

Socratic Pedagogy in the Introductory Physics Laboratory*

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What I cannot create I do not understand. Richard Feynman

Let us visit the university physics lab of Fig. 1. Why are the instructors asking questions? Why are the students talking so much? Why are they engrossed in seemingly childish activities?

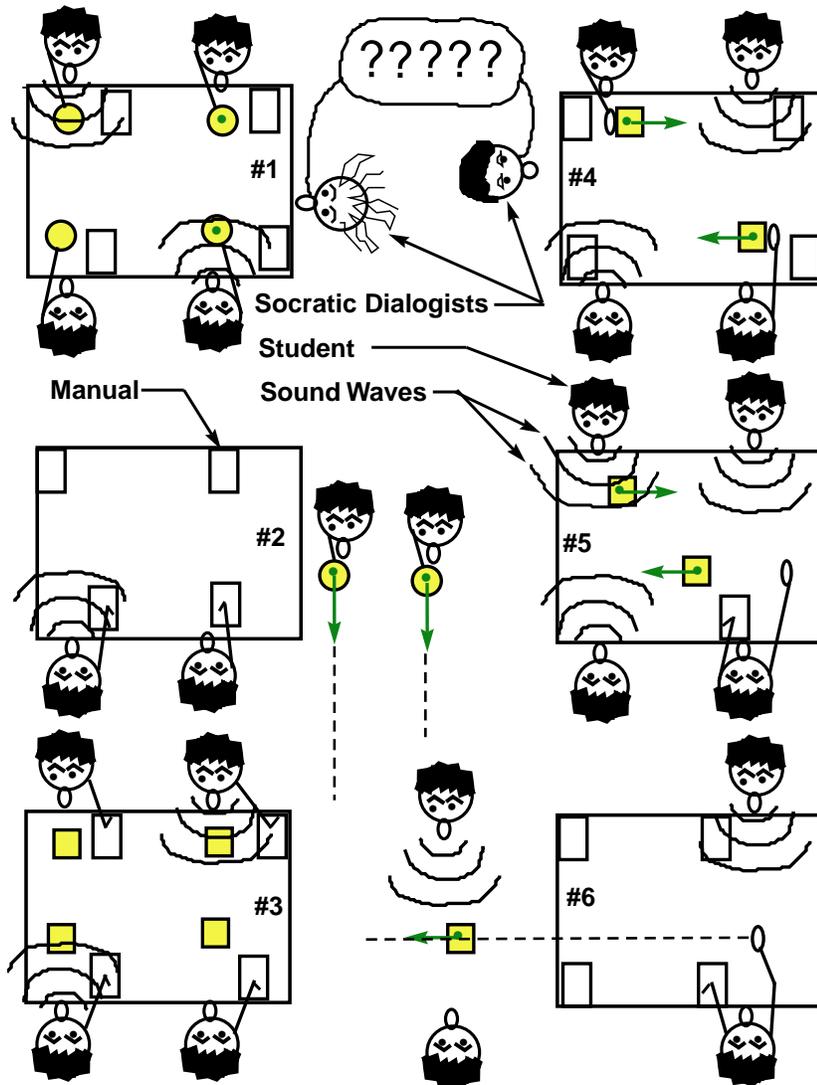


Fig. 1. Top view of a Socratic Dialogue Inducing (SDI) laboratory.
All depicted vectors are velocity vectors.

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The students are holding iron disks stationary in their hands, lifting the disks upward, carrying the disks across the room, pushing wooden blocks across the table, sliding blocks off the table into the air, observing a block which is slowing to a halt on the table:

"Look...there's a force in the forward direction because the block's moving in that direction!"

"Hey.....but the block's slowing down!"

"So what! Look-- here's the diagram-- the force's gotta be in this direction!! "

"But only the table's in contact with the block. A table can't push a block!"

"So what? I put some pushing power into the block when I started it off."

"Well, I'm really confused. Let's ask the prof for some help."

We observe that most of the students are still back with Aristotle or the medievalists, though they have been exposed to Newtonian mechanics for several weeks through text study, problem solving, lucid lectures, and exciting demonstrations. Furthermore, over 70% of them have completed a high-school physics course.^{6a,b}

Aside from exposing students' preconceptions, how can such elementary and non-analytical activities be of any value? Shouldn't someone just give these students the Newtonian "WORD"? Unfortunately, most research¹ has shown that the usual bombardment of passive students with a formidable flux of physics "factons," formulas, and problem-solving assignments fails to implant conceptual understanding, while there have been several recent studies^{2b,c; 3-8} demonstrating the relative success of active-engagement methods such as depicted in Fig. 1.

Several years ago I reported^{6a,b} that the use of Socratic pedagogy in university introductory physics laboratories appeared to be relatively effective in promoting student crossover to the Newtonian World as measured by pre- and post-course testing with the Halloun-Hestenes^{2a} exam of conceptual understanding of mechanics. Students' engagement in simple Newtonian experiments such as those of Fig. 1 produced conflict with their common-sense understanding and thereby induced collaborative discussion among them and/or Socratic dialogue with an instructor. Since that time I have continued to develop the Socratic Dialogue Inducing (SDI) lab method, extend its use to large-enrollment (100 - 400) classes, expand the lab coverage to a wider range of mechanics topics, collaborate in exporting SDI labs to other educational settings, and gather more test data.^{6c-e}

The test data are generally consistent with the earlier data^{6a,b} and will not be discussed here except to point out that in comparing the effectiveness of various introductory mechanics courses in promoting conceptual understanding, I have found it useful to plot the average pretest $\langle S_i \rangle$ to posttest $\langle S_f \rangle$ gain $\langle G \rangle \equiv (\langle S_f \rangle - \langle S_i \rangle)$ vs the average pretest score $\langle S_i \rangle$ on Halloun-Hestenes tests² of conceptual understanding, and to compare the effectiveness of various courses in promoting conceptual understanding in terms of an average normalized gain $\langle g \rangle = (\% \langle S_f \rangle - \% \langle S_i \rangle) / (100 - \% \langle S_i \rangle)$. Thus $\langle g \rangle$ is just the ratio of the actual average gain to the maximum possible average gain.

