get. The teachers present saw no parasites but rather children who were taking a delight in independent intelligent thinking. These children were very much alive and their was not a single instance of a child being self-conscious or wishing to be over-looked. These children were free and unhampered by formal procedure and were finding themselves a part of the great world and scheme of things in which their knowledge and opinions mingled with those of older folks. They were transmitting and acquiring knowledge, and by means of directed guessing, when in doubt, were developing judgment. These children of a sixth grade were, indeed, laying the

> foundation for worthwhile thinking and judgment which is so essential to intelligent citizenship. These active and thinking individuals not only transmitted and received knowledge but also lived and felt the things they talked about because they were being brought up on Mr. Benezet's formula for *intellectual curiosity*. [emphasis original] (Berman 1935, p. 50)

So YES! It is time for a science counterpart of the Benezet–Berman math experiment of the 1930's. **Why not give it a try in your classroom?**

8 Acknowledgements

We are indebted to David Brown, Jack Lochhead, and the late Arnold Arons for valuable comments on the work of Benezet.

9 References

Arons, A.B. (1959). Structure, methods, and objectives of the required freshman calculus-physics course at Amherst College. *American Journal of Physics* **27**(9): 658–666.

Arons, A.B. (1990). *A Guide to Introductory Physics Teaching*. Wiley. Reprinted with minor updates as *Teaching Introductory Physics* (Wiley, 1997), which also contains *Homework and Test Questions for Introductory Physics Teaching* (Wiley, 1994) along with a new monograph *Introduction to Classical Conservation Laws*. Both the 1990 and 1997 versions contain 'Achieving wider scientific literacy' (Chapter 12), with Arons's twelve 'marks of sicnetific literacy'. These 12 marks are also online in Hake (2000b), pp. 5–7.

Arons, A.B. (1993). Uses of the past: reflections on United States physics curriculum development, 1955 to 1990. *Interchange* **24**(1&2): 105–128.

Arons, A.B. (1997). Improvement of physics teaching in the heyday of the 1960's. In J. Wilson (ed.), *Conference on the introductory physics course on the occasion of the retirement of Robert Resnick*, Wiley, pp. 13–20.

Arons, A.B. (1998). Research in physics education: The early years. In T.C. Koch and R.G. Fuller, eds., *PERC 1998: Physics Education Research Conference Proceedings 1998*, online at ⟨http://physics.unl.edu/perc98⟩.

Arons, A.B. (2000). Private communication to R.R. Hake (30 June).

Benezet, L.P. (1935a). The Teaching of Arithmetic I: The Story of an Experiment. *Journal of the National Education Association* **24**: 241–244 (November). Reprinted in the *Humanistic Mathematics Newsletter* **6**: 2–14 (May 1991) and on the web at the Benezet Centre ⟨http://www.inference.phy.cam.ac.uk/sanjoy/benezet⟩.

Benezet, L.P. (1935b). The Teaching of Arithmetic II: The Story of an Experiment. *Journal of the National Education Association* **24**: 301–303 (December). Reprinted in the *Humanistic Mathematics Newsletter* **6**: 2–14 (May 1991) and on the web at the Benezet Centre ⟨http://www.inference.phy.cam.ac.uk/sanjoy/benezet⟩.

Benezet, L.P. (1936). The Teaching of Arithmetic III: The Story of an Experiment. *Journal of the National Education Association* **25**: 7–8 (January). Reprinted in the *Humanistic Mathematics Newsletter* **6**: 2–14 (May 1991) and on the web at the Benezet Centre ⟨http://www.inference.phy.cam.ac.uk/sanjoy/benezet⟩.

Berman, Etta (1935). *The Result of Deferring Systematic Teaching of Arithmetic to Grade Six as Disclosed by the Deferred Formal Arithmetic Plan at Manchester, New Hampshire*. Masters Thesis, Boston University, USA.

Bransford, J.D., A.L. Brown, and R.R. Cocking (eds.) (1999). *How People Learn: Brain, Mind, Experience, and School*. National Academy Press. Online at ⟨http://www.nap.edu/catalog/6160.html⟩.

Hake, R.R. (2000a). Is it finally time to implement curriculum S? *AAPT Announcer* **30**(4): 103. Online at ⟨http://www.physics.indiana.edu/~hake⟩.

Hake, R.R. (2000b). The general population's ignorancce of science-related societal issues: A challenge for the university. *AAPT Announcer* **30**(2): 105. Online at ⟨http://physics.indiana.edu/~hake⟩.

Hake, R.R. (2001b). Suggestions for administering and reporting pre/post diagnostic tests. Unpublished. Online at ⟨http://physics.indiana.edu/~hake⟩.

Kilpatrick, J., J. Swafford, and B. Findell, eds. 2001. *Adding It Up: Helping Children Learn Mathematics*. National Academy Press. Prepublication copy online at ⟨http://www.nap.edu/catalog/9822.html⟩.

Lederman, L.M. (1999). A science way of thinking. *Education Week* 16 June, ⟨http://www.edweek.org/ew/1999/40leder.h18⟩.

Livanis, O. (2000). Physics First Home Page; ⟨http://members.aol.com/physicsfirst/⟩

Mervis, J. (2001). Math education: Academy report aims to quiet debate. *Science* **291**: 808 (2 February). Reports on the National Research Council report of Kilpatrick et al. (2001).

National Research Council (1996a). *National Science Education Standards*. National Academy Press. ⟨http://books.nap.edu/catalog/4962.html⟩.

NISE [National Institute for Science Education] (2001). ⟨http://www.wcer.wisc.edu/NISE⟩: Field-tested Learning Assessment Guide (FLAG): For Science, Math, and Engineering Instructors. ⟨http://www.wcer.wisc.edu/nise/cl1/flag/flaghome.asp⟩, especially Introduction to CAT's [Classroom Assessment Techniques] at ⟨http://www.wcer.wisc.edu/nise/cl1/flag/cat/catframe.asp⟩.

NCSU [North Carolina State University] (2001). Physics Education R & D Group, Assessment Instrument Information Page, online at ⟨http://www.ncsu.edu/per/TestInfo.html⟩.

Radatz, H. (1983). Untersuchungen zum Lösen eingekleideter Aufgaben. [Studies of solving mathematical tasks] *Journal für Mathematikdidaktik* **3**: 205–217.

Reusser, Kurt (1988). Problem Solving beyond the Logic of Things: Contextual Effects on Understanding and Solving Word Problems. *Instructional Science* **17**: 309–38.

Schoenfeld, Alan (1987). What's all the fuss about metacognition? In *Cognitive Science and Mathematics Education*, Alan Schoenfeld, ed. (Hillsdale, NJ: Lawrence Erlbaum).

Schoenfeld, Alan H. (1989). Teaching mathematical thinking and problem solving. In Lauren B. Resnick and Leonard B. Klopfer, eds., *Toward the Thinking Curriculum: Current Cognitive Research*, Association for Supervision and Curriculum Development [ASCD], Alexandria, VA.

Schoenfeld, Alan H. (1991). On Mathematics as sense-making: An informal attack on the unfortunate divorce of formal and informal mathematics. In J.F. Voss, D.N. Perkins, and J.W. Segal, eds., *Informal Reasoning and Education*, Erlbaum, Hillsdale, NJ, pp. 311–344.

Swartz, C.E. (1993). Editorial: Standard reaction. *Physics Teacher* **31**: 334–335.

10 Appendix I

Resources for a Benezetian overhaul of K–12 science education.

(A slash '/' occurring outside a URL ⟨...⟩ means 'click on the following text'.)

AAHE's CASTL (2001). Carnegie Academy for the Scholarship of Teaching and Learning, Programs for K–12; online at ⟨http://www.carnegiefoundation.org/CASTL/k-12/index.htm⟩.

AAPT's Physical Science Resource Center ⟨http://www.psrc-online.org/⟩.

Active Learning Problem Sets (ALPS) ⟨http://www.physics.ohio-state.edu/~physedu/people/vanheu/index.html⟩.

Active Physics ⟨http://www.psrc-online.org/⟩ /Curriculum/High School/Comprehensive Curricula/; also ⟨http://www.its-about-time.com/htmls/index3.html⟩.

ActivPhysics ⟨http://www.physics.ohio-state.edu/~physedu/people/vanheu/index.html⟩.

Alive Education.net ⟨http://www.alincom.com/educ/sci.htm⟩ 'Excellence in Internet Education'.

The Coalition for Education in the Life Sciences [CELS], a 'national coalition of professional societies in the biological sciences that have joined together in an effort to improve undergraduate education in the life sciences' at ⟨http://www.wisc.edu/cels/⟩.

