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Abstract
We discuss a three-hour laboratory that is a microcosm of physics research, starting with the discovery of an intriguing phenomenon, and including participation in "research conferences" and the interplay of theory and experiment. Students are given a small segment of PVC pipe marked at opposite ends with different symbols and asked to observe what happens when the pipe is placed on a horizontal surface and one end is pushed downward by a finger to initiate a rotation. Most students immediately recognize that the symbol at one end is visible while the other is not, and set about trying to understand why. Students initially work in pairs and are provided with opportunities to request equipment from a "granting agency" and conferences and collaborations are encouraged. Students are quickly caught up in their search for explanations, usually culminating in a full-class effort with significant contributions coming from all students.

Keywords
scientific experimentation, physics experiments, research laboratories, microcosm and macrocosm

Disciplines
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Comments

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Spinning tubes: An authentic research experience in a three-hour laboratory

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We discuss a three-hour laboratory that is a microcosm of physics research, starting with the discovery of an intriguing phenomenon, and including participation in "research conferences" and the interplay of theory and experiment. Students are given a small segment of PVC pipe marked at opposite ends with different symbols and asked to observe what happens when the pipe is placed on a horizontal surface and one end is pushed downward by a finger to initiate a rotation. Most students immediately recognize that the symbol at one end is visible while the other is not, and set about trying to understand why. Students initially work in pairs and are provided with opportunities to request equipment from a "granting agency" and conferences and collaborations are encouraged. Students are quickly caught up in their search for explanations, usually culminating in a full-class effort with significant contributions coming from all students.

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I. SCIENTIFIC RESEARCH IN THE FIRST YEAR LABORATORY

We describe in this paper an activity that can be used in the latter portion of the first semester physics course to allow students to participate in the excitement of scientific research in a single three-hour laboratory period. This laboratory allows students to experience the scientific method and goes beyond the oversimplified version of forming, testing, and accepting or rejecting a hypothesis toward a more nuanced and rich approach.

II. INTRODUCTION TO THE ACTIVITY

Before doing the experiment, students read a two-page handout[1] summarizing the approach, particularly how equipment will be requested, that conferences will be held, and that collaborations will be allowed to evolve. At the beginning of the laboratory period, the instructor reviews these points and distributes one tube (see Fig. 1) to each group of two or three students. The tube is placed horizontally on a hard surface and then projected forward by pressing down and back at one of its ends (see Fig. 2), "squirting" it out so that it is both spinning and rotating.[2,3] After a successful launch, most students observe that even though there are two (different) symbols on opposite ends of the same side of the tube, only one symbol is visible during the motion (see Fig. 3). After some careful observations, it is noticed that the visible symbol is the one at the end of the tube that was pressed with the finger to launch it. Some students will notice that there are four visible copies of the symbol, and some notice that this number is the ratio of the tube's length and diameter. Most students focus on the mystery surrounding the symbols' visibility and invisibility, and a few try to explain the overall motion and how it results from the launching.

Reference 4 describes the physics of the spinning tube in some detail, as do some websites.[5] In this paper we discuss a novel use of the phenomenon in the introductory physics laboratory for purposes beyond rotational dynamics. Its unique combination of "fun factor," obviousness, and trickiness draws students into a readily perceived phenomenon and yet does not lend itself to a quick explanation.

III. EQUIPMENT LOANS

For most physics laboratory problems a list of equipment is given. In this laboratory the only equipment provided is the cylinder, which are made of PVC plumbing pipe and are available at most hardware stores in 8 or 10 ft lengths. Tubes of $\frac{3}{4}$ inch outer diameter work very well, but other diameters should also be obtained. Before cutting the pipe into segments, remove any printing by cleaning the pipe mechanically or chemically.[6] The tube lengths should be an integer multiple of the tube diameter.[7] A ratio of 4 works best, but ratios from 3 to 8 also function well. If the tubes are too long or too short, they are too difficult to launch or the phenomenon is too difficult to see. The pipes can be cut with a hacksaw, but because getting a nice square cut is important and a large collection is needed, a table saw and jig are helpful. Rough ends can be smoothed with sandpaper, and the X and O symbols are drawn with permanent markers.

