Helping Students to Think Like Scientists in Socratic Dialogue-Inducing Labs†

Richard Hake, Indiana University, Bloomington, IN

Socratic dialogue-inducing (SDI) labs [1,2] are based on Arnold Arons' half-century of ethnographic research, listening carefully to students' responses to probing Socratic questions on physics, science, and ways of thinking, and culminating in his landmark *Teaching Introductory Physics*. [3] They utilize "interactive engagement" methods [4] and are designed, in part, to help students think like scientists, e.g., to: (a) appreciate the need for operational definitions; (b) use and interpret pictorial, graphical, vectorial, mathematical, and written representations; and (c) consider dimensions, thought experiments, and limiting conditions. After giving some SDI lab examples from those categories, I conclude that the SDI lab attempts to help students think like scientists have been relatively successful.

Operational definitions

> *When we say force is the cause of motion we talk meta-physics, and this definition, if we were content with it, would be absolutely sterile. For a definition to be of any use, it must teach us to measure force; moreover, that suffices; it is not at all necessary that it teach us what force is in itself, nor whether it is the cause or the effect of motion.* — Henri Poincaré [5]

An operational definition of "X" simply gives the operations for measuring "X." [6] Operational definitions are therefore crucial in science and in critical thinking, even despite the protestations of the "anti-positivist vigilantes." [7]

An example of SDI labs' stress on operational definitions is the pre-lab assignment "Operational Definitions of Kinematic Terms" [8] adapted from Arons' book [3] (Sections 1.16-1.17, 2.2- 3.25). To adequately convey the SDI lab approach, here and below I quote directly from the pre-lab assignment (colored text), except that superscript reference numbers to important explanations for the present readers have been added to the quoted material. Such references do not, of course, appear in the assignment as distributed to students:

"**A. DEVISE OPERATIONAL DEFINITIONS OF KINEMATIC TERMS:**

We agree with the *The Mechanical Universe* [9] standpoint that it is almost impossible to understand terms such as 'velocity' and 'acceleration' without some knowledge of the basic ideas of differential calculus. Thus, in our view, the appellation 'non-calculus physics text' is a contradiction in terms. Authors of effective 'non-calculus' physics texts must negate their own 'non-calculus' claims: most of them give an expression for instantaneous velocity in one dimension:

$$v = \lim_{\Delta t \to 0} (\Delta x/\Delta t) = (dx/dt) \;.\;.\;.\;.\;.\;.\;.\; (1)$$

but omit the right-hand side of this equation (the identification of the derivative 'dx/dt'), possibly because they fear it might frighten students and/or jeopardize their book's posi- tion as a 'non-calculus' text.

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† The reference is: Hake, R.R. 2012. "Helping Students to Think Like Scientists in Socratic Dialogue Inducing Labs," *Phys. Teach.* **50**(1): 48-52; online to subscribers at <http://bit.ly/wLy3En>. This version, online at <http://www.physics.indiana.edu/~hake/HelpStudThink-L.pdf> = <http://bit.ly/x5ruYF> is identical to the *Phys. Teach* article except for (a) minor formatting changes, and (b) the addition of a few *hot-linked* URL's.

Satisfactory completion of this section will help to insure that you have entered into the Newtonian - Leibnitz world of differential calculus, [10] at least to the extent of understanding the operational meaning of the basic kinematic terms and thus being prepared to consider the experiments in SDI #2, *Newton's Second Law*. Please recall from the discussion in SDI Labs #0.1 (Frames of Reference, Position, and Vectors) and #1 (Newton's First and Third Laws) that an operational definition of a word or words specifies the experimental significance of those words in terms of well-defined measurement methods. Please indicate, in your own words and/or sketches [one sketch or graph is worth a teraword (1.0 x10^{12} words)] operational definitions of the crucial kinematic terms given on the following pages."

The first kinematic term that the students are asked to *operationally* define is:

"1. ***Position*** [HINT: Recall your work in SDI Lab #0.1. How did you measure your position in that lab? Recall that your operational definition of 'position' was to have consisted of a sketch of your position vector between an origin 'O' and a point 'P' in an xyz-coordinate reference frame, along with a statement of the operations for marking the coordinate scales and then measuring your position coordinates.]"

