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Richard R. Hake

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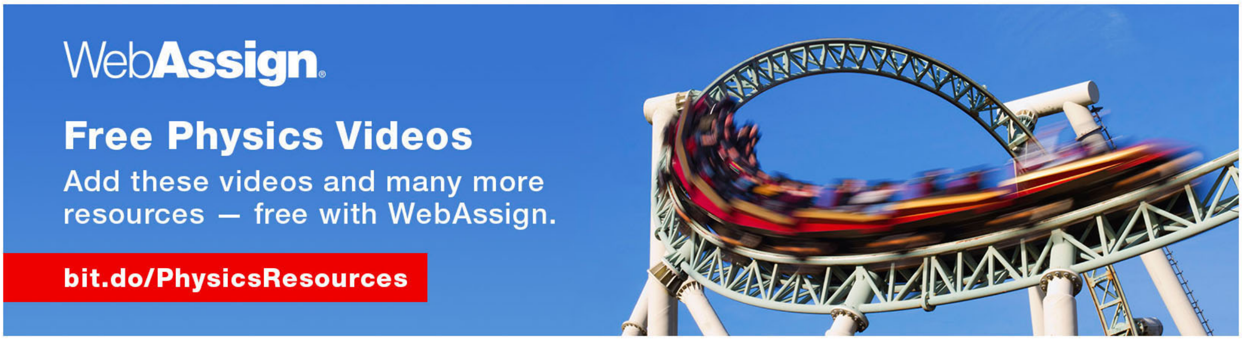
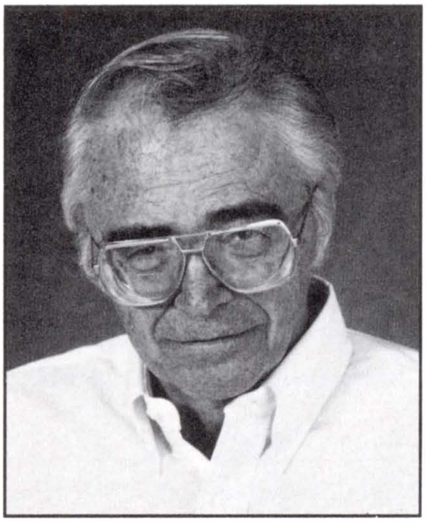


Socratic Pedagogy in the Introductory Physics Laboratory

By Richard R. Hake

What I cannot create I do not understand.
Richard Feynman



Richard Hake, *after receiving a Ph.D. in physics from the University of Illinois in 1955, was a researcher at North American Aviation and then became a professor of physics at Indiana University (Physics Department, Bloomington, IN 47405) in 1970. An early investigator of high-magnetic-field and Type-II superconducitivity, he has published over 60 papers in condensed-matter physics. In 1980 he was stunned by the failure of the traditional TRAnsmission to Passive Target (TRAPT) method of physics instruction when he discovered that his brilliant lectures and thrilling demonstrations passed though 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.*

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?

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 that 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 is slowing down!"

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

"But only the table is 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.

Aside from exposing students' preconceptions, how can such elementary and nonanalytical activities be of any value? Shouldn't someone just give these students the Newtonian "word"? Unfortunately, most research[1] 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[6] 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 commonsense understanding and thereby *induced* collaborative discussion among themselves 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 (90 to 120) 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. The latter are generally consistent with the earlier data[6] and will not be discussed here.

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.

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) extensive verbal, written, pictorial, diagrammatic, graphical, and mathematical analysis of concrete Newtonian experiments, (3) repeated exposure to experiments at increasing levels of sophistication, (4) peer discussion, and (5) Socratic dialogue with instructors.