For other equipment, we implement an equipment loan system, which simulates the grant process in scientific research. Students are given the opportunity to submit proposals for equipment that will help them investigate specific features of the phenomenon of interest. This process encourages students to think carefully about experimental design and to formulate their hypotheses. Students prepare their proposals in writing and present them orally to the laboratory instructor. Any equipment, besides the original tube, should be requested, including minor things such as markers and

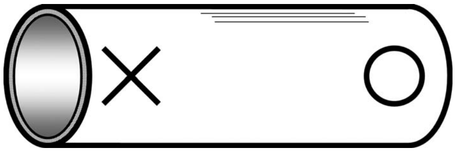

Fig. 1. A diagram of the cylinder made from the PVC pipe. Its outside diameter is $\frac{3}{4}$ in. and its length is 3 in.

rulers. Although many students would like to use a high-speed camera to study the motion, it is more educational to use simple equipment. To encourage creativity, it is advisable to have this equipment in an adjoining room rather than visibly available. If this laboratory activity is done near the end of the first semester, students will have seen some equipment in use in the laboratory and in lecture demonstrations.

Variations of the granting scheme are possible. Student teams may be given tokens (for example, washers) as start-up funds to spend on items on an available equipment list during the initial investigatory phase. Following this initial phase, all equipment is obtained by verbal grant proposals. They may ask for specific equipment or be more broadly funded by indicating the general ideas they are pursuing, and decide on how to spend their funds as their research evolves. One might then not limit the use of high-priced equipment such as cameras (which can be "rented" if supply is limited). Being more costly does not necessarily mean being effective, as students often find out when spending precious tokens on a flash camera that does not reveal much of value.

Equipment typically requested by students include a strobe light to "freeze" the motion; students can verify that both the X and O remain on the same side of the tube, and also that only the end of the tube opposite the launching end actually remains in contact with the surface. By using tubes of different lengths and/or diameters, students observe that a different number of symbols is seen for longer tubes and perhaps begin to notice the importance of a certain ratio of length to diameter if they measure the length and diameter with a ruler. By using a transparent tube, students will notice that both symbols are visible. This use, together with spinning the tube on a Plexiglas sheet, which shows that viewing from below allows the opposite symbol to appear, might lead them to determine an important symmetry of the situation. Markers of different colors can be used to explore the effect of placement of the symbol on the tube. A protractor might be used to measure the angle between the tube and the table (although this measurement will be useful only in an advanced analysis of the tube's highest-speed motion). Rubber bands wrapped around one or both ends might help explore whether the friction is static or kinetic. Inserting some putty will change the location of the center of mass.

Fig. 2. The tube is launched by pressing down with an index finger and pulling back a little at one end. It will shoot forward about 0.5 m and then undergo a spin/rotation combination at that point. See the supplementary material for a video demonstration of the launch and the subsequent motion.

Fig. 3. A time exposure of spinning and rotating tube confirms what is seen by eye, namely, that only one out of the two symbols is visible. (The diameter of the circle in the figure is essentially the tube length.) This photograph results from launching the tube from the "X" end, as shown in Fig. 2.

IV. STUDENT COOPERATION

Student cooperation is important in most physics laboratories, but in this research simulation, it is a crucial feature. This feature highlights the fact that science is a cultural activity, with its intrinsically human interaction, creativity, and judgment. Students are asked to start working in pairs (or their normal laboratory groupings), and the laboratory instructor should facilitate the first "research conference" after about 45 minutes. At this time, there will be a wide variety among the students in terms of progress and approach. During the conference, students share with the whole class what they have learned so far, their methods, and the kinds of questions they still have. In this way students have an excellent opportunity to learn from each other, to challenge and complement one another's ideas and results, to be stimulated into different lines of inquiry, and to verify the results of others.

In the conferences, the laboratory instructor can move beyond simply facilitating and commenting on the process of science to suggesting issues that students didn't think of, perhaps playing the role of the skeptic who asks probing questions at scientific meetings. For example, in rooms with fluorescent lights one might raise concerns about stroboscopic effects. This effect can be left up to students to probe if they wish and can generate discussion on whether this effect is relevant and prompt ideas for experiments such as using incandescent lights and strobe lights. The first conference is also a good time to ask if the apparent position of the symbols appears fixed in orientation. This question sometimes leads perceptive students to think of changing the length/diameter ratio.