Just below the above instruction is a rectangular grid to accommodate student sketches. The "HINT" above, and in the quoted material below, indicates the extensive guidance supplied by the SDI lab manual, in addition to that furnished by: (a) fellow students during collaborative discussion (just as in *Peer Instruction* [11]], and (b) the Socratic instructor in response to students' questions or lab manual entries. Thus SDI labs, as most other constructivist-type interactive engagement methods, are not "minimally guided," an appellation applied by Kirschner, Sweller, and Clark (KSC) [12] to "constructivist, discovery, problem-based, experiential, and inquiry-based teaching." KSC then proclaimed them all to be failures! For a counter to KSC see, e.g., Part II "Evidence for Constructivism" in Tobias & Duffy. [13] The author's counter to KSC is at <http://bit.ly/bHTebD>. Among other terms that the students are asked to operationally define are:

"2. ***Instantaneous Position*** [HINT: Return to this after completing '5' below.]

3. ***Displacement*** [HINT: Do you recall walking from one position to another position in the lab as part of SDI Lab #0.1? How did you define your displacement vector be- tween your initial and final positions in terms of initial and final position vectors?] Draw a diagram!

4. ***Time*** [HINT: What instrument measures 'time'? See SDI Lab Ground Rule #5[14] in SDI Lab #0.1, and Fig. 1 below.]

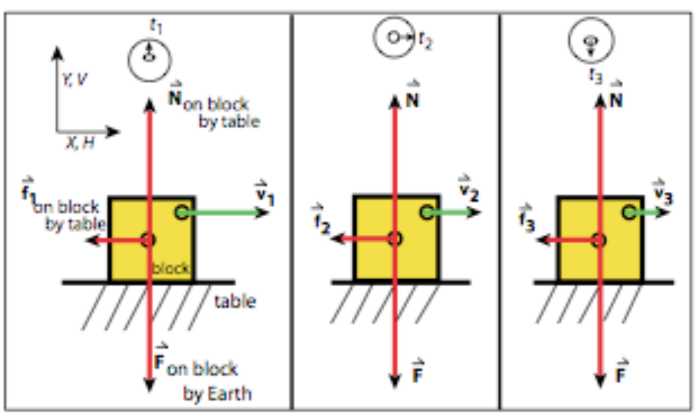

Fig. 1. Snapshot sketches at three sequential instants of time (t_1, t_2, t_3) show a wooden block sliding to rest on a table as observed in Sec. IV-C of SDI Lab #1, *Newton's First and Third Laws*. The force *f* is the frictional force exerted on the block by the table. *N* is the normal force exerted on the block by the table. *F* is the force exerted on the block by the Earth. The V-H axis designates the vertical and horizontal directions.

5. ***Instant of Time*** [HINT: What instrument measures an 'instant of time'? See Fig. 1 above.]

6. ***Clock reading*** [HINT: Its name is its definition! See also Fig. 1.]

7. ***Continuous (in time) Motion*** [HINT: Recall from your previous study of mathematics that a continuous function, say y as a function of x or y(x) is 'continuous' if Δy approaches 0 as Δx approaches 0. In graphical term y(x) is continuous if the curve y(x) can be drawn with one uninterrupted motion of a pencil. Applying this to kinematics, if the displacement x is a continuous function of the time, how would the curve of x(t) (i.e., x as a function of t) appear on a graph? Show such a curve in the space below and label it 'continuous.' If the displacement x is a discontinuous function of the time t, how would the curve of x(t) appear on a graph? Show such a curve in the space below and label it 'discontinuous.'
How could the continuous curve x(t) shown above be measured? (This, then, would be an operational definition of continuous motion.) Could the discontinuous x(t) curve shown above represent a physically reasonable situation? {Y, N, U, NOT}15

8. ***Time Interval***

9. ***Instantaneous Velocity*** (Henceforth, in this lab 'velocity' v will always mean 'instantaneous velocity.') [HINT: For simplicity consider only one-dimensional (1D) motion. For an operational definition of v in the x direction, consider the way in which you obtained your displacement x vs time t graph in SDI #0.2, Introduction to Kinematics. Alternatively, consider taking a sequence of camera snapshots at equal and closely spaced intervals of time. Could such a sequence of snapshots be used to construct a graph of x vs t for 1D motion or for the x-component of 3D motion? {Y, N, U, NOT} How could graphs of x vs t be used to define instantaneous velocity v in the x direction?]

