Helping Students to Think Like Physicists in Socratic Dialogue Inducing Labs

Richard Hake

Physics Department, Indiana University, Emeritus
24245 Hatteras Street, Woodland Hills, CA 91367

Abstract. Socratic Dialogue Inducing (SDI) labs are based on Arnold Arons' half-century 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.* Following Arons, SDI Labs are designed to help students *think like physicists*, e.g., to: (1) appreciate the need for *operational* definitions; (2) use and interpret pictorial, graphical, vectorial, mathematical, and written representations; and (3) consider 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 physicists have been successful judging from (a) the relatively high (~0.6) average pre-to-posttest *normalized* learning gains achieved by SDI Lab students on the Force Concept Inventory, and (b) the fact that thinking like a physicist is a necessary condition for proper understanding of scientific concepts.

Keywords: operational definitions, thinking like a physicist, Arnold Arons, ethnographic research, Socratic Dialogue, representations (pictorial, graphical, vectorial, mathematical, written), normalized gain
PACS: 01.40.Fk

INTRODUCTION

Socratic Dialogue Inducing (SDI) labs [1,2] emphasize hands-on and minds-on experience with simple mechanics experiments and facilitate "Interactive Engagement" of students with course material.

"Interactive Engagement" methods were *operationally* defined by Hake [3] 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., Black & Wiliam [5] and is, of course, a hallmark of "Socratic Dialogue" as practiced by the *historical* Socrates, not Plato's alter ego, as discussed in Ref. 6.

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*, as well as the SDI #2 Pre-Lab Assignment *Operational Definitions Of Kinematic Terms*, are all online at the SDI Lab website <http://bit.ly/9nGd3M>, but to save space they will not be separately referenced. Teacher's Guides are available by request to <rrhake@earthlink.net>.

SDI Labs are based, for the most part, on Arnold Arons' half-century ethnographic research (for a review see Ref. 7), listening carefully to students' responses to probing Socratic questions on physics, science, and ways of thinking, and culminating in his landmark *Teaching Introductory Physics* [8].

Following Arons, SDI Labs are designed to help students *think like physicists*, e.g., to: (1) appreciate the need for *operational* definitions; (2) use and interpret pictorial, graphical, vectorial, mathematical, and written representations; and (3) consider thought experiments and limiting conditions. SDI lab examples of the above are given below in the next two sections.

Operational Definitions

"When we say force is the cause of motion we talk metaphysics, 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

An operational definition of "X" simply gives the operations for *measuring* “X” (Holton & Brush [9]). Operational definitions are therefore crucial in science and in critical thinking, even despite the protestations of the “anti-positivist vigilantes” [10].

An example of SDI Lab's stress on operational definitions is the prelab assignment "Operational Definitions Of Kinematic Terms," adapted from Arons [8, Sections 1.16-1.17, 2.2-3.25]. The assignment is introduced as follows:

> "A. DEVISE *OPERATIONAL* DEFINITIONS OF KINEMATIC TERMS: Satisfactory completion of this section will help to insure that you have entered into the Newtonian-Leibnitz world of differential calculus, 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 x 10^{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 a 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 items below, indicates the extensive guidance supplied by the SDI lab manual, in addition to that furnished by the Socratic instructor in response to students' questions or lab manual entries.

Thus SDI labs, as most other "Interactive Engagement" methods surveyed by Hake [3,4] are *not* "minimally guided," an appellation applied by [Kirschner, Sweller, & Clark ([11] to "constructivist, discovery, problem-based, experiential, and inquiry-based teaching," who proclaimed them all to be failures! For counters see Hake [12] and Tobias & Duffy [13].

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 between 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 in SDI Lab #0.1, and Fig. 1 below.]

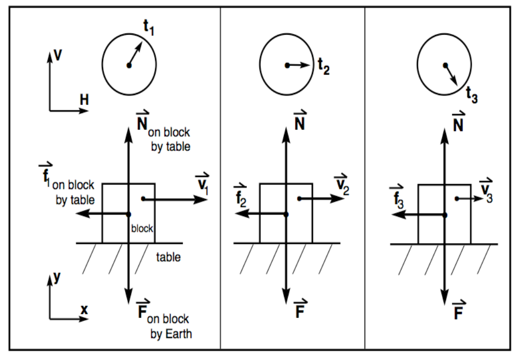


Fig. 1. Snapshot sketches at three sequential instants of time (t_1, t_2, t_3) show a wooden block sliding to rest on a table as observed in Sec. IV-C of SDI Lab #1, *Newton's First and Third Laws*. The force **f** is the frictional force exerted on the block by the table. **N** is the Normal force exerted 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 t, 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}

The letters {Y, N, U, NOT} stand for {Yes, No, Uncertain, None Of These}. A curly bracket {…} indicates that students should *encircle* a response within the bracket and then, briefly *explain* or *justify* their answers.

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.]

a. 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*?]

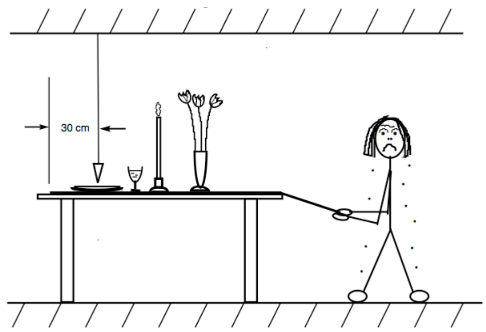
12. ***Uniform Acceleration***

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.]