Comprehensive Conceptual Curriculum for Physics (C3P) ⟨http://www.udallas.edu/physics/⟩.

Constructing Ideas in Physical Science ⟨http://cipsproject.sdsu.edu/⟩.

Constructing Physics Understanding (CPU) ⟨http://cpuproject.sdsu.edu/CPU⟩. See also ⟨http://learningteam.org/⟩ /CPU.

Cooperative Group Problem Solving ⟨http://www.physics.umn.edu/groups/physed/⟩.

Dewey web sites: (a) by Craig Cunningham ⟨http://cuip.uchicago.edu/~cac/dewey.html⟩. (b) Center for Dewey Studies ⟨http://www.siu.edu/~deweyctr/⟩ (c) Hoover's Teacher Ed Pages – Links to the World of John Dewey ⟨http://www.cisnet.com/teacher-ed/dewey.html⟩

Educational Development Center ⟨http://www.edc.org/⟩. 'Founded in 1958 when a group of scientists at the Massachusetts Institute of Technology joined forces with teachers and technical specialists to develop a new high school physics curriculum, PSSC Physics.'

Eison, J.A. et al. Bibliography of Active Learning in Science. At ⟨http://www.cte.usf.edu/resources/res_def.html⟩.

Event-Based Science: 'A new way to teach science at the middle school level'. ⟨http://www.mcps.k12.md.us/departments/eventscience/⟩.

Exemplary & Promising Science Programs. US Deptartment of Education. ⟨http://www.ed.gov/offices/OERI/ORAD/KAD/expert_panel/newscience_progs.html⟩.

Experiment Problems ⟨http://www.physics.ohio-state.edu/~physedu/people/vanheu/index.html⟩.

The Exploritorium Institute for Inquiry ⟨http://www.exploratorium.edu/IFI/index.html⟩.

Exploritorium Inquiry Bibliography: Professional Development Design Seminar Guide to Articles and Readings ⟨http://www.exploratorium.edu/IFI/resources/biblio.html⟩.

Harvard-Smithsonian Center for Astrophysics – Science Education Department ⟨http://cfa-www.harvard.edu/cfa/sed/projects.html⟩.

Hands On Physics ⟨http://hop.concord.org/⟩.

Insights, Center for Science Education ⟨http://www.edc.org/CSE/⟩, developers of *Insights: An Inquiry-Based Elementary School Science Curriculum* (K–6) ⟨http://www.edc.org/CSE/imd/insights3.html⟩ and *Insights: An Inquiry-Based, Middle School Science Curriculum* ⟨http://www.edc.org/CSE/imd/insights2.html⟩.

Lederman Science Center at Fermilab ⟨http://www-ed.fnal.gov/ed_lsc.html⟩.

Logo Foundation ⟨http://lcs.www.media.mit.edu/groups/logo-foundation/index.html⟩. According to Harold Abelson, 'Logo is the name for a philosophy of education and a continually evolving family of programming languages that aid in its realization.'

Mechanical Universe ⟨http://www.projmath.caltech.edu/mu.htm⟩.

Minds On Physics ⟨http://umperg.physics.umass.edu/projects/MindsOnPhysics/default⟩.

Modeling Instruction Program ⟨http://modeling.la.asu.edu/modeling.html⟩.

NSF Review of Instructional Materials for Middle School Science ⟨http://www.nsf.gov/pubs/1997/nsf9754/nsf9754.htm⟩.

Paideia Program ⟨http://www.paideia.org/⟩.

Peer Instruction and Concept Tests ⟨http://galileo.harvard.edu/⟩.

Physics InfoMall ⟨http://learningteam.org/⟩.

Physics by Inquiry ⟨http://www.phys.washington.edu/groups/peg/pbi.html⟩

Physics Instructional Resource Center ⟨http://pira.nu/⟩.

Physics Resources and Instructional Strategies for Motivating Students (PRISMS) ⟨http://www.prisms.uni.edu/⟩.

Physics Teachers Resource Agents (PTRA) ⟨http://www.aapt.org/programs/ptra/ptra.html⟩.

Powerful Ideas in Physical Science ⟨http://www.psrc-online.org/⟩ /Curriculum/College–University /Pre-service Teacher Education.

SEPUP Modular Materials ⟨http://www.lhs.berkeley.edu/SEPUP/general.html⟩. For a discussion see Wilson & Davis (1994), pp. 205–210.

Science Activities Manual: K–8 ⟨http://www.utm.edu/departments/ed/cece/SAMK8.shtml⟩.

Science Helper K–8 ⟨http://learningteam.org/⟩:

> Funded by the Carnegie Corporation of New York, and created by a team of leading teachers, specialists, and administrators, Science Helper K–8 CD-ROM offers 919 lesson plans which are the culmination of 15 years of development, field-testing and refinement. The lesson plans represent seven of the most effective and influential science curricula ever written – COPES, ESS, ESSP, MINNEMAST, SAPA, SCIS, and USMES. You can easily locate the lesson you're looking for by grade level, subject, process skill, keyword or content... then print it out. All in all, Science Helper is the single most effective, most comprehensive way to expand your K–8 science program immediately.

Socratic Dialogue Inducing (SDI) Labs ⟨http://www.physics.indiana.edu/~sdi⟩.

Tools for Scientific Thinking ⟨http://www.vernier.com/cmat/tst.html⟩.

Tutorials in Physics ⟨http://www.phys.washington.edu/groups/peg/tut.html⟩.

Workshop Physics ⟨http://physics.dickinson.edu/⟩ /Workshop Physics.

Workshop Science ⟨http://physics.dickinson.edu/⟩ /Workshop Science Project.

11 Appendix II

References for a Benezetian overhaul of K–12 science education[6]

AAAS (1989) [American Academy of Arts and Sciences]. *Science for All Americans: A Project 2061 Report on the Literacy Goals in Science, Mathematics, and Technology*. American Association for the Advancement of Science.

AAAS (1993). *Benchmarks for Science Literacy: Project 2061*. American Association for the Advancement of Science.

AAAS (1998). *Daedalus* **127**(4). For a description see ⟨http://daedalus.amacad.org/inprint.html⟩. Contains essays by researchers in education and by historians of more rapidly developing institutions such as power systems, communications, health care, and agriculture. Sets out to answer a challenge posed by Kenneth Wilson:

> If other major American 'systems' have so effectively demonstrated the ability to change, why has the educational 'system' been so singularly resistant to change? What might the

---

[6] A * preceding a reference indicates that the reference is also given in Section 9.

> lessons learned from other systems' efforts to adapt and evolve, have to teach us about bringing about change – successful change – in America's schools?

See also ⟨http://www.physics.ohio-state.edu/~redesign/⟩.

Adey, P.S. (1999). The Science of Thinking and Science for Thinking: A Description of Cognitive Acceleration through Science Education (CASE). UNESCO, International Bureau of Education, Switzerland. Online at ⟨http://www.ibe.unesco.org/International/Databanks/Innodata/inograph.htm⟩.

Adler, M.J. (1977). *Reforming Education: The Opening of the American Mind*. Macmillan.

Allen, D.E. (1997). Bringing Problem-Based Learning to the Introductory Biology Classroom. In A.P. McNeal and C. D'Avanzo, eds., *Student-Active Science: Models of Innovation in College Science Teaching*, Saunders. Online at ⟨http://www.saunderscollege.com/lifesci/studact/chapters/ch15.html⟩.

Allen, D.E. and B. Duch (1998). *Thinking Towards Solutions: Problem-Based Learning Activities for General Biology*. Saunders.

Allen, D.E., B.J. Duch, and S. E. Groh (1996). The power of problem-based learning in teaching introductory science courses. *New Directions for Teaching and Learning* **68**: 43–52.

American Mathematical Society Staff, American Institute of Physics Staff, American Chemical Society (2001). *The Best of Wonder Science: Elementary Science Activities*, Volume 2. Wadsworth Publishing. Recommended by Hubisz et al. (2001).

Anderson, L.W. and D.R. Krathwohl (2000). *Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*. Longman.

Anderson, J.R. (1999). *Cognitive Psychology and Its Implications*. 5th ed. Especially the chapter on 'Cognitive Development'. W.H. Freeman.

Ansbacher, T. (2000). An interview with John Dewey on science education. *Physics Teacher* **38**(4): 224–227. A thoughtful and well-researched treatment showing the consonance of Dewey's educational ideas – as quoted straight from Dewey's own writings, not from the views of sometimes confused Dewey interpreters – with the thinking of most current science-education researchers, including your friendly authors.