Over a ten-year period at Indiana University, SDI labs were integrated into courses in which lectures, discussions, and exams emphasized conceptual understanding and interactive engagement. Lectures usually employed a standard textbook and back-of-chapter problem assignments and, after 1993, included Concept Tests^{22a}; discussions were devoted to cooperative group problem solving with Socratic guidance. The courses enrolled a total of 1263 students (primarily pre-med and pre-health professionals) and achieved an average normalized gain on the conceptual Halloun-Hestenes tests of

$\langle g \rangle_{IU} = 0.60$ (see ref. 6e), considerably higher than the average gains of other courses considered in the survey of ref. 6d : $\langle g \rangle_T = 0.23$ for 14 traditional (T) courses, and $\langle g \rangle_{IE} = 0.47$ for 43 interactive engagement (IE) courses. The Hestenes-Wells Mechanics Baseline test^{2c} of problem solving was administered in two of the Indiana courses. The course-averaged score was 58%, close to the 62% for 11 other university IE courses of ref. 6e.

In this paper I describe SDI labs and procedures, give an example of a typical beginning SDI-lab-manual section and a representative Socratic dialogue, describe a few examples of recently developed lab experiments, and draw some conclusions.

I. WHAT IS AN SDI LAB?

SDI labs are inspired by the work of Arnold Arons,⁹ whose methods are, for the most part, empirically derived. Nevertheless, the Arons methods are consistent with much of the recent research in cognitive science,¹⁰ and some of the ideas of Socrates, Plato, Montaigne, Rousseau, Dewey, Whitehead, and Piaget. SDI labs emphasize hands-on experience with simple mechanics experiments and facilitate interactive engagement of students with course material. They are designed to promote students' mental construction of concepts through their (1) conceptual conflict, (2) kinesthetic involvement, (3) extensive verbal, written, pictorial, diagrammatic, graphical, and mathematical analysis of concrete Newtonian experiments, (4) repeated exposure to experiments at increasing levels of sophistication, (5) peer discussion, and (6) Socratic dialogue with instructors. The labs have been shown by pre/post testing^{6d,e} to be one of the more effective methods for enhancing students conceptual understanding of Newtonian mechanics. Among other advantages, SDI Labs:

- (a) are adaptable to a wide range of student populations [high school,¹¹ college,¹² university (science major,^{6a-e}; ¹³ physics major,¹³ engineering major-in-need-of-remediation,¹⁴ professor^{6b}),
- (b) diminish the impersonality of large-enrollment introductory classes,
- (c) are well received and popular^{6a,b;13;15} with students,
- (d) are inexpensive as far as equipment costs are concerned,
- (e) are easily modified^{11-14,16} to suit local conditions,
- (f) may be combined¹²⁻¹⁴ with other active engagement methods or combined¹³ with standard methods,
- (g) provide good training grounds for instructors who discover undreamed of learning problems when they "shut up and listen carefully to the response...(to a Socratic question)." (ref. 5a, p. 325).
- (h) set a good example of inquiry learning for prospective teachers,
- (i) can provide valuable research data on physics learning, particularly if dialogues and conversations are recorded and analyzed,^{22c}
- (j) are lots of fun for both students and instructors.

II. SDI LAB PROCEDURES

Questions are sometimes raised regarding the practicality of Socratic pedagogy in large-enrollment classes.¹⁷ Thus, it may be worthwhile to indicate the procedures which facilitate its application at Indiana University. At Indiana,⁶ SDI labs are one component of a five-credit-hour course which also includes large class-size lectures (100-400 students) and smaller class size (30-50 students) problem-solving discussions. There are normally 24 students (4 at each of 6 lab tables) and two Socratic dialogists in an SDI lab as shown in Fig. 1.

Students work through lab manuals, now available electronically.²⁹ These promote active involvement in concrete experiments which exemplify Newton's laws, construct "snapshot sketches," (i.e., time-sequential "force-motion-vector diagrams," Fig. 2), and write down answers to lab-manual questions. Manuals and experiments can be modified by instructors to suit local tastes or circumstances and considerable selectivity can be exercised since most manuals contain more material than can be adequately covered in two two-hour lab periods. SDI Labs 1 - 3 are on the "The Physics InfoMall."¹⁸ The electronic availability of manuals has the advantage that instructors with computers can easily copy, cut, paste, and delete so as to modify them to suit their own pedagogic styles, equipment, and curriculum.

A better understanding of the nature of the beginning lab activities (SDI Lab #1) can be obtained by considering the experiments^{6a} at the six lab tables of Fig. 1 in more detail:

- #1. Students (a) hold an iron disk (standard 1-kg lab mass) stationary in the hand, (b) lift it vertically upward at constant speed, (c) lift it vertically upward at a continuously increasing speed.
- #2. Students carry an iron disk at nearly constant speed in a nearly horizontal straight line (for a typical student's force-motion-vector diagram see Fig. 2).
- #3. Students consider a wooden block at rest on a table. (It helps to place a ball-and-spring model of the atomic structure of the table before the students.)
- #4. Students push blocks at nearly constant speeds in straight lines across the table. (It helps to place a photomicrograph of a solid surface before the students.)
- #5. Students give blocks initial pushes so that they slow to a stop on the table after leaving contact with the hand.
- #6. A student gives a block an initial push so that it slides across the table and is projected horizontally into the air while other students (after drawing their prediction of the path in their manuals) observe the path of the block through the air.