Aside from the strictly cognitive issues, other advantages of SDI labs are: they (1) are adaptable to a wide range of student populations [high school,[11] college,[12] university (science major,[6,13] physics major,[13] engineering major-in-need-of-remediation,[14] professor[6b])], (2) are well received and popular[6,13,15] with students, (3) are inexpensive as far as equipment costs are concerned, (4) are easily modified[11-14,16] to suit local conditions, (5) may be combined[12-14] with other active engagement methods or combined[13] with standard methods, (6) provide good training grounds for instructors who discover undreamed of learning problems when they *shut up and listen to students,* (7) set a good example of inquiry learning for prospective teachers, (8) diminish the impersonality of large-enrollment introductory classes, (9) can provide valuable research data on physics learning, particularly if dialogues and conversations are recorded and analyzed, and (10) are lots of fun for both students and instructors.

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 that 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 (100–250 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.

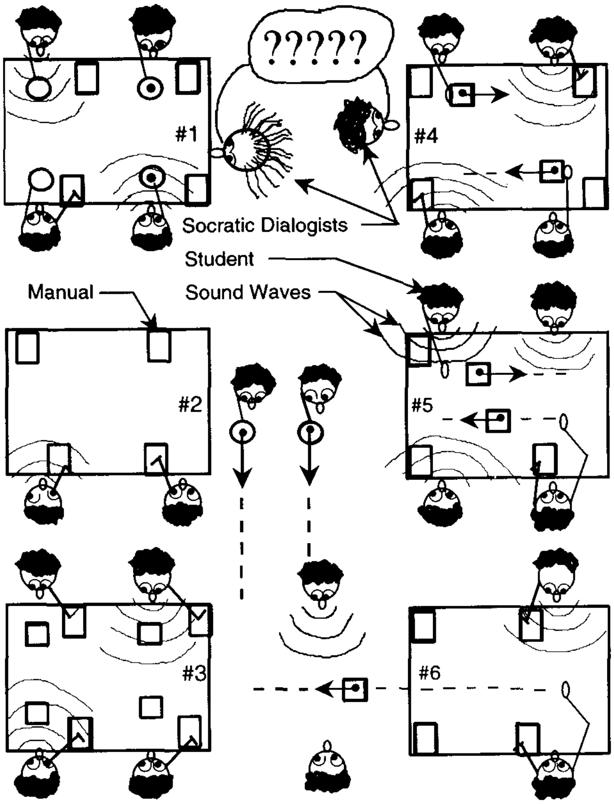


Fig. 1. Top view of a Socratic Dialogue Inducing (SDI) laboratory. All depicted vectors are velocity vectors.

Students work through lab manuals. These promote active involvement in concrete experiments that 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. A better understanding of the nature of the beginning lab activities 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.

Five lab manuals along with instructor's guides have now been written: #1—Newton's First and Third Laws, #2—Newton's Second Law, #3—Circular Motion and Frictional Forces, #4—Rotational Dynamics, and #5—Angular Momentum. These provide blank quadrille-ruled spaces for student sketches and answers and average about 30 pages in length. Manuals and experiments can be modified by instructors to suit local tastes or circumstances and considerable selectivity can be exercised since four of the manuals each contain more material than can be adequately covered in two two-hour lab periods. A sample manual and guide are available upon request. Labs #1 and #3 have been accepted for inclusion in the "Physics Teachers CD-ROM Toolkit."[18]

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 brackets.)

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. You should proceed at your own pace. 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).*

[Many of the experiments have been selected from literature[19] as those for which commonsense understanding is contrary to the Newtonian viewpoint. Each student is urged to carry out all experiments individually and not rely on simply observing the performance of other students.]