Apelman, M. (1993). Co-creating primary curriculum: Boulder Valley schools. In E. Jones, ed., *Growing Teachers: Partnerships in Staff Development* (National Association for the Education of Young Children). Online at ⟨http://www.clas.uiuc.edu/fulltext/cl01141/ch6.html⟩.

Apelman, M., D. Hawkins, and P. Morrison (1985). *Critical Barriers Phenomenon in Elementary Science*. University of North Dakota, Center for Teaching and Learning. See also Hawkins (1974c).

*Arons, A.B. (1959). Structure, methods, and objectives of the required freshman calculus-physics course at Amherst College. *American Journal of Physics* **27**(9): 658–666.

Arons, A.B. (1960). The New high school physics course: A report on PSSC. *Physics Today*, June, pp. 20–25.

Arons, A.B. (1977). *The Various Language: An Inquiry Approach to the Physical Sciences*. Oxford. With teachers' guide.

Arons, A.B. (1990). *A Guide To Introductory Physics Teaching*, Wiley. Reprinted with minor updates in *Teaching Introductory Physics* (Wiley, 1997), which also contains *Homework and Test Questions for Introductory Physics Teaching* (Wiley, 1994) along with a new monograph *Introduction to Classical Conservation Laws*.

Arons, A.B. (1991). Guiding insight and inquiry in the introductory physics lab. *Physics Teacher* **31**: 278–282 (May).

*Arons, A.B. (1993). Uses of the past: reflections on United States physics curriculum development, 1955 to 1990. *Interchange* **24**(1&2): 105–128.

*Arons, A.B. (1997). Improvement of physics teaching in the heyday of the 1960's. In J. Wilson (ed.), *Conference on the Introductory Physics Course on the Occasion of the Retirement of Robert Resnick*, Wiley, pp. 13–20.

*Arons, A.B. (1998). Research in physics education: The early years. In T.C. Koch and R.G. Fuller, eds., *PERC 1998: Physics Education Research Conference Proceedings 1998*, online at ⟨http://physics.unl.edu/perc98⟩.

Arons, A.B. (1999). Development of energy concepts in introductory physics courses. *American Journal of Physics* **67**(12): 1063.

Arons, A.B. (1999). Closet foot-pounders? *American Journal of Physics* **67**(6): 468.

Arons, A.B. and R. Karplus (1976). Implications of accumulating data on levels of intellectual development. *American Journal of Physics* **44**(4): 396.

Asimov, I. and R.A. Galant (1973). *Ginn Science Program*. Ginn & Company. For elementary schools – many volumes, out of print. Recommended by Hubisz et al. (2001): 'Has what is missing from most of the books in this report.'

Aubrecht, G.J. (1991). Is there a connection between testing and teaching? *Journal of College Science Teaching* **20**: 152–157.

Ausubel, D.P. (2000). *The Acquisition and Retention of Knowledge*. Kluwer.

Ball, D.L. and H. Bass (2000). Interweaving content and pedagogy in teaching and learning to teach: Knowing and using mathematics. In J. Boaler, ed., *Multiple Perspectives on Mathematics Teaching and Learning* (Ablex), pp. 83–104.

*Benezet, L.P. (1935, 1936). The Teaching of Arithmetic I, II, III: The Story of an Experiment. *Journal of the National Education Association* **24**(8): 241–244 (1935); **24**(9): 301–303 (1935); **25**(1): 7–8 (1936). The articles (a) were reprinted in the *Humanistic Mathematics Newsletter* **6**: 2–14 (May 1991); (b) are on the web along with other Benezetia at the Benezet Centre ⟨http://www.inference.phy.cam.ac.uk/sanjoy/benezet/⟩.

*Berman, Etta (1935). *The Result of Deferring Systematic Teaching of Arithmetic to Grade Six as Disclosed by the Deferred Formal Arithmetic Plan at Manchester, New Hampshire*. Masters Thesis, Boston University, USA.

Black, P. and D. Wiliam (1998). The black box: Raising standards through classroom assessment. *Phi Delta Kappan*, October, online at ⟨http://www.pdkintl.org/kappan/kbla9810.htm⟩:

> Firm evidence shows that formative assessment is an essential component of classroom work and that its development can raise standards of achievement, Mr. Black and Mr. Wiliam point out. Indeed, they know of no other way of raising standards for which such a strong *prima facie* case can be made.

Bloom, B.S. (1984). The 2-sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. *Educational Researcher* **13**(6): 4–16.

Bohren, C.F. (1991). *What Light Through Yonder Window Breaks?: More Experiments in Atmospheric Physics*. John Wiley.

Bohren, C.F. (2001). *Clouds in a Glass of Beer: Simple Experiments in Atmospheric Physics*. Dover.

*Bransford, J.D., A.L. Brown, and R.R. Cocking (eds.) (1999). *How People Learn: Brain, Mind, Experience, and School*. National Academy Press. Online at ⟨http://www.nap.edu/catalog/6160.html⟩.

Brown, D. E. (1993). Refocusing core intuitions: A concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching* **30**(10): 1273–1290.

Brown, D.E. (2000). Merging dynamics: An integrating perspective on learning, conceptual change, and teaching, and its implications for educational research. Paper presented at AERA 2000, New Orleans. Online at ⟨http://faculty.ed.uiuc.edu/debrown/merge/⟩.

Brown, J.S., A. Collins, and P. Duguid (1989). Situated cognition and the culture of learning. *Educational Researcher* **18**(1): 34–41. Online at ⟨http://www.ilt.columbia.edu/ilt/papers/JohnBrown.html⟩.

Bruer, J.T. (1994). *Schools for Thought: A Science of Learning in the Classroom*. MIT Press.

Bruer, J.T. (1997). Education and the brain: A bridge too far. *Educational Researcher* **26**(8): 4–16.

Bruer, J.T. (1999). In search of... brain-based education. *Phi Delta Kappan*, May, p. 648. Online at ⟨http://www.pdkintl.org/kappan/kbru9905.htm⟩.

Bruer, J.T. (1999). *The Myth of the First Three Years*. Free Press. See also ⟨http://www.jsmf.org/zarticles&pap/John/myth_of_the_first_three_years.htm⟩

Bunge, M. (1998). *Philosophy of Science: From Explanation to Justification*. Science & Technology Series, Transaction Pub.

Bunge, M. and N. Mahner, ed. (2001). *Scientific Realism: Selected Essays of Mario Bunge*. Prometheus Books.

Butterworth, B. (1999). *What Counts: How Every Brain Is Hardwired for Math*. Free Press, New York. Published in England as *The Mathematical Brain*, Macmillan, London, 1999.

Bybee, R.W. (1991). Planet Earth in Crisis: How Should Science Educators Respond? *American Biology Teacher* **53**(3): 146–153.

Bybee, R.W. (1993). *Reforming Science Education: Social Perspectives & Personal Reflections*. Teachers College Press.

Chabay, R.W. and B.A. Sherwood (1999). Bringing atoms into first-year physics. *American Journal of Physics* **67**(12): 1045.

Chin, C. and D.E. Brown (2000). Learning in science: A comparison of deep and surface approaches. *Journal of Research in Science Teaching* **37**: 109–138.

Clement, J.M. (2000). Using physics to raise thinking skills. *AAPT Announcer* **30**(4): 81.

Collins, A. J.S. Brown, and S. Newman (1989). Cognitive apprenticeship: Teaching students the craft of reading, writing, and mathematics. In L.B. Resnick, ed., *Knowing, Learning, and Instruction: Essays in Honor of Robert Glaser*, Erlbaum, pp. 453–494.

Cooper, J., and P. Robinson (1998). Small group instruction in science, mathematics, engineering, and technology: A discipline status report and teaching agenda for the future. *Journal of College Science Teaching*, May, pp. 383–388.

Csikszentmihalyi, M. (1990). Literacy and intrinsic motivation. *Daedalus* **119**(2): 115–140.

> The chief impediments to learning are not cognitive. It is not that students cannot learn; it is that they do not wish to. If educators invested a fraction of the energy they now spend trying to transmit information in trying to stimulate the students enjoyment of learning, we could achieve much better results.

D'Avanzo, C. and A.P. McNeal, eds. (1997). *Student-Active Science: Models of Innovation in College Science Teaching*. Saunders. Saunders is advancing education reform: (a) 'professionals' may order a free copy by calling +1 800.782.4479; (b) the entire book will soon be available electronically as an Adobe Acrobat portable document file! ⟨http://www.saunderscollege.com/lifesci/studact/⟩.

Dewey, J. (1996). *Collected Works of John Dewey, 1882–1953*. Southern Illinois University Press. On CDROM; for information see ⟨http://www.siu.edu/~deweyctr/index.html⟩.