10. ***Uniform Velocity*** [HINT: 'Uniform' simply means constant in time.] Suppose an object moves at a uniform velocity. Does it stay at one position during some small time interval? {Y, N, U, NOT}

11. ***Instantaneous Acceleration*** (Henceforth, in this lab 'acceleration' a will always mean 'instantaneous acceleration.') [HINT: The operations suggested to define instantaneous velocity v above in '9' will allow the construction of a v-vs-t curve. How could such a curve be used to define instantaneous acceleration?]

12. ***Uniform Acceleration***

13. ***Inertia*** [HINT: Newton's first law is often called the 'law of inertia.']

14. ***Inertial Reference Frame*** [HINT: Recall the discussion of Inertial Reference Frames (IRF) in the 'Forces on a Kid in a Truck' exercise of SDI Lab #1.]"

Vectorial representations

In SDI Lab #3 Circular Motion and Frictional Forces, students take turns performing the old “Tablecloth Slipout Trick”:

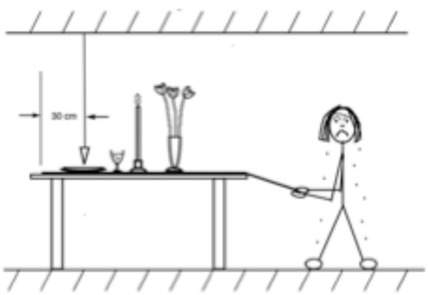

Fig. 2. A nervous student prepares to yank a tablecloth.

A plumb bob hanging from the ceiling and centered on the plate allows measurement of displacement d of a plate from start to finish of the trick. This trick is normally done as a qualitative lecture demonstration of Newton’s first law (wrong! – it demonstrates the second law – see below) to the delight (if not the enlightenment) of students. The lab manual instructions are as follows:

“During the downward pull on the tablecloth, the force applied to the tablecloth increases rapidly in time. There are four phases to the motion of the plate as shown in Fig. 3.

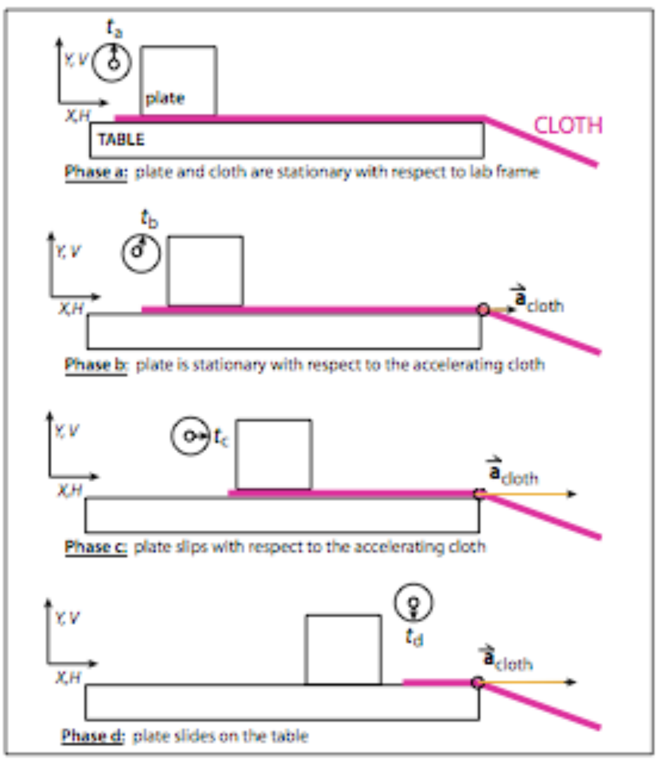

Fig. 3. Four phases of the motion of the plate (shown here as a block so as to facilitate the placement of vectors – see below): (a) plate and cloth stationary with respect to (wrt) the lab frame; (b) plate stationary wrt the accelerating cloth; (c) plate slips wrt the accelerating cloth; and (d) plate slides on the table.

During the four phases of the motion, draw in Fig. 3: (a) the velocity **v** and acceleration **a** vectors for the motion of the plate, and then (b) all the contact and action-at-a-distance vector force $\mathbf{F}_{\text{on plate by X}}$ acting on the plate.”

Figure 4 shows a student's correct response to the above instructions, utilizing the SDI lab color code: RED, force **F**; GREEN, velocity **v**; ORANGE, acceleration **a**; YELLOW, bodies to which Newton's first and second laws are applied.