Measure and Then Derive the Displacement of a Plate in the Tablecloth Slipout Trick: Dimensions And Limiting Conditions

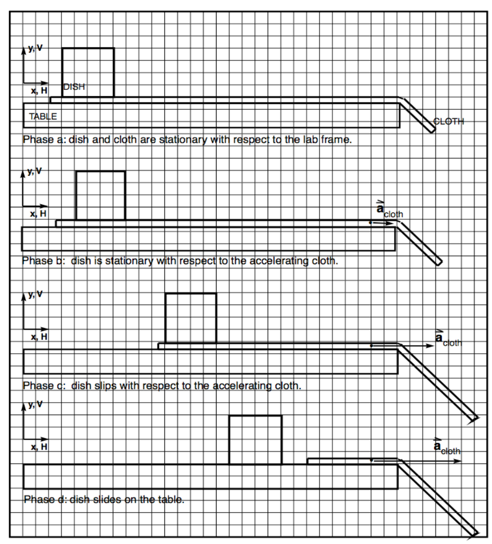
In SDI Lab #3 *Circular Motion And Frictional Forces,* students take turns performing the old "Tablecloth Slipout Trick":



A plumb bob hanging from the ceiling and centered on the plate allows measurement of displacement δ 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:

"Diagram the contact and action-at-a-distance vector forces $\mathbf{F}_{\text{on dish by X}}$ acting on the dish during the four phases of the motion: (a) dish & cloth stationary with respect to (wrt) the lab frame;(b) dish stationary wrt the accelerating cloth; (c) dish slips wrt the accelerating cloth: (d) dish slides on the table:



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 a dish just before and during the pull as indicated above. In the figure above show **ALL** the force vectors acting ON the dish during the four phases a, b, c, and d of the motion. Draw velocity and acceleration vectors (if they exist) for the dish.

Derive the following expression for δ:

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

In Eq. (1), g is the acceleration due to gravity; 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. [HINT: Use Newton's second law, $\mathbf{F}_{\text{net on body}} = m_{\text{body}}\, a_{\text{body}}$, to obtain accelerations in terms of μ and g for the phases b and c 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 dish is on the cloth and while the dish is on the table.

Is Eq. (1) physically reasonable? {Y, N, U, NOT} [HINT: Consider dimensions and the predicted magnitude of δ for both realistic and extreme limiting conditions.]"

Eq. (1) has been derived by Haber-Schaim & Dodge [14].

Has the SDI-Lab Attempt to Help Students Think Like Physicists Succeeded?

In "Achieving Wider Scientific Literacy," Arons [8, 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 defined; 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 [4, Table Ic) on the Force Concept Inventory [15, 16] suggests that the SDI-Lab attempt to help students think like physicists has been relatively successful.

REFERENCES

1. R.R. Hake, "Socratic Pedagogy in the Introductory physics Lab," *Phys. Teach.* **30**: 546-552 (1992); updated version (4/27/98) online at <http://bit.ly/9tSTdB>.
2. R.R Hake, "Design-Based Research in Physics Education Research: A Review," online at <http://bit.ly/9kORMZ>, in *Handbook of Design Research Methods in Education: Innovations in Science, Technology, Engineering, and Mathematics Learning and* Teaching, edited by Kelly, Lesh, & Baek, 2008. Routledge.
3. 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**(1): 64-74 (1998); online at <http://bit.ly/d16ne6>.
4. R.R. Hake, "Interactive- engagement methods in introductory mechanics courses" (1998), online at <http://bit.ly/aH2JQN>, a crucial companion paper to the preceding reference.
5. P. Black & 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>.
6. R.R. Hake, "The Socratic Method of the Historical Socrates, Plato's Socrates, and the Law School's Socrates"; online at <http://bit.ly/b5v58m>. Post of 21 Jun 2007 to AERA-L and other discussion lists.
7. R.R. Hake, "The Arons Advocated Method," submitted to the *Am. J. Phys.* on 24 April 2004; online at <http://bit.ly/boeQQt>.
8. A.B. Arons, *Teaching Introductory Physics*. Wiley, 1997.
9. G. Holton & S.G. Brush. *Physics the Human Adventure: From Copernicus to Einstein and Beyond.* Rutgers University Press, 2001.
10. D.C. Phillips, *Expanded Social Scientist's Bestiary: A Guide To Fabled Threats to, and Defenses of, Naturalistic Social Science*. Rowman & Littlefield, 2000.
11. P.A. Kirschner, J. Sweller, & 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," *Educational Psychologist* **41**(2): 75-86 (2006); online at <http://tinyurl.com/3xmp2m>.
12. R.R. Hake ,"Language Ambiguities in Education Research," submitted to the *Journal of Learning Sciences* on 21 August 2008; online at <http://bit.ly/bHTebD>.
13. S. Tobias & T.M. Duffy. *Constructivist Instruction: Success or Failure?* Routledge, 2009.
14. U. Haber-Schaim & J.H. Dodge, "There's More to It than Friction," *Phys. Teach.* **29**(1): 56-57 (1991).
15. D. Hestenes, M. Wells, & G. Swackhamer, "Force Concept Inventory," Phys. Teach. **30**: 141 (1992); online (but without the test itself) at <http://bit.ly/b1488v>.
16. I Halloun, R.R. Hake, E.P. Mosca, & D. Hestenes, "Force Concept Inventory, 1995 revision," online (password protected) at <http://bit.ly/b1488v>.