Dewey, J. (1997). *Democracy and Education: An Introduction to the Philosophy of Education*. Simon & Schuster.

Dewey, J. (1997). *Experience and Education*. Macmillan.

Dewey, J. and R.D. Archambault (ed.) (1983). *John Dewey on Education*. University of Chicago Press.

Dewey, J. and Jo Ann Boydston (contributor) (1980). *The School and Society*. Southern Illinois University Press.

Dewey, J., L. Hickman, T.M. Alexander (eds.) (1998). *The Essential Dewey: Pragmatism, Education, Democracy*. Indiana University Press.

Dewey, J. and P.W. Jackson (illustrator) (1991). *The School and Society and the Child and the Curriculum*. A Centennial Publication; University of Chicago Press.

diSessa, A.A. (1987). The third revolution in computers and education. *Journal of Research in Science Teaching* **24**: 343–367.

diSessa, A.A. (2000). *Changing Minds: Computers, Learning, and Literacy*. MIT Press.

Dobey, D.C., R.J. Beichner, and S.L. Raimondi (1998). *Essentials of elementary science*. Allyn & Bacon. Recommended by Hubisz et al. (2001).

Druckman, D. and R.A. Bjork, eds. (1994). *Learning, Remembering, and Believing: Enhancing Human Performance*. National Academy Press. See especially the Epilogue, 'Institutional Impediments to Effective Training'.

Duckworth, E., J. Easley, D. Hawkins, and A. Henriques, eds. (1990). *Science Education: A Minds-on Approach for the Elementary Years*. Erlbaum.

Duckworth, E. (1996). *The Having of Wonderful Ideas and Other Essays on Teaching and Learning*. Teachers' College Press.

Elby, A. (1999). Another reason that physics students learn by rote. *Physics Education Research* supplement 1 to the *American Journal of Physics* **67**(7): S52–S57.

Elmore, D.A. , S.E. Olsen, and P.M. Smith (1998). *Reinventing Schools: The Technology is Now*. National Academy Press. Available only on the web at ⟨http://www.nap.edu/readingroom/books/techgap/pdf.html⟩.

Epstein, J. (1997/8). Cognitive development in an integrated mathematics and science program. *Journal of College Science Teaching*, December 1997 and January 1998, pp. 194–201.

Ericsson, K.A., R.T. Krampe, and C. Tesch-Romer (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review* **100**(3): 363–406.

Ericsson, K.A. and N. Charness (1994). Expert performance, its structure and acquisition. *American Psychologist* **49**: 725–747.

Ericsson, K.A. and J. Smith, eds. (1991). *Toward a General Theory of Expertise: Prospects and Limits*. Cambridge University Press.

Ericsson, K.A, ed. (1996). *The Road to Excellence: The Acquisition of Expert Performance in the Arts and Sciences, Sports, and Games*. Erlbaum.

Fawcett, H.P. (1938). *The Nature of Proof: A Description and Evaluation of Certain Procedures Used in a Senior High School to Develop an Understanding of the Nature of Proof*. Teachers' College Press. It was the 1938 *Yearbook* of the National Council of Teachers of Mathematics and is now available from them as H.P. Fawcett, *The Thirteenth Yearbook: The Nature of Proof*, 1995. For a discussion of Fawcett's brilliant work see Schoenfeld (1991).

Fisher, K.M., J.H. Wandersee, and D. Moody (2000). *Mapping Biology Knowledge*. Kluwer.

Fiske, E.B. (1992). *Smart Schools, Smart Kids*. Touchstone.

Flener, F. (2001). A geometry course that changed their lives: the guinea pigs after 60 years. Talk presented on the work of Fawcett (1938) at the National Council of Teachers of Mathematics on 6 April 2001, Orlando, Florida. Online at ⟨http://groups.yahoo.com/group/math-learn/files/NatureOfProof.txt⟩. Unfortunately, one must either be a subscriber to math-learn ⟨http://groups.yahoo.com/group/math-learn⟩ or else sign in as a subscriber to access the talk.

Ford, K.W. (1989). Guest Comment: Is physics difficult? *American Journal of Physics* **57**(10): 871–872. For quotes from this insightful piece regarding physics in the early grades see Hake (2000):

> Physics is difficult in the same way that all serious intellectual effort is difficult. Solid understanding of English literature, or economics, or history, or music, or biology or physics does not come without hard work. But we typically act on the assumption (and argue to our principals and deans) that ours is a discipline that only a few are capable of comprehending. The priesthood syndrome that flows from this assumption is, regrettably, seductive…If physics is not more difficult than other disciplines, why does everyone think that it is? To answer indirectly, let me turn again to English. Six-year-olds write English and (to pick a skilled physicist writer) Jeremy Bernstein writes English. What separates them? A long, gradual incline of increased ability, understanding, and practice. Some few people, illiterates, do not start up the hill. Most people climb some distance. A few climb as far as Bernstein. *For physics, on the other hand, we have fashioned a cliff. There is no gradual ramp, only a near-vertical ascent to its high plateau.* When the cliff is encountered for the first time by 16- or 17-year olds, it is small wonder that only a few have courage (and the skill) to climb it. *There is no good reason for this difference of intellectual topography. First-graders could be taught some physics…* (Hammer 1999)…, *second-graders a little more, and third-graders still more.* Then for the eleventh- or twelfth-grader, a physics course would be a manageable step upward. Some might choose to take it, some not, but few would be barred by lack of 'talent' or 'background'. [Our italics.]

Forman, G. and P.B. Pufall, eds. (1988). *Constructivism in the Computer Age*. Erlbaum.

French, A.P. (1997). The Nature of Physics. In Tiberghien, A., E.L. Jossem, and J. Barojas, eds., *Connecting Research in Physics Education with Teacher Education*, International Commission on Physics Education. Online at ⟨http://www.physics.ohio-state.edu/~jossem/ICPE/B1.html⟩.

Fullan, M.G. (1991). *The New Meaning of Educational Change*. Teachers' College Press.

Fuller, R.G. , R. Karplus, and A.E. Lawson (1977). Can physics develop reasoning? *Physics Today*, February, pp. 23–28.

Fuller, R.G. (1982). Solving physics problems – how do we do it? *Physics Today*, September, pp. 43–47.

Fuller, R.G. (1993). Millikan lecture 1992; Hypermedia and the knowing of physics: Standing upon the shoulders of giants. *American Journal of Physics* **61**(4): 300–304.

Karplus, R. (2001). *A Love of Discovery: Science Education and the Second Career of Robert Karplus*, R.G. Fuller, ed., to be published.

Gardner, H. (1985). *The Mind's New Science: A History of the Cognitive Revolution*. Basic Books. See especially 'Jean Piaget's Developmental Concerns', pp. 116–118.

Gardner, H. (1985). *Frames of Mind: The Theory of Multiple Intelligences*. Basic Books.

Gardner, H. (1991). *The Unschooled Mind: How Children Think & How Schools Should Teach*. Basic Books. Especially Chapter 2, 'Conceptualizing the Development of Mind'.

Gardner, H. (1999). *The Disciplined Mind: What All Students Should Understand*. Simon & Schuster.

Gardner, H. (2000). *Intelligence Reframed: Multiple Intelligences for the 21st Century*. Basic Books.

D. Gentner and A.L. Stevens, eds. (1983). *Mental Models*. Erlbaum.

Goldberg, F. and S. Bendall (1995). Making the invisible visible: A teaching/learning environment that builds on a new view of the physics learner. *American Journal of Physics* **63**: 978–991.

Goodland, J.I. (1990). *Teachers for Our Nation's Schools*. Jossey–Bass.

Goodland, J.I. (1994). *Educational Renewal: Better Teachers, Better Schools*. Jossey-Bass.

Goodstein, D. (2000). The Coming Revolution in Physics Education. *APS News*, June. Online at ⟨http://www.aps.org/apsnews/0600/060017.html⟩.

Haber-Schaim, U., J.H. Dodge, R. Gardner, E.A. Shore (1991). *PSSC Physics*. Kendall/Hunt. See Arons (1960) and Swartz (1999) for reviews.

Haber-Schaim, U., R. Cutting, H.G. Kirksey, H. Pratt (1999). *Introductory Physical Science*. 7th ed. Science Curriculum Inc. ⟨http://www.sci-ips.com/⟩. See Raloff (2001) for a review; also mentioned but not reviewed by Hubisz et al. (2001).

Hake, R.R. (1987). Promoting student crossover to the Newtonian world. *American Journal of Physics* **55**(10): 878–884.