The primary ground rules for SDI labs are given below in italics more or less as they appear in the lab manual. [Explanatory paragraphs appear in parentheses].

1. The primary goal of SDI labs is to help you attain a good understanding of the basic concepts of Newtonian mechanics through creative engagement with simple mechanics experiments involving a body at rest or in motion as indicated in the lab manual. You will often be asked to predict the outcome of an experiment before you perform it. It is more important for you to understand the material you work on rather than to "cover" all the prescribed sections. You must take responsibility for your own learning. If you find yourself somewhat ahead of your lab partners why not try to explain some physics to them (explainers often learn more than listeners).

[We earlier^{6a,b} advised students to "proceed at your own pace," but we now believe that such advice is counterproductive in that some students consider "their own pace" to be near zero.].

[Many of the experiments have been selected from the literature¹⁹ as those for which common-sense understanding is contrary to the Newtonian viewpoint. Each student is urged to carry out all experiments for him or herself and not rely on simply observing the performance of other students.]

2. Draw "snapshot sketches" showing color-coded force (red), velocity (green), momentum (purple), and acceleration (orange) vectors for a BODY (yellow) at various "clock-readings." Except in end-on views, show Vector Tails as dots (\bullet) and always place them ON the BODY (VTOB) to which the vector applies. Label force vectors as, e.g., $\vec{\mathbf{F}}_{\text{on A by B}}$ where A is the BODY and B is some other interacting body. Use pencil (erasable) since you may wish to revise your work as the lab progresses and your ideas change. Work collaboratively with other students but the diagrams and commentary in your report should be your own work and not simply copied from the work of others. Show vertical and horizontal axes in each sketch (recall their operational definitions).

[Early SDI exercises emphasize operational interpretations of kinematic parameters.⁹ Using different colors²⁰ for force, velocity, and acceleration continually reminds the students that they are NOT all the same! In addition, the color and VTOB coding allow (1) unambiguous construction of single "force-motion-vector diagrams" (rather than separate²¹ force and motion diagrams) and (2) embedding of the standard "free-body diagram" in context so that motion constraints and TOUCHING bodies (see below) can more easily be kept in mind by beginners. Our experience indicates that both "1" and "2" facilitate the application of the extremely effective "Heller-Reif Strategy"²¹ for delineating and checking forces: students ask themselves (a) Are there any action-at-a-distance forces acting ON the body? (Usually only the Earth's gravitational force $\vec{\mathbf{W}}_{\text{on body by Earth}}$ acting vertically down is significant.) (b) Are there any contact forces acting ON the body? (Only objects which TOUCH the BODY (Study your diagram!) can exert contact forces on the body.) (c) If the vector summation of all forces acting ON the body yields a net force $\vec{\mathbf{F}}_{\text{net}}$, is there an acceleration \mathbf{a} in the direction of $\vec{\mathbf{F}}_{\text{net}}$ as required by Newton's second law $\vec{\mathbf{F}}_{\text{net}} = m_{\text{body}} \mathbf{a}_{\text{body}}$? (Study your diagram!) We find that SDI lab practice in the qualitative verbal and diagrammatic description of forces and motion is of great benefit in helping students to achieve more effective problem-solving skills.^{3,6,10]}

[The subscripting of $\vec{\mathbf{F}}$ reminds students that, in the Newtonian world, forces are always due to interactions between particles or systems of particles. It is emphasized that for most situations considered in elementary mechanics, the Newton's Third Law reaction to the force $\vec{\mathbf{F}}_{\text{on A by B}}$ is just $-\vec{\mathbf{F}}_{\text{on B by A}}$ (the "AB switch")].

3. Collaborate with fellow students to discuss and answer the lab-manual questions. You will often be asked to encircle one of the items {Yes, No, Uncertain, None of These}, abbreviated as {Y, N, U, NOT}. We insist that you always justify your response with a thoughtful explanation and/or sketch (one labeled sketch is often worth 10^{12} words).

[Our experience in monitoring collaborative discussion among students indicates that such interchange provides a remarkably effective learning experience,²² especially when discussion is guided to crucial conceptual matters by disequilibrating experiences.]

[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. 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 ref. 9a, p. 319).

[Many lab-manual questions probe for conceptual understanding through the students' reconciliation of their force-motion vector diagrams with kinematic principles and with Newton's Laws. (Both diagrammatic and mathematical formulations of Newton's Laws or models²³ derived therefrom are prominently displayed above each lab table to constantly emphasize the coherent Newtonian view and its unflinching consistency with the results of all SDI-lab experiments.) Some of the manual questions (see ref. 6a and "Some SDI Lab Experiments" below) introduce students to various effective strategies for scientific thinking and problem-solving and stress the physical interpretation of formulae.]

4. *If confused or uncertain (after serious effort and discussion with other students) call in a Socratic dialogist by inverting the HELP sign above your table.*

[Displaying the HELP sign allows students to continue their work while waiting for assistance. The dialogists move from table to table, both in response to "HELP" signs and to check student progress. We have found that it is very important to constantly monitor student performance so that difficulties can be diagnosed *as they occur* in the lab and not later on during the annotation of manuals (see "5" below). Effective dialogue requires considerable skill, knowledge, and experience. Ideally, the Socratic method involves questioning students in such a way that they are lead to express their ideas and figure things out for themselves. Instructors may at first fall short of this ideal, but generally improve with time. We recommend that at least one experienced Socratic dialogist be present at lab sessions to act as a second and role model for apprentice dialogists. We have found that top undergraduate physics majors are among the best (and least expensive) apprentices and allow the SDI lab method to be brought to the masses in a cost-effective manner.]

