Hands-On Demonstrations in Introductory Mechanics

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Introduction

Students often have difficulty grasping the reality of what is being discussed in introductory courses in mechanics. For some students, especially those who are struggling, physical reality becomes mired in seemingly endless equations and the apparent mish-mash of theory and practical application. This should be prevented if at all possible, as mechanics is the first course in which students can participate in designs that include material type and geometry in a realistic way. One essential method of convincing students of the importance and truth of what you are teaching is to actually show them that truth up close. Student feedback gathered during and after the semester consistently reinforces the effectiveness of hands-on demonstrations in driving home key points in mechanics.

This paper presents several simple, low-cost and rapid classroom demonstrations that enhance student understanding by allowing for the direct observation of physical phenomenon. Included here are demonstrations of shear, stress transformation, pressure vessels, and statically indeterminate systems. Each of these demonstrations has been thoroughly classroom-tested, and comments on the use of each demonstration are presented.

Conversion of Force and Stress

Objective: To clearly show the relationship between force, area and stress, while simultaneously demonstrating a key mechanical concept; the pressurized cylinder and piston system.

Equipment: The equipment required for this demonstration is shown in Figure 1. While somewhat more costly and complex than the other systems presented in this paper, the total cost for materials is still less than $250. Some machining is also required. The device consists of a 3 ft acrylic tube having an inside diameter of 3 in, capped at each end with a threaded PVC cap. The top cap has a hole for the pushrod, and the bottom cap has an access port to which a 15 psi pressure gage and bleeder valve is attached. Additionally, the top of the half-inch pushrod is fitted with a load platform. The bottom of the pushrod is fitted with a soft rubber wiper. Initially, a tight-fitting reinforced hard-rubber wiper was contemplated, but the friction from the wiper-cylinder interface was too large and ruined the demonstration. The relatively light friction from the soft rubber wiper should be balanced with the weight of the platform and pushrod assembly, so that the added weight on the platform directly converts to the pressure seen on the gage. A portable scale with a capacity of about 100 lbs is also useful, and a calibrated bathroom scale will serve this purpose nicely.

Procedure: Place the demonstrator atop a sturdy desk or table where it can be seen well by everyone in the room, with the pressure gage facing the students. Pick two students to help you out with the demonstration. Have them pick up student textbooks for use as the load, making sure the students donating books write their names on the inside cover or can otherwise identify their textbook. While this is going on, open the bleeder valve and lift the piston to near the top of its stroke. This is a good time to explain to the students how the device works and how air pressure, a stress, will support the textbooks on the platform, a force, and how those are related. We typically do not get into a deep discussion about piston friction, as this tends to obscure the key point of the demonstration.

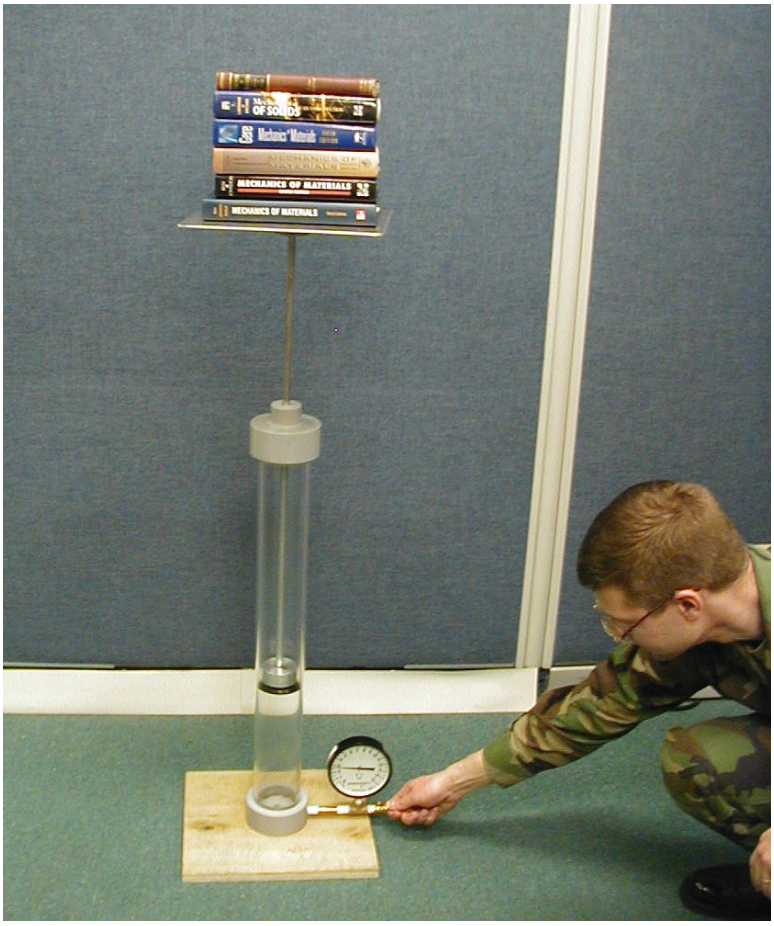

Figure 1: The Stress Demonstrator
(Shown here on the ground. Recommend elevated use for student visibility)

The textbooks are then weighed, and then the students are told the diameter of the cylinder and given an opportunity to compute the expected stress reading on the pressure gage. Once a general consensus on the expected stress level is reached, the books are placed on the loading platform by one student, and the instructor slowly opens the bleeder until a constant, slow downward motion is observed. The second volunteer then reads the pressure gage, which should remain constant (with the bleeder open) until the device "bottoms out".