Hake, R.R.. (1992). Socratic pedagogy in the introductory physics lab. *Physics Teacher* **30**: 546–552. Version updated 27 April 1998, online at ⟨http://physics.indiana.edu/˜sdi/⟩.

Hake, R.R. (1998a). Interactive-engagement vs traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics* **66**: 64–74. Online at ⟨http://www.physics.indiana.edu/˜sdi/⟩.

Hake, R.R. (1998b). Interactive-engagement methods in introductory mechanics courses. Online at ⟨http://www.physics.indiana.edu/˜sdi/⟩ and submitted on 19 June 1998 to the *Physics Education Research Supplement to AJP (PERS)*. See especially footnotes #39 on the Socratic method, #57 on classroom communication systems, and #66 on sources of conceptual questions and problems.

Hake, R.R. (1999). *REsearch, Development, and Change in Undergraduate Biology Education: A Web Guide for Non-Biologists (REDCUBE)*. Online at ⟨http://www.physics.indiana.edu/˜redcube⟩.

*Hake, R.R. (2000a). Is it finally time to implement curriculum S? *AAPT Announcer* **30**(4): 103. Online at ⟨http://www.physics.indiana.edu/˜hake⟩.

*Hake, R.R. (2000b). The general population's ignorancce of science-related societal issues: A challenge for the university. *AAPT Announcer* **30**(2): 105. Online at ⟨http://physics.indiana.edu/˜hake⟩.

Hake, R.R. (2001a). Lessons from the physics education reform effort. Accepted for publication in *Conservation Ecology*. Online at ⟨http://www.physics.indiana.edu/˜hake⟩.

*Hake, R.R. (2001b). Suggestions for administering and reporting pre/post diagnostic tests. Unpublished. Online at ⟨http://physics.indiana.edu/˜hake/⟩.

Hammer, D. (1995). Epistemological considerations in teaching introductory physics. *Science Education* **79**: 393–413.

Hammer, D. (1997). Discovery learning and discovery teaching. *Cognition and Instruc.* **15**(4): 485–529. Abstract Online at ⟨http://www.physics.umd.edu/perg/cpt.html⟩.

Hammer, D. (1999). Physics for first-graders? *Science Education* **83**(6): 797–799. Online at ⟨http://www.physics.umd.edu/perg/cpt.html⟩.

Hammer, D. (2000). Student resources for learning introductory physics. *Physics Education Research*, supplement 1 to the *American Journal of Physics* **68**(7): S52–S59.

Hammer, D. (2001). Teacher inquiry. To appear in J. Minstrell and E. van Zee, eds., *Teaching and Learning in an Inquiry-Based Science Classrooom*. (Also to appear in the Paper Series of the Center for the Development of Teaching at EDC, in Newton, MA.) Pre-publication draft online at ⟨http://www.physics.umd.edu/perg/cpt.html⟩.

J. Handlesman, B. Houser, and H. Kriegel (1997). *Biology Brought to Life: A guide to teaching students to think like scientists*. Times Mirror Higher Education Group.

Hargan, J.D.D. and M.S. Rivkin (1999). *Science Experiences in the Early Childhood Years: An Integrated Approach*. Prentice–Hall. Recommended by Hubisz et al. (2001).

Harte, J. (1988). *Consider a Spherical Cow: A Course in Environmental Problem Solving*. University Science Books.

Hawkins, D. (1974a). On Living in Trees. In *The Informed Vision: Essays on Learning and Human Nature* (Agathon Press).

Hawkins, D. (1974b). Messing about in science. In *The Informed Vision: Essays on Learning and Human Nature* (Agathon Press).

Hawkins, D. (1974c). Critical barriers to science learning. Online at ⟨http://www.exploratorium.edu/IFI/resources/museumeducation/criticalbarriers.html⟩.

Hawkins, D. (2001). *The Roots of Literacy.* University of Colorado Press.

Hazen R.M. and J. Trefil (1991). *Science Matters: Achieving Scientific Literacy.* Doubleday.

Heibert, J., T.P. Carpenter, and E. Fennema (1997). *Making Sense: Teaching and Learning Mathematics With Understanding.* Heinemann.

Heller, K.J. (1999). Introductory physics reform in the traditional format: an intellectual framework. *APS Forum on Education Newsletter*, Summer. Online at ⟨http://webs.csu.edu/~bisb2/FEdnl/heller.htm⟩.

Heller, K.J. (2001). The time has come to make teaching a real profession. *APS Forum on Education Newsletter*, Spring. Online at ⟨http://www.aps.org/units/fed/index.html⟩. Suggests raising K–12 teacher's average salary so as to equal mechanical engineer's average salary, with a Fermi-problem estimated cost of about 450 billion over 10 years. A similar proposal and cost estimate was made by Langenberg (2000).

Herron J. D. and S.C. Nurrenbern (1999). Chemical education research: Improving chemistry learning. *Journal of Chemical Education* **76**(10): 1353–1361.

Hestenes, D. (1992). Modeling games in the Newtonian world. *American Journal of Physics* **60**(8): 732–748.

Hillocks, G. (1999). *Ways of Thinking, Ways of Teaching.* Teachers' College Press.

Hobson, A. (2000/2001). Teaching relevant science for scientific literacy. *Journal of College Science Teaching*, December 2000/January 2001.

Hobson, A. (1999). *Physics: Concepts and Connections.* Prentice–Hall.

Holton, G. (1998/99). The New Imperative for Science Literacy. *Journal of College Science Teaching*, Dec. 1998/January 1999, 181–185.

Holton, G. and S.G. Brush. (2001). *Physics, the Human Adventure: From Copernicus to Einstein and Beyond.* Rutgers University Press.

Hubisz, J.L. et al. (2000?). *Final Report to the David & Lucile Packard Foundation, Review of Middle School Texts.* Online at ⟨http://www.aapt.org⟩ / 'Hubisz Report on Middle School Textbooks'.

Hubisz, J.L. et al. (2001). Report on a study of middle school science texts. *Physics Teacher* **39**(5): 304–309.

> If good materials are to be used, we must bring them to the attention of teachers and administrators. Our two year search, unfortunately, has led us to say *that the available text books are not the tools that will effect a change in the way physical science is taught in the middle schools of the United States.* [emphasis added]

With seeming inconsistency, Raloff (2001) reports that

> . . . Hubisz. . . would have liked to include the book . . . Haber-Schaim et al. (1999) – an 'available' textbook. . . in his recent review of science texts 'because it would have allowed us to say something really positive.' But since it was not among the top dozen sellers, it didn't make the cut.

See especially 'Suggestions for Middle School Teachers'.

Hurd, P.D. (1994). New minds for a new age: Prologue to modernizing the science curriculum. *Science Education* **78**(1): 103–116.

Hurd, P.D. (1997). *Inventing Science Education for the New Millennium.* Teachers' College Press.

Hurd, P.D. (2000). *Transforming Middle School Science.* Teachers College Press.

Inhelder, B., D. DeCaprona, and A. Cornu-Wells (1987). *Piaget Today.* Psychology Press.

Inhelder, B. and J. Piaget (1958). *Growth of Logical Thinking from Childhood to Adolescence: An Essay on the Construction of Formal Operational Structures.* Basic Books.

Jungck, J.R. (1972). The Three I's: Interdisciplinary, Investigative, and Independent study. In R.K. Gibbs and P.A. Taylor, eds., *How Ought Science Be Taught?*, MSS Educational Publishers, pp. 209–210.

Jungck, J.R. (1985). A Problem Posing Approach to Biology Education. *American Biology Teacher* **47**(5): 264–266. Reprinted in S. Brown and M. Walter, eds., *Problem Posing: Reflections and Applications*, Erlbaum, 1993.

Jungck, J.R. and N.S Peterson (1988). Problem-posing, problem-solving, and persuasion in biology education. *Academic Computing* **2**(6): 14–17, 48–50.

Kaput, J.J. (1992). Technology and mathematics education. In D.A. Grouws, ed., *Handbook of Research on Mathematics Teaching and Learning*, Macmillan.

Karplus, R. (1977). Science teaching and the development of reasoning. *Journal of Research in Science Education* **14**: 169.

Kessler, J.H., A. Benbrow, and T. Sweitzer (1996). *The Best of Wonder Science: Elementary Science Activities.* Delmar Thomson Learning. Recommended by Hubicz et al. (2001).

Kindfield, A.C.H. (1994). Assessing understanding of biological processes: Elucidating students models of meiosis. *American Biology Teacher* **56**(6): 367–371.