After the first conference, students should be encouraged to evolve their collaborations in whatever ways seem natural and beneficial. There will be migration of students between research groups, some mergers, as well as friendly competition. We have found that after two or three conferences, held

30–45 minutes apart, a significant interplay of ideas results; often large groups form, perhaps consisting of the entire class, with two or three leaders emerging.

V. PHYSICAL PRINCIPLES INVOLVED

It is advisable for the laboratory instructor not to provide any verification or rejection of the students' hypotheses or theories during or even at the end of the period. In research there is no consultant available to give advice or adjudication, and science never reaches full explanatory closure. The scientific community (the class) is the arbiter of scientific truth using empirical and other means to judge theories. This approach provides a realistic research experience for the students. With this in mind, students' questions can be addressed in a later class period, which might help advance their understanding of the phenomenon. If this laboratory activity is later repeated with different groups of students, care should be taken to not allow a future set of students to take advantage of a previous group's findings or of the instructor's explanation. This point is worthwhile making to the students, along the lines of them not sharing "inside information." Therefore, this article should not be mentioned or provided to students.

The main physical principles involved in the phenomenon of the spinning tube are those with which students will be somewhat familiar near the end of the mechanics portion of the introductory physics sequence, in either calculus- or algebra-based physics. However, a full explanation is not a requirement for success; even without fully understanding the physics involved, students develop descriptive models and can appreciate much about the process of science.

The motion of the tube immediately after launching involves kinetic friction, which limits the tube from continuing to move away from its launch point. Static friction quickly replaces kinetic friction as one end of the tube begins to roll on the surface, tracing out a circle whose diameter is initially a little smaller than the length of the tube. As the tube settles down onto the table due to air resistance and rolling friction, this circle's diameter approaches the cylinder's length. The velocity of any point on the tube is found from the addition of velocities: the velocity due to the cylinder's spin about its axis plus the velocity due to its rotation about a vertical axis running through the center of the circle it traces out. Due to the rolling motion, the velocity of the part of the tube in contact with the table is zero, as is the velocity of the highest point (the opposite side of the tube at the opposite end), which, by symmetry, rolls on an imaginary circle parallel to the table. At these two points, the velocities due to spin and rotation sum to zero. The symbol is visible, both to the human eye and a camera with open aperture, whenever its velocity is near zero,[8] at which time the opposite symbol is whizzing past as the spin and rotation velocities are equal both in magnitude and direction. The number of times the symbol is seen in one revolution approaches the ratio of the circle's diameter to the tube's diameter (equal to the ratio of the tube's length to its diameter) as it settles down.

The visibility and invisibility of the opposite symbols involves the speed of neural processing and persistence of vision. Students often have a general notion that their visual system is being tricked. Eventually some understand how the geometry of this rolling system forces the visible symbol to be roughly stationary during the brief instant that it comes repetitively into view.

Some students might also find that the angle above the table by which the tube is tipped as it rolls on one edge is consistent with the required precession of the total angular momentum vector produced by the torque about the center of mass due to the normal force, and may consider the inertia tensor in the body-fixed and laboratory reference frames. Because this full range of topics is typically not covered in the introductory sequence, and because these quantities change over time due to friction, these topics are not as amenable to analysis in the context of this laboratory. It can be revisited in more advanced mechanics courses or be made into an advanced class project for extra credit. Such an analysis has been done using air jets in an enclosure, where the motion has been sustained for detailed quantitative analysis.[9]

VI. WHAT STUDENTS LEARN ABOUT SCIENCE

During the course of the laboratory, students are given the opportunity to experience many aspects of the nature of science. They find discovery exciting, and neither linear nor automatic. Trying to explain a phenomenon is both challenging and rewarding. By working in groups and collaborations, they see that different people notice different aspects of the phenomenon being studied. They see how collaborations develop over time. The articulation of ideas while explaining them to others advances the idea itself. Students experience the interplay of theory and experiment, and the value of scientific equipment. It is seen that investigations of the real world are often multidisciplinary as we find here that a full explanation involves both physics and physiology. They feel the urge to duplicate or challenge others' results, and the way that physical reality acts as a corrective to wrong ideas. They experience the way research groups engage in friendly competition for first and best explanations. Some of the complications of how the scientific community judges theories are unveiled. They see that apart from the scientific community and physical reality, there is no authority to appeal to for final explanations or judgments. Another lesson is that even in a simple system, there can be many intriguing questions to explore with ingenuity and persistence.