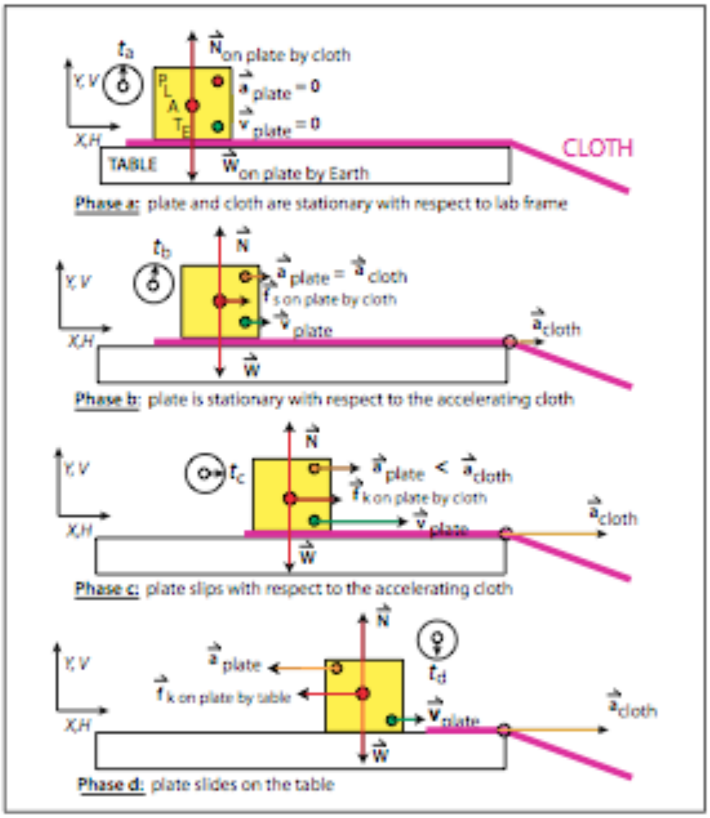

Fig. 4. Velocity, acceleration, and force vectors for phases a, b, c, and d of the motion of the plate.

Mathematical representations, dimensional analysis, and limiting conditions

Students are then challenged to derive the following expression16 for δ:

$$\delta = (1/2)\mu_{kc} g \tau^2 \, [1+(\mu_{kc} / \mu_{kt})] \text{..........} \quad (2)$$

In Eq. (2), g is the free-fall acceleration; τ is the time required to pull the cloth out from under the plate (i.e., the time duration of the "phase-c motion" (see above); and μ_{kc} and μ_{kt} are the coefficients of kinetic friction for, respectively, the plate on the cloth and the plate on the table. The lab manual provides the following HINT:

"Use Newton's second law, $\mathbf{F}_{\text{net on body}} = m_{\text{body}} \, \mathbf{a}_{\text{body}}$, to obtain accelerations in terms of μ and g for the phases c and d of the motion diagrammed above. (Assume that the distance moved during phase b is negligible.) Then use the constant-acceleration kinematic equations to calculate displacements while the plate is on the cloth and while the plate is on the table."

The lab manual then asks:

"Is Eq. (2) physically reasonable? {Y, N, U, NOT} [HINT: Consider dimensions and the predicted magnitude of δ for both realistic and extreme limiting conditions."

Has the SDI-lab attempt to help students think like scientists been relatively successful?

In "Achieving Wider Scientific Literacy," Arons3 (Chapter 12) gave, as the first two "hallmarks of science literacy":

1. Recognize that scientific concepts . . . . are invented (or created) by acts of human intelligence and are not tangible objects or substances accidentally discovered, like a fossil, or a new plant or mineral.

2. *Recognize that to be understood and correctly used such terms* **require careful operational definition**, rooted in shared experience and in simpler words previously de- fined; to comprehend, in other words, that a scientific concept involves an idea first and a name afterwards, and that *understanding does not reside in the technical terms themselves*.

Thus, in Arons' view, thinking like a scientist (e.g., appreciation for operational definitions) is a necessary condition for proper understanding of scientific concepts. The fact that SDI labs have resulted in relatively high (~0.6) average pre-to-post-test normalized learning gains (Hake [17], Table Ic) on the Force Concept Inventory [18,19] suggests that the SDI-lab attempt to help students think like scientists has been relatively successful.