5. *Hand in lab manuals at the end of each lab period.*

[The manuals are annotated but not graded by the instructor. Instructors request the students to repeat deficient work or discuss confused responses at the next lab period. We have found that discussion of previous lab manual work *must usually be initiated by the instructors*, who need to keep careful records to be sure that all necessary discussions have been completed. The lab grade is determined by several written lab exams containing questions demanding a good conceptual understanding of experiments similar to those performed in the lab. Thus even those students who are concerned only with the course grade are motivated to understand the material.]

III. TYPICAL PERFORMANCE ON A TYPICAL BEGINNING LAB EXPERIMENT

An early section of SDI Lab Manual #1, Newton's First and Third Laws, is devoted to "Forces Exerted by Your Hand" (Fig.1, Tables #1, 2). In these experiments a relatively massive iron disk (a standard 1-kg laboratory mass) is used as the BODY to promote kinesthetic awareness. Because the disk is being modeled as a point particle, students are requested to place the tails of the force vectors on a point (later to be identified as the center of mass) near the center of the disk. After completing part A (a disk held stationary in the hand), part B (the disk lifted vertically upward at a constant speed), and C (the disk lifted vertically upward at a continuously increasing speed), the students consider the disk-carry experiment of part D (Fig.1, Table 2):

Holding a disk at about eye-level walk about 6 ft. (2m) at a nearly constant horizontal velocity \vec{v} (i.e., in a nearly straight horizontal line at constant speed). Sketch the disk and your hand while they are in motion at 3 positions: near the start, middle, and end of the constant \vec{v} motion. Show ALL the force vectors acting on the disk at these three positions. Draw velocity vectors at each of the three positions (here, again these are "snap-shot sketches" -- be sure to show the clocks!)

After each of the four students at a table has performed this experiment they discuss it and proceed to draw force-motion vector diagrams. With the course now in the second or third week, two of the students draw the diagrams correctly (perhaps only guessing or copying text or lecture diagrams with little understanding). Two of them with very deeply ingrained beliefs in "forces of motion" draw in their manuals the erroneous force-motion-vector diagram shown in Fig. 2 .

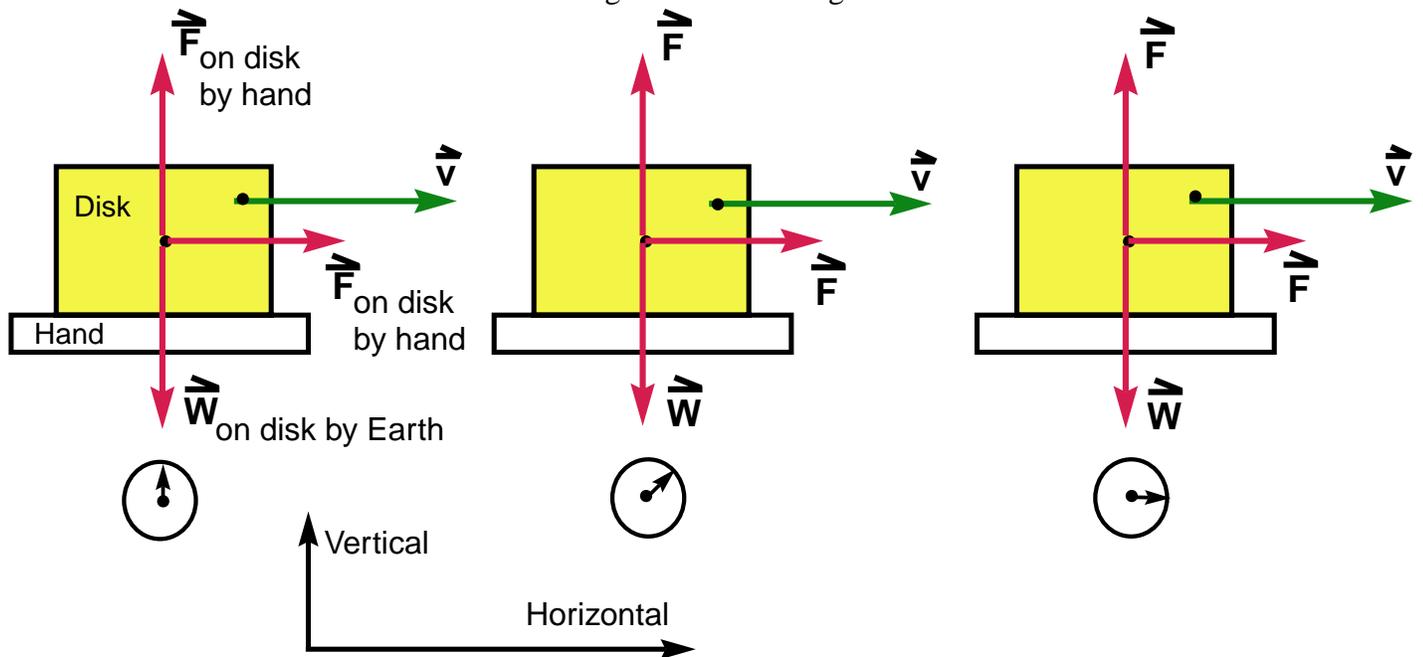


Fig. 2. Students' initial (erroneous) force-motion-vector diagram of the disk-carry experiment. The color-coding of vectors is in accord with that used by Giancoli, ref. 20a.

Discussions then continue as students think about the questions below and attempt to write down justifications of their encircled responses.

1. Is the disk sketched above in equilibrium? {Yes, No, Uncertain, None Of These "Y, N, U, NOT"}.
2. Is there a horizontal force vector acting on the disk? {Y, N, U, NOT}.
3. Is the force exerted on the disk by your hand equal and opposite to the force exerted on the disk by the Earth ? {Y, N, U, NOT} . Show a sketch! (This illustrates Newton's _____ Law.)
4. Is the force exerted on the disk by the Earth equal and opposite to the force exerted on the Earth by the disk? {Y, N, U, NOT}. Show a sketch! (This illustrates Newton's _____ Law.)
5. Is the force exerted on the disk by your hand equal and opposite to the force exerted on your hand by the disk? {Y, N, U, NOT}. Show a sketch! (This illustrates Newton's _____ Law.)