It is helpful to discuss a number of these points at the end of the experience, summarizing what was learned about the phenomenon and the process of science.

This laboratory activity does not encompass all aspects of the scientific research experience. There is no prior literature review of work done on the subject by others. Neither is the subject matter cutting-edge, representing truly novel studies done using the most advanced equipment. The conferences and collaborations here are informal and do not require proper publications. And there is a short time limit. Nevertheless, this three-hour laboratory provides an introduction to key features of an authentic research experience for students in an introductory physics course. Applying for and receiving grants, along with the conference experience of presenting, critiquing, and learning from others' work are rarely encountered in introductory laboratory exercises.

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One of the authors (S.D.S.) saw a demonstration of the phenomenon by an unknown participant of a Michigan AAPT meeting at Grand Valley State University about 1990, prompting the beginnings of this exercise. The authors would also like to thank their students for their active participation in this activity over the years.

[1]See supplementary material at http://dx.doi.org/10.1119/1.3273196 for a few short videos, a poster, and the laboratory manual, which may be copied or adapted with acknowledgment.

[2]J. W. Zwart and S. D. Steenwyk, "Spinning tubes: An exercise in laboratory problem solving," Proceedings of the 1996 North Midwest Section Meeting, American Society for Engineering Education, Fargo, ND, 3–5 October 1996, pp. II.C-4.1–II.C-4.4.

[3]See Ref. 1 for videos.

[4]Karl C. Mamola, "A rotational dynamics demonstration," Phys. Teach. **32** (4), 216–219 (1994).

[5]Paul Doherty, "Spinning cylinder: Like a wheel within a wheel" ⟨www.exploratorium.edu/snacks/spinning_cyl⟩; Donald E. Simanek, "Physics toys, tricks and teasers: The frugal physicist's demo collection" ⟨www.lhup.edu/~dsimanek/scenario/toytrick.htm⟩.

[6]In most cases (using different types of PVC or CPVC), a very fine-grade steel wool works well. In other cases, methanol or acetone gives better results in dissolving the ink.

[7]Although integer length/diameter ratios are not necessary to render the symbols alternately visible and invisible, they do allow the pattern to be approximately stationary in orientation and thus help elicit both curiosity and insight.

[8]If several markings are made adjacent to one another from the end toward the center of the tube, it is interesting to note that at least two are typically viewed as stationary, showing that there is a range of velocities near zero that will make it work. Being near zero here means that a visible symbol's speed is below some "blurring limit" of the eye.

[9]Lorne A. Whitehead and Frank L. Curzon, "Spinning objects on horizontal planes," Am. J. Phys. **51** (5), 449–452 (1983); popularized in Jearl Walker, "Amateur scientist: Delights of the 'wobbler,' a coin or a cylinder that precesses as it spins," Sci. Am. **247** (4), 184–192 (1982); reprinted with corrections and notes as Chap. 8 of Jearl Walker, *Roundabout: The Physics of Rotation in the Everyday World* (Freeman, New York, 1985), pp. 45–49. These articles do not discuss the appearance of the symbol at one end, which is the feature we focus on here.

Microphone Hummer. This instrument produces a 1000 Hz signal for use with alternating current bridges. The power supply is about six volts, and the tuning fork is used with a make-and-break contact to produce the signal and control its frequency. This instrument is labeled Made for Leeds & Northrup and was sold by them for $34 in the later 1930s. The actual maker is General Radio, which sold it as a Type 213 Audio Oscillator. This example is in the Greenslade Collection, along with examples by GR. (Photograph and Notes by Thomas B. Greenslade, Jr., Kenyon College)