King, J.G. (2001). 'Observation, experiment, and the future of physics': John G. King's acceptance speech for the 2000 Oersted medal presented by the American Association of Physics Teachers, 18 January 2000. *American Journal of Physics* **69**(1): 11–25. From the abstract:

> Looking at our built world, most physicists see order where many others see magic. This view of order should be available to all, and physics would flourish better in an appreciative society. Despite the remarkable developments in the teaching of physics in the last half century, too many people, whether they've had physics courses or not, don't have an inkling of the power and value of our subject, whose importance ranges from the practical to the psychological. We need to supplement people's experiences in ways that are applicable to different groups, from physics majors to people without formal education. I will describe and explain an ambitious program to stimulate scientific, engineering, and technological interest and understanding through direct observation of a wide range of phenomena and experimentation with them. For the very young: toys, playgrounds, kits, projects. For older students: indoor showcases, projects, and courses taught in intensive form. For all ages: more instructive everyday surroundings with outdoor showcases and large demonstrations

Kohn, A. (1999). *Punishment By Rewards: The Trouble with Gold Stars, Incentive Plans, A's, Praise, and Other Bribes.* Houghton Mifflin.

Kolb, D.A. (1984). *Experiental Learning: Experience as the Source of Learning and Development.* Prentice–Hall.

Langer, E.J. (1997). *The Power of Mindful Learning.* Addison–Wesley.

Langenberg, D.N. (2000). Rising to the challenge. *Thinking K–16* **4**(1): 19. Online as 'Honor in the Boxcar' ⟨http://www.edtrust.org/main/reports.asp⟩:

> . . . 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.

Lave J. and E. Wenger (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge University Press.

Laws, P. (1997). Millikan lecture 1996: Promoting active learning based on physics education research in introductory physics courses. *American Journal of Physics* **65**(1): 13–21.

Lawson, A.E. (1993a). Deductive reasoning, brain maturation, and science concept acquisition: Are they linked? *Journal of Research in Science Teaching* **30**(9): 1029–1052.

Lawson, A.E. (1993b). Neural principles of memory and a neural theory of analogical insight. *Journal of Research in Science Teaching* **30**(10): 1327–1348.

Lawson, A.E. ed. (1993c). Special issue on the role of analogy in science and science teaching. *Journal of Research in Science Teaching* **30**(10): 1211–1364.

Lawson, A.E., W.P. Baker, L. DiDonato, M.P. Verdi, and M.A. Johnson (1993). The role of physical analogues of molecular interactions and hypothetico-deductive reasoning in conceptual change. *Journal of Research in Science Teaching* **30**(9): 1073–1086.

Lawson, A.E. (1994). Epistemological foundations of cognition. In D. Gabel, ed., *Handbook of Research on Science Teaching and Learning*, Macmillan.

Lawson, A.E. (1995). *Science Teaching and the Development of Thinking*. Wadsworth Publishing. See especially Appendix C, 'What is Science' by R.P. Feynman; Appendix F, 'Classroom Test of Scientific Reasoning'; and the excellent bibliography.

Lawson, A.E. (1999). What should students learn about the nature of science and how should we teach it? *Journal of College Science Teaching* **28**(6): 401.

Layman, J. W., G. Ochoa, and H. Heikkinne (1996). *Inquiry and Learning: Realizing Science Standards in the Classroom*. College Entrance Examination Board. Online at ⟨http://www.nap.edu/readingroom/books/rtmss/7.19.html⟩.

*Lederman, L.M. (1999). A science way of thinking. *Education Week*, 16 June. ⟨http://www.edweek.org/ew/1999/40leder.h18⟩.

*Livanis, O. (2000). *Physics First Home Page*. ⟨http://members.aol.com/physicsfirst/index.html⟩.

Lochhead, J. (2000). *Thinkback: A User's Guide to Minding the Mind*. Erlbaum. See also at ⟨http://www.whimbey.com/Books/Thinkback/thinkback.htm⟩

Ma, L. (1999). *Knowing and Teaching Elementary Mathematics: Teachers' Understanding of Fundamental Mathematics in China and theUnited States*. Erlbaum. For a review of see R. Askey, *American Educator*, Fall 1999; on the web at the back-to-basics site 'Mathematically Correct' ⟨http://ourworld.compuserve.com/homepages/mathman/⟩.

Marshall R. and M. Tucker. (1992). *Thinking for a Living*. Basic Books.

McDermott, L.C. (1990). A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers. *American Journal of Physics* **58**: 734–742.

McDermott, L.C. (1991). Millikan lecture 1990: What we teach and what is learned: Closing the gap. *American Journal of Physics* **59**(4): 301–315.

McDermott, L.C. (1993). Guest comment: How we teach and how students learn – a mismatch? *American Journal of Physics* **61**(4): 295–298.

McDermott, L.C. (2000). Oersted medal lecture: Research – key to student understanding. *AAPT Announcer* **30**(4): 88.

McDermott L.C. and Redish E.F. (1999). RL-PER1: Resource letter on physics education research. *American Journal of Physics* **67**(9): 755–767. Online at ⟨http://www.physics.umd.edu/rgroups/ripe/perg/cpt.html⟩.

Mervis, J. (2001). Math education: Academy report aims to quiet debate. *Science* **291**: 808 (2 February). Describes a panel report by the National Academy of Sciences ⟨http://www.nap.

edu/catalog/9822.html⟩ on the ‘skills versus understanding’ wars in mathematics education. The article quotes the chair of the panel, Professor Jeremy Kilpatrick of the University of Georgia:

> We want to move past the debate over skills versus understanding. It’s not one or the other. The point is that both are needed, and more, to learn and understand mathematics.

Mestre, J.P. (1991). learning and instruction in pre-college physical science. *Physics Today* **44**(9): 56–62.

> Traditional teaching practices only poorly reflect what is known about the learning process. To improve science education, teachers and scientists must take note of the implications of cognitive science.

Mestre, J. and J. Touger (1989). Cognitive research – what’s in it for physics teachers? *Physics Teacher* **27**: 447–456.

Minstrell, J. (1989). Teaching science for understanding. In L.B. Resnick and L.E. Klopfer, eds., *Toward the Thinking Curriculum: Current Cognitive Research*. Association for Supervision and Curriculum Development [ASCD] Yearbook.

Moore, J.A. (1993). We need a revolution – teaching biology for the twenty-first century. *Bioscience* **43**(11): 782–786.

Moore, J.A. (1993). *Science as a Way of Knowing: The Foundations of Modern Biology*. Harvard University Press.

Moyer, A.E. (1982). John Dewey on physics teaching. *Physics Teacher* **20**(3): 173–175.

*NISE [National Institute for Science Education] (2001). ⟨http://www.wcer.wisc.edu/NISE⟩: Field-tested Learning Assessment Guide (FLAG): For Science, Math, and Engineering Instructors. ⟨http://www.wcer.wisc.edu/nise/cl1/flag/flaghome.asp⟩, especially Introduction to CAT’s [Classroom Assessment Techniques] at ⟨http://www.wcer.wisc.edu/nise/cl1/flag/cat/catframe.asp⟩.

National Research Council (1989). *Everybody Counts: A Report to the Nation on the Future of Mathematics Education*. Mathematical Sciences Education Board and the Board on Mathematical Sciences. Online at ⟨http://www.nap.edu/catalog/1199.html⟩.

National Research Council (1990). *Fulfilling the Promise: Biology Education in the Nation’s Schools*. National Academy Press. For a description see ⟨http://www.nap.edu/bookstore/isbn/0309051479.html⟩.

*National Research Council (1996a). *National Science Education Standards*. National Academy Press. ⟨http://books.nap.edu/catalog/4962.html⟩.

National Research Council (1996b). *Resources for Teaching Elementary School Science*. National Academy Press. Online at ⟨http://www.nap.edu/catalog/4966.html⟩.

National Research Council (1997a). *Introducing the National Science Education Standards*, Booklet. National Academy Press. Online at ⟨http://books.nap.edu/catalog/5704.html⟩.

National Research Council (1997b). *Improving Teacher Preparation and Credentialing Consistent with the National Science Education Standards: Report of a Symposium*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/5592.html⟩.

National Research Council (1997c). *Science Teaching Reconsidered: A Handbook*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/5287.html⟩.

National Research Council (1997d). *Science for All Children: A Guide to Improving Elementary Science Education in Your School District*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/4964.html⟩.

National Research Council (1997e). *Preparing for the 21st Century: The Education Imperative*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/9537.html⟩.

National Research Council (1998a). *Resources for Teaching Middle School Science*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/5774.html⟩.

National Research Council (1998b). *Every Child a Scientist: Achieving Scientific Literacy for All*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/6005.html⟩.