Acknowledgment

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References [All URLs were accessed 08 Jan. 2012.]

1. R. R. Hake, "Socratic pedagogy in the introductory physics lab," *Phys. Teach.* **30**, 546–552 (Dec. 1992); updated version (4/27/98) online at <http://bit.ly/9tSTdB>. The author discusses pervasive misunderstandings of the Socratic method at <http://bit.ly/ b5v58m>.

2. R. R Hake, "Design-based research in Physics Education Research: A review," in A. E. Kelly, R. A. Lesh, and J. Y. Baek, *Handbook of Design Research Methods in Education: Innovations in Science, Technology, Engineering, and Mathematics Learning and Teaching* (Routledge, 2008), pp. 493–508, online at <http://bit.ly/9kORMZ>.

3. A. B. Arons, *Teaching Introductory Physics* (Wiley, 1997). See also A. B. Arons, "Guiding insight and inquiry in the introductory physics laboratory," *Phys. Teach.* **31**, 278–282 (May 1993). The author's appreciation of Arons is at <http://bit.ly/boeQQt>.

4. "Interactive engagement" methods were operationally defined by Hake [R. R. Hake, "Interactive-engagement vs traditional methods: A six thousand-student survey of mechanics test data for introductory physics courses," *Am. J. Phys.* **66**, 64–74 (Jan. 1998) online at <http://bit.ly/d16ne6> and Ref. 17] as those "designed at least in part to promote conceptual understanding through active engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors." The immediate formative assessment afforded by such feedback and its importance in promoting student learning has been emphasized by, e.g., P. Black and D. Wiliam, "Inside the black box: Raising standards through classroom assessment," *Phi Delta Kappan* **80**(2), 139-148 (1998) online at <http://bit.ly/c7ZQlr> and R. J. Shavelson et al., "On the impact of curriculum-embedded formative assessment on learning: A collaboration between curriculum and assessment developers," *Appl. Meas. Educ.* **21**(4), 295–310 (2008); online at <http://bit.ly/rMrGLi>.

5. H. Poincaré, *Science and Hypothesis* (Walter Scott Publishing, 1905); online at <http://bit.ly/9hVfA8>, thanks to the Mead Project. An essay on Poincaré by Jean Mawhin in "Notices of the AMS" is at <http://bit.ly/tVGIJt>. A Wikipedia entry on Poincaré is at <http://bit.ly/b4jGVS>.

6. G. Holton and S. G. Brush, *Physics the Human Adventure: From Copernicus to Einstein and Beyond* (Rutgers University Press, 2001). Operational definitions are discussed in Chap. 12, "On the Nature of Concepts."

7. D. C. Phillips, *Expanded Social Scientist's Bestiary: A Guide To Fabled Threats to, and Defenses of, Naturalistic Social Science* (Rowman & Littlefield, 2000), p. 157.

8. SDI #2 Pre-Lab Assignment Operational Definitions of Kine- matic Terms, as well as the SDI lab manuals referred to in this paper: #0.1, Frames of Reference, Position, and Vectors; #0.2, Introduction to Kinematics; #1, Newton's First and Third Laws; #2, Newton's Second Law; and #3, Circular Motion and Frictional Forces, are all online at the SDI lab website, <http://bit.ly/9nGd3M>, but to save space they will not be separately referenced. Some Teacher's Guides are available by request to <rrhake@earthlink.net>.

9. At the website <http://www.its.caltech.edu/~tmu/> it is stated that "The Mechanical Universe...and Beyond is a critically acclaimed series of 52 thirty-minute videotape programs covering the basic top- ics of an introductory university physics course. The series was originally produced as a broadcast telecourse by the California Institute of Technology and Intelecom, Inc. with program funding from the Annenberg/CPB Project." See also D. L. Goodstein and R. P. Olenick, "Making 'The Mechanical Universe,'" *Am. J. Phys.* **56**(9), 779–785 (1988). Some of these videotapes were shown to students in the "lecture" portion of the course that included SDI labs, but some students, thinking that the videotape material would not be covered on the tests, headed for the doors when the lights dimmed! To counter this tendency I started to use a few test questions based on historical or literary details discussed in the videotapes. Some students were outraged: "What is this, a poetry class?"