IV. A REPRESENTATIVE SOCRATIC DIALOGUE

In thinking about question 2 above, considerable uncertainty arises and the students call in a Socratic instructor, Fig. 3.

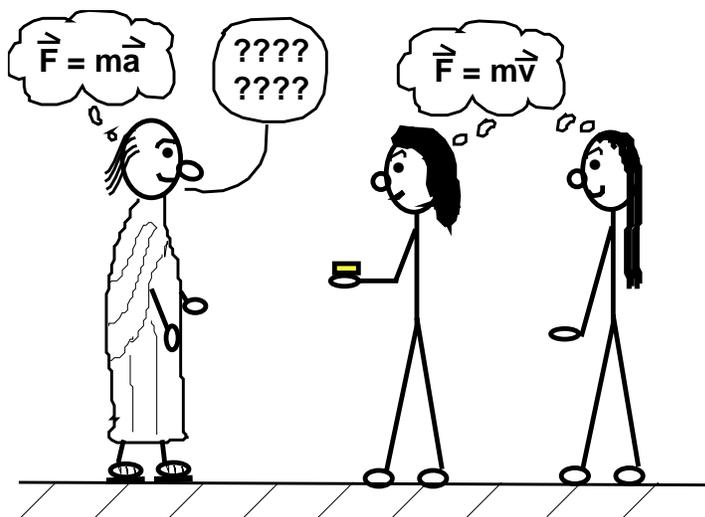


Fig. 3. A Socratic dialogue with two Aristotelian students.

The dialogue with the two overt force-of-motion students might typically run as follows:

Student 1: Our table can't agree on this but I think I have it right.

Socrates: *Why did you put a horizontal force vector on your sketches?*

Student 1: Because the disk is moving. If it's moving it's gotta have a force on it.

Socrates: *How is the disk moving?*

Student 2: Because we pushed on it.

Socrates: *Can you describe the motion?*

Student 2: Like it says: "in a straight line at a constant speed."

Socrates: *Did it feel as if you were exerting a horizontal force?*

Student 2: Not much -- I walked pretty slow.

Student 1: So did I.

Socrates: *Why, then, did you both draw horizontal force vectors as large as the vertical force vectors?*

Student 1: I guess that's wrong. Maybe it should be a tenth as big.

Student 2: I'd say more like a fifth.

Student 1: Anyway, pretty tiny..... but it's gotta be there, otherwise it wouldn't move.

Student 2: Yeah, that's right.

Socrates: *How fast did you walk?*

Student 2: Pretty slow.....um....um.....maybe.....uhh.....5 miles an hour.

Socrates: *So if you moved at 500 miles an hour?*

Student 2: Oh yeah.....we'd feel it then!!

Socrates: *Feel what?*

Student 2: The horizontal force on the disk.

Socrates: *You mean \vec{F} on disk by hand ?*

Student 2 : Hmm.....um....um.....Oh yeah.....

Student 1 : Well....ah.....What we'd feel is the reaction \vec{F} on hand by disk

Student 2:Yep.....That's it.

Socrates: GOOD! Have you flown in an airplane?

Student 1: Yeah.....Pretty fast.....um.....maybe 500 miles an hour.

Socrates: What does Newton's First Law say about that? Think about this and I'll return latter if you still need some assistance.

This might well be enough Socratic coaching to enable the four students at the table to construct a Newtonian understanding of the disk-carry experiment through collaborative discussion. If more assistance is required, the instructor might suggest that the students contrast the sensations of holding a disk when it is stationary, moving at constant horizontal velocity, and moving at an increasing horizontal velocity (as by suddenly thrusting the disk forward). Or if a return to the airplane example appears worthwhile, the instructor might ask the students to imagine themselves sitting on airplane seats. Do they recall feeling any horizontal force \vec{F} on student by seat as they moved at a constant horizontal velocity of 500 miles per hour in an airplane? How about when the airplane was increasing its speed down the runway just prior to takeoff? Would students feel a horizontal force \vec{F} on student by seat if they held a disk while sitting in an airplane with a 500 mph constant velocity? How about during takeoff?

If the dialogues get nowhere then it might be best for students to move on to latter sections of the lab where similar problems are considered in other contexts and then return to the above experiment.

V. SOME SDI LAB EXPERIMENTS

The nature of three of the more recently developed²⁴ SDI lab experiments is given below in abridged outline form. For brevity I do not explicitly include instructions (as shown in the above example) which require (a) time-sequential force-motion-vector diagraming (marked below by an asterisk*), and (b) thoughtful explanations, justifications, graphs, and/or sketches (not simply yes-or-no answers). Potential users should be cautioned that the present condensed descriptions may not be effective substitutes for the lab manual and teacher's guide material.²⁹

1. Water Bucket Swing ^{24a}

- Hold a bucket about half full of water inverted and stationary over your head.* (You may wish to do this as a "thought experiment.") Do you understand why the water does fall out of the bucket? (HINT: Consider Newton's Second Law and the definition of acceleration.)
- Same as "a" above but now swing the bucket rapidly in a vertical circle so that the bucket passes directly over your head.* Do you understand why the water does NOT fall out of the bucket? (HINT: Consider Newton's Second Law and the definition of acceleration.)
- Do you understand why the moon does not fall out of its orbit around the Earth?*
- Same as "b" above but now rotate the bucket at nearly constant tangential speed v such that the water is on the verge of spilling out of the bucket at its highest point over your head, Fig. 4.*