National Research Council (1999a). *Global Perspectives for Local Action: Using TIMSS to Improve U.S. Mathematics and Science Education*. National Academy Press. Online at ⟨http://www.nap.edu/catalog/9605.html⟩.

National Research Council (1999b). *Improving Student Learning: A Strategic Plan for Education Research and Its Utilization*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/6488.html⟩.

National Research Council (1999c). *Selecting Instructional Materials: A Guide for K–12 Science*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/9607.html⟩.

National Research Council (1999d). *Designing Mathematics or Science Curriculum Programs: A Guide for Using Mathematics and Science Education Standards*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/9658.html⟩.

National Research Council (2000a). *Educating Teachers of Science, Mathematics, and Technology: New Practices for the New Millennium*. National Academy Press. Online at ⟨http://www.nap.edu/catalog/9832.html⟩.

National Research Council (2000b). Steve Olson and Susan Loucks-Horsley, eds. Committee on the Development of an Addendum to the National Science Education Standards on Scientific Inquiry, National Research Council. *Inquiry and the 'National Science Education Standards': A Guide for Teaching and Learning*. National Academy Press. Online at ⟨http://books.nap.edu/catalog/9596.html⟩.

National Research Council (2001a). Committee on Development of an Addendum to the National Science Education Standards on Science and Technology. *Science and Technology and the National Science Education Standards: A Guide for Teaching and Learning*. National Academy Press. Final forthcoming / no prepublication copies for sale; see ⟨http://books.nap.edu/catalog/9833.html⟩.

National Research Council (2001b). J. Myron Atkin, Paul Black, and Janet Coffey, eds. *Classroom Assessment and the National Science Education Standards: A Guide for Teaching and Learning*. National Academy Press. Final forthcoming / no prepublication copies for sale; see ⟨http://books.nap.edu/catalog/9847.html⟩.

National Research Council. (2001c). Committee on Understanding the Influence of Standards in Science, Mathematics, and Technology Education, Iris R. Weiss, Karen S. Hollweg, and Gail Burrill, eds. *Considering the Influence: A Framework for Research on the Effects of Nationally Developed Mathematics, Science, and Technology Education Standards*. National Academy Press. Final forthcoming / no prepublication copies for sale; see ⟨http://books.nap.edu/catalog/10023.html⟩.

National Science Foundation (no date). *Inquiry: Thoughts, Views, and Strategies for the K–5 Classroom*. Online at ⟨http://www.nsf.gov/pubs/2000/nsf99148/htmstart.htm⟩.

Nelson, C.E. (1989). Skewered on the unicorn's horn: The illusion of tragic tradeoff between content and critical thinking in the teaching of science. In L.W. Crow, ed., *Enhancing Critical Thinking in the Sciences*, Society for College Science Teachers/National Science Teachers Association, pp. 17–27.

Nelson, C.E. (1994). Critical thinking and collaborative learning. *New Directions for Teaching and Learning* **59**: 45–58.

Nelson, C. (2000). Bibliography: how to find out more about college teaching and its scholarship: A not too brief, very selective hyperlinked list; college pedagogy *is* a major area of scholarship!. ⟨http://php.indiana.edu/˜nelson1/TCHNGBKS.html⟩.

Neuschatz, M. (1999). What can the TIMSS teach us? *Science Teacher* **66**(1): 23–26.

*NCSU [North Carolina State University] (2001). Physics Education R & D Group, Assessment Instrument Information Page, online at ⟨http://www.ncsu.edu/per/TestInfo.html⟩.

Novak, G. M., E.T. Patterson, A.D. Gavrin, and W. Christian. (1999). *Just in Time Teaching*. Prentice–Hall. For a description see ⟨http://webphysics.iupui.edu/jitt/jitt.html⟩.

Novak, J.D., (1998). *Learning, Creating, and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Classrooms*. Erlbaum.

Novak, J.D., J.J. Mintzes, and J.H. Wandersee, eds. (1998). *Teaching Science for Understanding – A Human Constructivist View*. Academic Press.

Nuffield Foundation (1999). *Beyond 2000 – Science Education for the Future*. Nuffield Foundation, UK. Produced by prominent UK science educators; makes 10 major recommendations for the future direction of science education. Online at ⟨http://www.kcl.ac.uk/depsta/education/be2000/index.html⟩.

Paulos, J.A. (1992). *Beyond Numeracy: Ruminations of a Numbers Man*. Vintage Books.

Perkins, D. (1992). *Smart Schools: Better Thinking and Learning for Every Child*. Free Press.

Perry, W.G. (1970). *Forms of Intellectual and Ethical Development in the College Years: A Scheme*. Holt, Rinehart, and Winston.

Pinker, S. (1999). *How the Mind Works*. Norton. See also ⟨http://web.mit.edu/bcs/pinker.html⟩.

Polya, G. (1954). *Mathematics and Plausible Reasoning* (2 volumes). Volume I: *Induction and Analogy in Mathematics*. Volume II: *Patterns of Plausible Inference*. Princeton University Press. At a higher level than Polya (1957); his most brilliant books on mathematics teaching and thinking.

Polya, G. (1957). *How to Solve It: A New Aspect of Mathematical Method*. Princeton University Press.

Polya (1962, 1965). *Mathematical Discovery: On Understanding, Learning, and Teaching Problem Solving* (2 volumes). Wiley. Almost as good as Polya (1954) and contains his famous 'Ten Commandments for Teachers' (p. 116).

Polya, G. (1965). *Let Us Teach Guessing* (60-minute videotape). Mathematical Association of America. Available from ⟨http://www.maa.org/pubs/books/ltg.html⟩.

*Radatz, H. (1983). Untersuchungen zum Lösen eingekleideter Aufgaben. [Studies of solving mathematical tasks] *Journal für Mathematikdidaktik* **3**: 205–217.

Raloff, J. (2001). Where's the book? Science education is redefining texts. *Science News* **159**(12) (March 24). Online at ⟨http://www.sciencenews.org/20010324/bob12.asp⟩ (second in a two-part series on middle-school science curricula). This article extols Haber-Schaim et al. (1999):

> Common to the origin of many of these… (newer science education programs)… is funding from the NSF. Explains Janice Earle, a senior program director… (at NSF)… qualifying projects must now exhibit 'a coherent content… aligned with national standards', foster critical thinking and problem solving, and be grounded in research on how children learn. Moreover, NSF recommends that any new curriculum be developed by teams of practicing scientists, engineers, and mathematicians, along with classroom teachers. 'I would be surprised if most textbooks were developed like that,' Earle says. They aren't. One exception, however, is (Haber-Schaim et al. 1999)… notes Uri Haber-Schaim, one of this textbook's authors. Launched in 1967, the book briefly became a top selection for eighth- and ninth-grade classrooms. Developed with NSF funding, the book was initially issued by a big publisher, but sales dropped when newer texts entered the field. In the early 1990's, the company decided not to publish further editions but permitted Haber-Schaim to pick up rights to the book. His firm, Science Curriculum Inc. of Belmont, Mass., now produces it. Unlike other science texts for early adolescents, Haber-Schaim says, 'we very

> thoroughly field-tested our experiments in classrooms over a period of 2 years. We even field-tested every homework question. . . (Among extollers). . . of the book is John L. Hubisz . . . He would have liked to include the book in his recent review of science texts. . . ⟨http://www.aapt.org⟩ 'because it would have allowed us to say something really positive.' But since it was not among the top dozen sellers, it didn't make the cut.

Rath, A. and D. E. Brown (1996). Modes of engagement in science inquiry: A microanalysis of elementary students' orientations toward phenomena at a summer science camp. *Journal of Research in Science Teaching* **33**: 1083–1097.

Redish, E.F. (1994). Implications of cognitive studies for teaching physics. *American Journal of Physics* **62**(9): 796–803. Online at ⟨http://www.physics.umd.edu/rgroups/ripe/perg/cpt.html⟩.

Redish, E.F. (1999). Millikan lecture 1998: Building a science of teaching physics. *American Journal of Physics* **67**(7): 562–573. Online at ⟨http://www.physics.umd.edu/rgroups/ripe/perg/cpt.html⟩.

Reif, F. (1995). Millikan lecture 1994: Understanding and teaching important scientific thought processes. *American Journal of Physics* **63**(1): 17–32.

Reif, F. (1999). Thermal physics in the introductory physics course: Why and how to teach it from a unified atomic perspective. *American Journal of Physics* **67**(12): 1051–1062.

Resnick, L.B. and M.W. Hall (1998). Learning organizations for sustainable education reform. *Daedalus* **127**(4): 89–118.