2. *Draw "snapshot sketches" showing color-coded force (red), velocity (blue), momentum (brown), and acceleration (green) vectors for a BODY (yellow) at various "clock-readings." Except in end-on views, show Vector Tails as dots(•) and always place them ON the BODY (VTOB) to which the vector applies. Label force vectors as e.g.,* $\vec{F}_{on\ A\ by\ B}$ *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 kinematics parameters.[9] Using different colors[20] 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 separate[21] 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 $\vec{W}_{on\ body\ by\ Earth}$ acting vertically down is significant.) (b) *Are there any contact forces acting ON the body?* Only objects that 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 $\vec{F}_{net}$, is there an acceleration $\vec{a}$ in the direction of $\vec{F}_{net}$ as required by Newton's second law $\vec{F}_{net} = m\vec{a}$? (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 achieve more effective problem-solving skills.[3,6,10]]

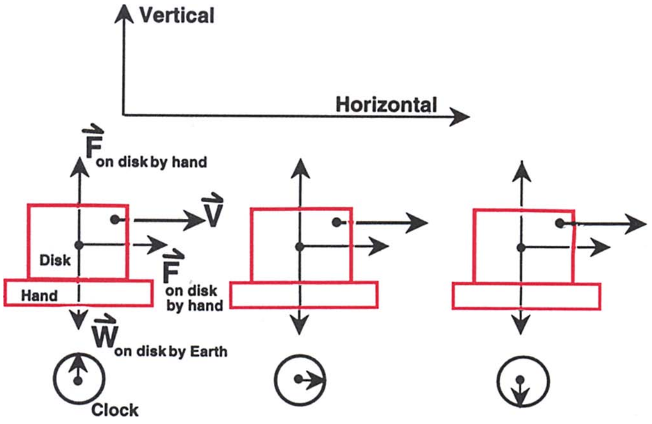


Fig. 2. Students' initial (erroneous) force-motion-vector diagram of the disk-carry experiment.

[The subscripting of $\vec{F}$ 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, Newton's third law reaction to the force $\vec{F}_{on\ A\ by\ B}$ is just $-\vec{F}_{on\ B\ by\ A}$ (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.]

[Many lab-manual questions probe for conceptual understanding through the students' reconciliation of their force-motion-vector diagrams with kinematics principles and with Newton's laws. (Both diagrammatic and mathematical formulations of Newton's laws or *models*[23] derived therefrom are prominently displayed above each lab table to constantly emphasize the coherent Newtonian view and its unfailing consistency with the results of all SDI-lab experiments.) Some of the manual questions (see Ref. 6a and "Some SDI Lab Experiments" that follow here) introduce students to various strategies of experimental and theoretical physics and stress the physical interpretation of formulas.]

4. If confused or uncertain (after serious effort and discussion with other students) call in a Socratic dialogist.

[The dialogist moves from table to table in response to requests, asking questions so as to put the students on the right track before moving to another group. Effective dialogue requires considerable skill, knowledge, and experience. We recommend that at least one experienced Socratic dialogist be present at lab sessions to act as a second and role model for beginning instructors.]

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. 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.]

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" (see Tables #1 and #2 of Fig. 1). 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 (see Table #2 of Fig. 1):

Holding a disk at about eye level, walk about 6 ft (2 m) at 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.

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.)

A Representative Socratic Dialogue

In thinking about question 2 above, considerable uncertainty arises and the students call in a Socratic instructor, Fig. 3. 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...umm...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 $F_{\textit{on disk by hand}}$*?*

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

Student 1: Well...ah...What *we'd* feel is the reaction $F_{\textit{on hand by disk}}$

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

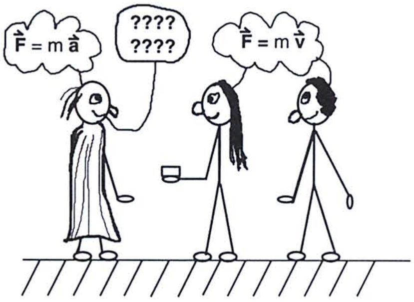


Fig. 3. A Socratic dialogue with two Aristotelian students.

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 later 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 $\vec{F}_{\textit{on student by seat}}$ 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 $\vec{F}_{\textit{on hand by disk}}$ 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 later sections of the lab where similar problems are considered in other contexts and then return to the horizontal-force experiment.