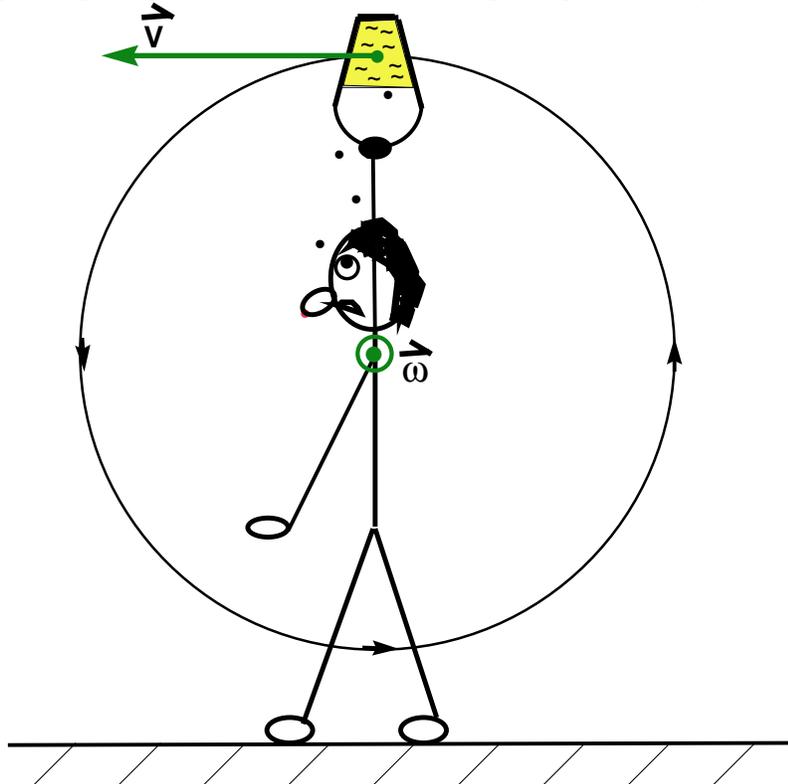


Fig. 4. The Water Bucket Swing.

- Can you derive an expression for this critical angular velocity ω_c ? Is your expression physically reasonable? (Is it dimensionally correct? Does it yield reasonable values for ω_c for both realistic and extreme limiting values of the other variables?)
- Time the period T for the motion of "d" above. Does your expression for ω_c give a value for T in reasonable agreement with experiment?
- In the force-motion vector drawing for "d" above show the bucket and the water at the bottom of the circular path and at two points midway between the top and bottom of the path.*
- Would it be possible to rotate the bucket in a vertical circle *at constant tangential speed* (hence constant $\vec{\omega}$) if the bucket were tied to a rope and the rope were pivoted about the center of the circle?

2. *The Old Spinning-Wheel-in-the-Suitcase Trick* ^{24b, 25}

R.W. Wood (famous American physicist, pioneer in physical optics, boomerang expert, legendary trickster, and author of the invaluable guide book *How to Tell the Birds from the Flowers*³⁰) sometimes carried a suitcase containing a spinning bicycle wheel. He would hand his suitcase to a porter with the instructions "Follow Me!" He would then walk rapidly through a door and make a sharp 90° turn, Fig. 5.

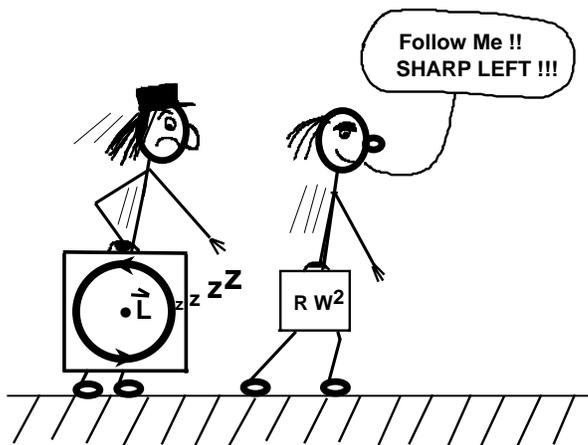


Fig. 5. The Old Spinning-Wheel-In-The-Suitcase Trick. R.W. Wood (RW²) leads a porter around a sharp turn.

a. Use a drill motor to rev up the wheel in such a suitcase and play the role of the porter. Notice the behavior of the suitcase when you make sharp turns first to the right and then to the left. Can you sketch front and top views of the wheel, the porter, the suitcase, and the ground at the instant the porter first applies a torque $\vec{\tau}$ on the suitcase grip so as to initiate a turn to the right or left? Can you show all $\vec{\tau}$, \vec{L} and $\Delta\vec{L}$ (\vec{L} is the angular momentum) vectors?* Can you predict what will happen to the suitcase during the turn? Try the experiment and record the results.

b. Sam Smart tried to out-torque the notorious R.W. Wood by disguising himself as a porter. When Wood handed Smart the spinning-wheel suitcase, Smart applied torques $\vec{\tau}_s$ to the suitcase so as to keep the suitcase vertical and follow Wood in tight turns either right or left. For the situation shown in "a" above, can you show the smart torque $\vec{\tau}_s$ applied by Smart for the turn you have indicated?* Pose as Smart, try the experiment, and record your results.