*Reusser, Kurt (1988). Problem Solving beyond the Logic of Things: Contextual Effects on Understanding and Solving Word Problems. *Instructional Science* **17**: 309–38.

Sadler P.M. and R.H. Tai. (1997). The role of high-school physics in preparing students for college physics. *Physics Teacher* **35**(5): 282–285.

Salinger, G.L. (1991). The materials of physics instruction. *Physics Today* **44**(9): 39–45.

> The mathematics and science communities are redefining what students should know and how they should learn it. Much new instructional material is available embodying the new reforms.

Sarason, S.B. (1993). *The Case for Change: Rethinking the Preparation of Educators*. Jossey–Bass.

Sarason, S.B. (1996). *Revisiting 'The culture of the school and the problem of change'*. Teachers' College Press.

Schneps, M.H. and P.M. Sadler (1985). Private universe project. Harvard–Smithsonian Center for Astrophysics, Science Education Department. ⟨http://cfa-www.harvard.edu/cfa/sed/resources/privateuniv.html⟩.

Schwartz, R.B. (1999). Lessons from TIMSS. *Hands On* **21**(1): 4. ⟨http://www.terc.edu/handsonIssues/s98/schwartz.html⟩. *Hands On* is a publication of TERC [Technical Education Research Center] ⟨http://www.terc.edu⟩. Schwartz is president of ACHIEVE (2001), and on the faculty of the Harvard Graduate School of Education.

Shapiro, I., C. Whitney, P. Sadler, and M. Schneps (1997). *Simple Minds*. Harvard–Smithsonian Center for Astrophysics, Science Education Department, Media Group. ⟨http://www.learner.org/catalog/science/mooo/⟩ and ⟨http://www.learner.org/catalog/science/mooo/mooodes.html⟩.

Simon, H.A. (1998). What we know about learning. *Journal of Engineering Education* **87**(4): 343–348.

Schoenfeld, A.H. (1985). *Mathematical Problem Solving*. Academic Press.

*Schoenfeld, Alan (1987). What's all the fuss about metacognition? In *Cognitive Science and Mathematics Education*, Alan Schoenfeld, ed. (Hillsdale, NJ: Lawrence Erlbaum).

*Schoenfeld, Alan H. (1989). Teaching mathematical thinking and problem solving. In Lauren B. Resnick and Leonard B. Klopfer, eds., *Toward the thinking curriculum: Current cognitive research*, Association for Supervision and Curriculum Development [ASCD], Alexandria, VA.

Schultz, T. (2001). *Science Education Through the Eyes of a Physicist*. National Academy Of Sciences/National Research Council. Online at ⟨http://www.nas.edu/rise/backg2d.htm⟩.

Sizer, T.R. (1985.) *Horace's Compromise: The Dilemma of the American High School*. Houghton Mifflin.

Sizer, T.R. (1992). *Horace's School: Redesigning the American High School*. Houghton Mifflin.

Sizer, T.R. (1996). *Horace's Hope: What Works for the American High School*. Houghton Mifflin.

Sizer, T.R. and N.F. Sizer (1999). *The Students Are Watching: Schools and the Moral Contract*. Beacon Press. See also ⟨http://www.essentialschools.org/⟩.

Slavin, R.E. (1994). *Cooperative Learning: Theory, Research and Practice*. Allyn & Bacon.

Springer, L., M.E. Stanne, and S.D. Donovan (1999). Undergraduates in science, mathematics, engineering, and technology: a meta-analysis. *Review of Educational Research* **69**(1): 21–51. Abstract online at ⟨http://www.aera.net/pubs/rer/abs/rer691-3.htm⟩.

Stein, S.K. (1996). *Strength in Numbers: Discovering the Joy and Power of Mathematics in Everyday Life*. John Wiley.

Sternberg, R.J. (1995). *In Search of the Human Mind*. Harcourt Brace. Especially 'Evaluation of Piaget's Theory', pp. 427–428.

Stevenson H.W., and J.W. Stigler (1992). *The Learning Gap: Why Our Schools are Failing and What We Can Learn from Japanese and Chinese Education*. Summit Books.

Stigler, J.W. and J. Hiebert (1997). Understanding and Improving Classroom Mathematics Instruction: An Overview of the TIMSS Video Study. *Phi Delta Kappan*, September. Online at ⟨http://www.pdkintl.org/kappan/kstg9709.htm⟩.

Stigler, J.W. and J. Hiebert (1999). *The Teaching Gap*. Free Press. See also ⟨http://www.lessonlab.com/teaching-gap/⟩. Contains an illuminating analysis of TIMSS videotapes.

Swartz, C.E. (1969). Measure and find out: A quantitative approach to science. Scott, Foresman, & Company. 3 volumes. Recommended by Hubisz et al. (2001): 'Has what is missing from most of the books in this report'.

Swartz, C.E. (1986). Elementary-school science by a quantitative approach. Unnpublished.

Swartz, C.E. (1991). The physicists intervene. *Physics Today* **44**(9): 22–28.

> For over 150 years American physicists have been making forays into elementary and high school science teaching. Their novel approaches have usually worked–but the results have always been short-lived.

*Swartz, C.E. (1993). Editorial: Standard reaction. *Physics Teacher* **31**: 334–335.

Swartz, C.E. et al. (1999). Survey of high-school texts. *Physics Teacher* **37**(5): 283–296.

Swartz C.E. and T. Miner (1998). *Teaching Introductory Physics: A Source Book*. Springer-Verlag. For a description see ⟨http://www.springer-ny.com/catalog/np/apr98np/1-56396-320-5.html⟩.

Schwartz, B.B. and J.J. Wynne (1991). Pre-college physics education programs from the research community. *Physics Today* **44**(9): 48–54.

> Physicists from professional societies, the national laboratories and industry run many active programs for teachers and students of pre-college physics.

Tyack, D. and L. Cuban (1995). *Tinkering Toward Utopia: A Century of Public School Reform*. Harvard University Press.

Uno, G.E. (1994) (principal author). *Developing Biological Literacy*. Biological Sciences Curriculum Study [BSCS], Kendall/Hunt.

Uno, G.E. and R.W. Bybee (1994). Understanding the dimensions of biological literacy. *BioScience* **44**(8): 553–557.

Uno, G.E. (1992). *Co-author and editor of Biological Science: An Ecological Approach* (BSCS text). 7th edition. Kendall/Hunt.

Uno, G.E. (1984). *Investigating the Human Environment: Land Use* (BSCS text). Kendall/Hunt.

Uno, G.E. (1988). Teaching College and College-Bound Biology Students. *American Biology Teacher* **50**(4): 213–216.

von Glasersfeld, E. (1997). Homage to Jean Piaget (1896-1982). *Irish Journal of Psychology* **18**(2): 293–. Online at ⟨http://www.oikos.org/Piagethom.htm⟩ and maybe at ⟨http://www.umass.edu/srri/vonGlasersfeld/onlinePapers.html⟩.

Wells, M., D. Hestenes, and G. Swackhamer (1995). A modeling method for high school physics instruction. *American Journal of Physics* **63**(7): 606–619. Online at ⟨http://modeling.la.asu.edu/modeling/MalcolmMeth.html⟩.

West, L.H.T. and A.L. Pines, eds. (1985). *Cognitive Structure and Conceptual Change*. Academic Press.

Whimbey, A. and J. Lochhead (1999). *Problem Solving and Comprehension*. 6th edition. Erlbaum. See also at ⟨http://www.whimbey.com/Books/psc6/psc6.htm⟩.

Whimbey, A., J. Lochhead, and P.B. Potter (1999). *Thinking Through Math Word Problems: Strategies for Intermediate Elementary School Students*. Erlbaum. See also at ⟨http://www.whimbey.com/Books/thinking/thinking.htm⟩.

Williams, P.H. (1993). *Bottle Biology*. Kendall/Hunt.

Whitehead, A.N. (1967). *The Aims of Education, and Other Essays*. Free Press. Originally published in 1929.

Wilson K.G. and B. Daviss (1994). *Redesigning Education*. Henry Holt. See also at ⟨http://www-physics.mps.ohio-state.edu/~kgw/RE.html⟩.

Wyckoff, S. (2001). Changing the culture of undergraduate science teaching. *Journal of College Science Teaching* **30**(5): 306–312. Figure 2 shows pre/post Lawson-reasoning test [Lawson(1995/99)] results for 584 students in a 'Biology 100' class that 'demonstrates' a 41% gain in students reasoning abilities. For related work see Clement (2000) and Adey (1999).

Zollman, D.A. (1996). Millikan lecture 1995: Do they just sit there? Reflections on helping students learn physics. *American Journal of Physics* **64**(2): 114–119.