10. The Teacher's Guide to SDI Lab 0.2 Introduction to Kinematics, states: "Although about 70% of students entering the non-calculus-based Indiana University (IU) introductory physics course have completed a university calculus course, almost none seems to have the foggiest notion of the graphical meaning of a derivative or integral, as addressed in this section. Similar calculus illiteracy is commonly found among students in calculus-based introductory physics courses at IU. In my judgment, these calculus interpretations are essential to the crucial operational definitions of instantaneous position, velocity, and acceleration: the term 'substantive non-calculus-based mechanics course' is an oxymoron."

11. E. Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, 1997); ComPADRE information at <http://bit.ly/bygvAd>.

12. P. A. Kirschner, J. Sweller, and R. E. Clark, "Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching," *Educ. Psychol.* 41(2), 75–86 (2006); online at <http://bit.ly/duJVG4>.

13. S. Tobias and T. M. Duffy, *Constructivist Instruction: Success or Failure*? (Routledge, 2009).

14. Ground Rules for SDI labs are given in SDI Lab #0.1 *Frames of Reference, Position, and Vectors*. Rule #5 states: "In some cases you will draw a series of 'snapshot sketches' at sequential instants of time, e.g., t_1, t_2, t_3. In such cases always show clocks near each sketch to emphasize the time sequence." A figure and explanation similar to that of the present Fig. 1 is shown.

15. SDI Lab Ground Rule #11 states: “The lab manual questions are designed to help you think about the experiments and how they relate to Newton’s laws. You will often be asked to predict the outcome of an experiment and then perform that experiment. A curly bracket {.......} indicates that you should encircle (O) a response within the bracket and then, we insist, briefly explain or justify your answers in the space provided on these sheets. The letters {Y, N, U, NOT} stand for {Yes, No, Uncertain, None of These}.” And the Teacher’s Guide to SDI Lab # 0.1 Introduction to Kinematics states: “Requiring students to encircle one of {Y, N, U, NOT} serves to initiate their thinking processes and forces them to give some definite signal (useful to dialogists) as to their mental states even if they are unable, at the moment, to clearly articulate those states. An annotator’s check (correct) or cross (wrong) just above an encirclement yields quick and valuable feedback to a student. Requiring students to write explanations or justifications induces at least some to partake of the ‘intolerable labor of thought, that most distasteful of all our activities’ (Justice Learned Hand as quoted by Arons in his book cited in Ref. 3, p. 383). To avoid this painful and unaccustomed activity, students may lapse into merely encircling a letter unless the justification rule is rigidly enforced.”

16. U. Haber-Schaim and J. H. Dodge, “There’s more to it than friction,” *Phys. Teach.* **29**, 56–57 (Jan. 1991).

17. R. R. Hake, “Interactive-engagement methods in introductory mechanics courses” (1998), online at <http://bit.ly/aH2JQN>.

18. D. Hestenes, M. Wells, and G. Swackhamer, “Force Concept Inventory,” *Phys. Teach.* **30**, 141–158 (March 1992); online (but without the test itself) at <http://bit.ly/b1488v>; scroll down to “Articles about the FCI.”

19. I. Halloun, R.R. Hake, E.P. Mosca, and D. Hestenes, “Force Concept Inventory (1995 Revision),” online (password protected) at <http://bit.ly/b1488v>; scroll down to “Evaluation Instruments.” Currently available in 20! languages: Arabic, Chinese, Croatian, Czech, English, Finnish, French, French (Canadian), German, Greek, Italian, Japanese, Malaysian, Persian, Portuguese, Russian, Spanish, Slovak, Swedish, & Turkish.

Richard Hake received a PhD in physics from the University of Illinois in 1955, and then researched high-magnetic-field superconductivity at North American Aviation in California. In 1970 he became a professor of physics at Indiana University where, becoming aware of the failure of traditional university pedagogy to enhance students’ conceptual understanding, he developed Socratic Dialogue-Inducing Labs (links at <http://bit.ly/9nGd3M>). He has published over 80 peer-reviewed articles on superconductivity, magnetism, and education (links at <http://bit.ly/a6M5y0>) and is a Fellow of the American Physical Society. Since retirement in 1995, he has attempted to promulgate the “interactive engagement” methods that have been relatively successful in undergraduate physics. He blogs at <http://bit.ly/9yGsXh>.
<rrhake@earthlink.net>