3. *The Cat Twist* ^{24b, 26}

a. Suppose that a cat is held upside down and stationary so that her initial angular momentum $\vec{L} = 0$ (see the snapshots of the cat twist in your manual). If she is then released a meter or so from the ground, she will rotate so as to land on her feet. It would appear that \vec{L} about the cat's center of mass (CM) must remain zero because there's no torque $\vec{\tau}$ about her CM due to the gravitational force \vec{F} on cat by Earth and air frictional effects are negligible. Study the snapshots. Can you explain how the cat manages to do a 180° twist? (Even the experts have some difficulty understanding how cats manage their twists and the cats aren't talking.) Fortunately, astronauts have discovered simple ways to perform cat twists--see below.)

b. Study the Skylab videotape. Can you explain the physics of the "Cat Twist" performed by the astronaut in the sequence "Initial Conditions: zero velocity, zero rotation"?

c. Can you perform a cat twist? Have two partners hold you upside down near the ceiling as in the the first cat snapshot and then release you. Or, if you prefer, simply stand on a low friction turntable, Fig. 6, and do a twist about a vertical axis. Have a partner steady you so that your initial $\vec{L} = 0$. Your diagram should explain the physics of your twist.

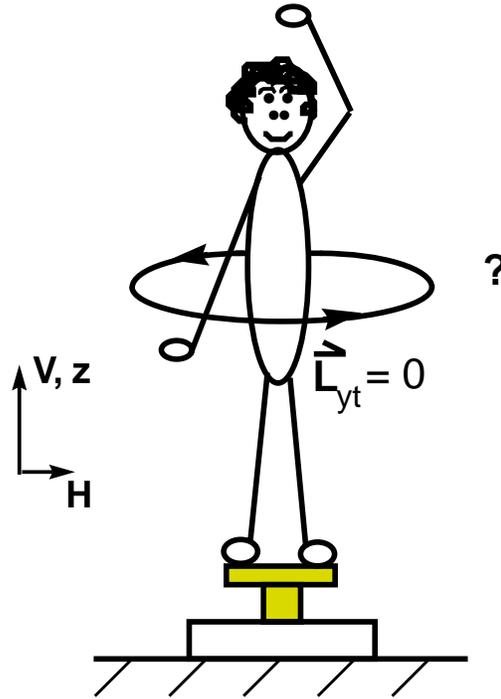


Fig. 6. The Cat Twist. \vec{L}_{yt} is the angular momentum of you plus the turntable about the z axis.

VI. CONCLUSIONS

SDI labs have been shown⁶ to be relatively effective in guiding students to construct a coherent conceptual understanding of Newtonian mechanics. The method might be characterized as "guided construction," rather than "guided discovery" or "inquiry." We think the efficacy of SDI labs is primarily due to the following essential features: (a) interactive engagement of students who are induced to think constructively about simple Newtonian experiments which produce conflict with their common-sense understandings, (b) the Socratic method⁹ utilized by experienced instructors who have a good understanding of the material and are aware of common student preconceptions and failings, (c) considerable interaction between students and instructor and thus a degree of individualized instruction, (d) extensive use of multiple representations (verbal, written, pictorial, diagrammatic, graphical, and mathematical) to model physical systems, (e) real world situations and kinesthetic sensations (which promote student interest and intensify cognitive conflict when students' direct sensory experience does not conform to their conceptions), (f) cooperative group effort and peer discussions, (g) repeated exposure to the coherent Newtonian explanation in many different contexts.

More research and development is needed to (1) more widely field test the SDI lab method and modify it for various instructional settings, possibly with the assistance of some of the readers of this article, (2) better understand the influence and relative importance of features (a-g) above and improve their effectiveness, (3) more fully systematize and develop the Socratic technique,⁹ especially through the analysis of recorded laboratory dialogues, and (4) move some of the instructional load to computers,^{27,28} and take advantage of the computer's unique ability to convey dynamic aspects of mechanics through real-time graphing of kinematic parameters^{4,8,12} and interactive "force-motion-vector animations."^{22d,28}

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References and Footnotes (minor updates on 4/27/98)

1. See, e.g., refs. 2-5 and references therein.
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15. R.R. Hake, student evaluations for non-calculus-based introductory physics classes of 90-120 students, all of whom took SDI labs at Indiana University in the Spring semesters of 1990-91, unpublished.
16. Steve Spicklemire, University of Indianapolis, private communication.
17. See, e.g., (a) C. Holbrow, "Physics in the classroom: How can we do better?", review of ref. 9a, *Phys.Today* **43**(12), 67 (1990); (b) R.R. Hake, "Socratic Pedagogy in Introductory Physics," *ibid.* **44** (9), 110 (1991).
18. R.G. Fuller, "Millikan Lecture 1992: Hypermedia and the knowing of physics: Standing upon the shoulders of giants," *Am. J. Phys.* **61**, 300-304 (1993). D. Zollman, "Millikan Lecture 1995: Do they just sit there? Reflections on helping students learn physics," *ibid.* **64**, 114-119 (1996); R.G. Fuller and D.A. Zollman, "Doing the Physics InfoMall: What the CD-ROM Developers Don't Tell You," *AAPT Announcer* **25** (4), 75 (1995). The InfoMall is now available commercially from The Learning Team, 84 Business Park Suite 307, Armonk, NY 10504, 1-800-793-8326.
19. For references to studies showing that common-sense understanding is contrary to the Newtonian viewpoint see ref. 6a.
20. With the advent of four-color printing, consistent color-coding of vectors [ref. 6 and D.L Goodstein and R.P. Olenick, "Making The Mechanical Universe'," *Am. J. Phys.* **56**, 779 (1988)] is now penetrating into standard introductory physics texts, e.g., (a) D.C. Giancoli, *Physics* (third ed.) 1991; (b) R.A. Serway and J.S. Faughn, *College Physics* (third ed.) 1992; (c) P.M. Fishbane, S. Gasiorowicz, and S.T. Thornton, *Physics* (1993), (d) P.J. Nolan, *Physics* (1993). Unfortunately, among authors there is little uniformity in the coding. We recommend that until a uniform color code is adopted, the SDI-lab color code be shifted to substantially agree with that of the text being used in the course.
21. J.I. Heller and F. Reif, "Prescribing Effective Human Problem-Solving Processes: Problem Description in Physics," *Cognition and Instruction* **1**, 177 (1984).
22. (a) Tests demonstrating the effectiveness of peer discussions during lecture periods at Harvard have been carried out by E. Mazur, as indicated in ref. 2c and in E. Mazur, *Peer Instruction: A User's Manual* (Prentice Hall, 1997, also available at <<http://galileo.harvard.edu/>>). (b) For a discussion of Mazur's methods, see S. Tobias, *Revitalizing Undergraduate Science* (Research Corporation, 1992), Chap. 8, "Students Teaching Students, Harvard Revisited." (c) Videotape evidence of the effectiveness of collaborative learning as stimulated by disequilibrating experiences and Socratic-dialogues during SDI labs has been shown by (1) A. Bhattacharyya, R.R. Hake, R. Sirochman, "Improving Socratic Dialogue Inducing (SDI) Labs," *AAPT Announcer* **25**(2), 80 (1995); (2) R.R. Hake and R. Bird, "Why Doesn't The Water Fall Out Of The Bucket? Concept Construction Through Experiment, Discussion, Drawing, Dialogue, Writing, and Animations," *ibid.* **25**(2), 70 (1995).
23. D. Hestenes, (a) "Toward a modeling theory of instruction," *Am J. Phys.* **55**, 440 (1987); (b) "Modeling games in the Newtonian World," *Am. J. Phys.* **60**, 732 (1992).