> "R.W. Wood (famous American physicist, pioneer in physical optics, boomerang expert, legendary trickster...) sometimes carried a suitcase containing a spinning bicycle wheel."

Some SDI Lab Experiments

The nature of three of the more recently developed[24] SDI lab experiments is given here in abridged outline form. For brevity I do not explicitly include instructions (as shown in the above example) that require (a) time-sequential force-motion-vector diagramming (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.

1. *Water Bucket Swing*[24a]

a. 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.)

b. 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.)

c. Do you understand why the Moon does not fall out of its orbit around the Earth?*

d. Same as "b" above but now rotate the bucket at *nearly constant tangential speed* v so that the water is on the verge of spilling out of the bucket at its highest point over your head, Fig. 4.*

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?)

e. 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?

f. 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.*

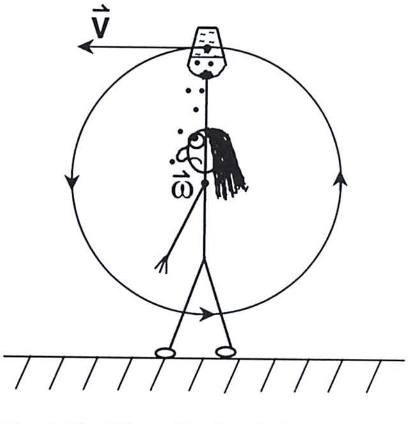


Fig. 4. The Water Bucket Swing.

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[19]) 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).

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 that situation, 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.

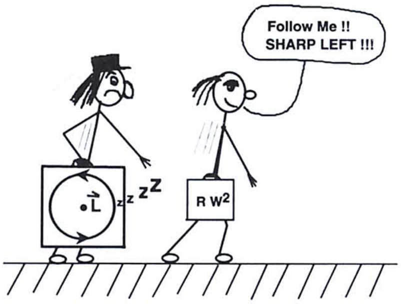


Fig. 5. The Old Spinning-Wheel-In-The Suitcase Trick. R.W. Wood (RW^2) leads a porter around a sharp turn.

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 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.

"Can you perform a cat twist? Have two partners hold you upside down near the ceiling (as in the first cat snapshot) and then release you."

Conclusions

SDI labs have been shown[6] 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 that produce conflict with their common-sense understandings, (b) the *Socratic method*[9] 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

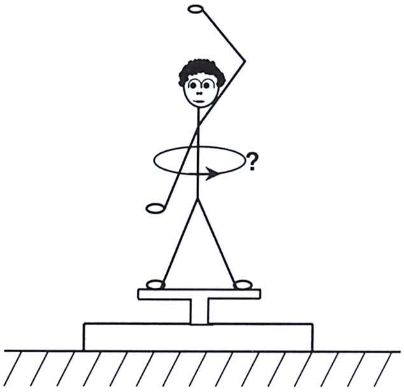


Fig. 6. The Cat Twist.

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."[28]

Acknowledgments

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11. J. Inman, Edgewood High School, Elletsville, Indiana; private communication.
12. N.C. Steph, "Improving the instructional laboratory with TST and SDI labs: Mixing, matching, and modifying ideas," *AAPT Announcer* **21** (4), 61 (1991); Jack Uretsky, College of DuPage, private communication. Uretsky has combined SDI labs with an engineering physics course using *The Mechanical Universe* text and video sequence.
13. R. Wakeland, Indiana University Physics Lab Coordinator, private communication. Wakeland has employed SDI Lab #1 in classes for physics majors and has recently extended its use to a 400-student P201 class for science (but not physics) majors. The latter class is also making use of the Thornton-Sokoloff (Ref. 4) "Tools for Scientific Thinking."
14. A. Van Heuvelen, New Mexico State University, private communication. Van Heuvelen has successfully utilized SDI labs in an informal manner during lecture periods in a remedial bridging (interface) course for engineers (22 students).
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.
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