24. R.R. Hake, (a) "A Socratic-Dialogue-Inducing Lab on Circular Motion and Frictional Forces," *AAPT Announcer* **21**(2), 95 (1991); (b) "A Socratic-Dialogue-Inducing Lab on Angular Momentum," *ibid.* **20**(4), 53 (1990); (c) "A Socratic-Dialogue-Inducing Lab on Rotational Dynamics," *ibid.* **21**(4), 58(1991); (d) R.R. Hake and R. Wakeland, "What's F? What's m, What's a?: A Non-Circular SDI-TST Lab Treatment of Newton's Second Law," *Conference on the Introductory Physics Course*, Jack Wilson, ed. (Wiley, 1997), p. 277.
25. J.F. Koser, "The Suitcase Gyroscope – An Angular Momentum Device," *Phys. Teach.* **25**, 231 (1987).
26. C. Frohlich, "The physics of somersaulting and twisting," *Sci. Am.* **242**(3), 154 (1980). For excellent snapshots of a cat twist by Stephen Dalton see ref. 20c, p. 312. "Skylab Physics" is available on both videodisk and videotape from the AAPT, Publication Sales, 5112 Berwyn R., College Park MD 20740 (301-345-4200).
27. A.B. Arons, "Computer-based instructional dialogues in science courses," *Science* **224**, 1051(1984).
28. R.B. Bird, B. Wildasin, and R.R. Hake, "Socratic-Dialogue-Graphical Computer Tutorials on the NeXT Workstation," *AAPT Announcer* **21**(4), 57 (1991). R. Bird and R.R. Hake, "Force- Motion-Vector Animations on NeXTSTEP," *ibid.*, **23** (2), 64 (1993). R. Bird and R.R. Hake, "Force Motion Vector Animations on the Power Mac," *ibid.* **25**(2), 80 (1995). Animations written by Randall Bird for SDI Labs (currently running only on Power Macs) are available by request to R. Hake <hake@ix.netcom.com>: (a) Trajectory (SDI Labs #1 and #2), (b) Pendulum (SDI Lab #2), (c) Conical Pendulum (SDI Lab #3), (f) Bucket (SDI Lab #3).
29. Nine lab manuals have now been written and are available electronically as Adobe Acrobat portable document files downloadable at <<http://carini.physics.indiana.edu/SDI/>> and also at <<http://galileo.harvard.edu/>> under Hands-on Methods/SDI Labs/Resources:
- #0.1 - Frames of Reference, Position, and Vectors (with Ground Rules), 27 pages, 77 kB;
 - #0.2 - Introduction to Kinematics*, 26 pages, 55 kB;
 - #1 - Newton's First and Third Laws*, 51 pages, 220 kB;
 - #2 - Prelab Assignment on Operational Definitions*, 8 pages, 22 kB;
 - #2 - Newton's Second Law*, 44 pages, 231 kB;
 - #3 - Circular Motion and Frictional Forces*, 57 pages, 506 kB;
 - #4 - Rotational Dynamics*, 26 pages, 198 kB;
 - #5 - Angular Momentum, 47 pages, 275 kB;
 - #6 - Newtons Second Law Revisited*, 17 pages, 165 kB;
 - #7 - Newton's Laws Revisited, 11 pages, 33 kB.
- An asterisk * means that a Teacher's Guide is currently available; electronic versions of some guides can be downloaded at the Galileo site (see above).
30. R.W. Wood, *How to Tell the Birds from the Flowers* (Dover, NY, 1959; first published in 1917).

BIOGRAPHY (at p. 546 of article in *The Physics Teacher*)

After receiving a Ph.D in physics from the University of Illinois in 1955, Richard Hake was a researcher at North American Aviation and then became a professor of physics at Indiana University in 1970. An early investigator of high-magnetic-field and Type-II superconductivity, he has published over 60 papers in condensed-matter physics. In 1980 he was stunned by the failure of the traditional TRAnsmiission to Passive Target (TRAPT) method of physics instruction when he discovered that his brilliant lectures and thrilling demonstrations passed through the minds of prospective elementary teachers leaving no measurable trace. Similar results were then obtained for science majors when confronted with conceptually oriented questions. Still stunned, for the past seven years he has been engaged in a research and development program at Indiana to improve introductory physics education.