Observations: The observed pressure value corresponds to the weight of the books divided by the internal area of the cylinder. It is necessary to read the gage while the piston is in motion because of differences between static and kinetic friction. The device DOES NOT produce reliable or even correct results in the at-rest position. This demonstration also provides a direct connection between something many students understand well (pressure) and something they are just learning (stress).

Stress Transformation

Objective: To show first-hand how a simple change in orientation can change the observed effects of the stress at a point.

Equipment: A big book with identical squares drawn 45 degrees offset, as shown in Figure 2. Catalogs available from various machine-tool suppliers work well, and the cost of this demonstrator is thus very minimal. The key is that the book MUST have a stiff binding, not a soft paper binding such as that found in telephone directories. The stiff board on the binding maintains page alignment.

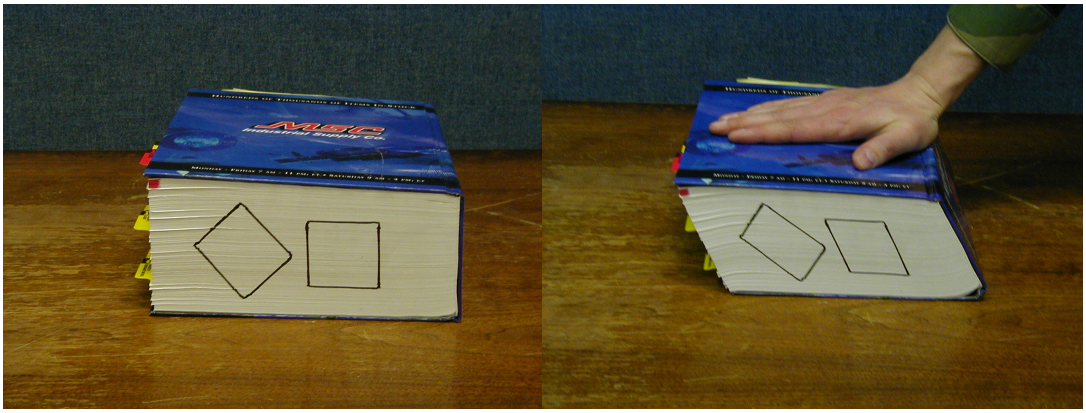

Figure 2: Demonstration of Stress Transformation

Procedure: Place the book on the desktop and point out to the students that there are two identical squares. Be sure to call attention to the 90 degree corners in both squares. Then, place the book in shear by pushing on the top parallel to the desk.

Observations: The student should observe that the two squares have deformed quite differently. The unrotated square shows clear shear deformation, but little or no normal deformation. This block is oriented to show the planes of maximum shear. The corners are no longer oriented at 90 degrees. Conversely, the square which began offset 45 degrees has undergone no shear whatsoever, but has experience significant normal deformation. This block contains the two principal planes. This effect is shown in Figure 2. The clear implication is that despite having identical states of stress, the observer sees different effects depending on the orientation of the reference frame. This is the essence of stress transformation.

Shear Stress and Single versus Double Shear

Objective: To teach students to identify shearing forces and stresses, and to establish the clear difference between single and double shear.

Equipment: As of this writing, the equipment is still in development. Our first attempt, which did not work out, was a wooden shear device, shown in Figure 3, combined with a simple spring scale. The demonstrator was constructed from plywood and clear pine, and provided for both single and double shear in a variety of hole sizes. This device worked very well for the first semester of use, and we found that shearing a single strand of spaghetti worked well, while shearing multiple strands was chancier because all the strands don't necessarily act together, and progressive rather than group failure can occur, skewing results. However, because of differences in wood types, the pine pull-board expanded significantly during the summer, and by fall was wedged tight in the internal channel. The pull board was extracted with repeated impact loadings and planed down to fit in the channel. Despite these efforts, the device would not provide consistent results, most likely due to a poor fit of parts, and a noticeable growth of the holes near the shear plane. In essence, the device wore out due to poor wear characteristics of the wood. It is possible that this problem could have been avoided by constructing the device out of hardwoods, but that is by no means certain. It is also worth noting that we attempted to use an electronic fishing scale as a load readout, but the update rate was far too slow to allow for an accurate reading. A spring scale is recommended, preferably with a max load indicator.

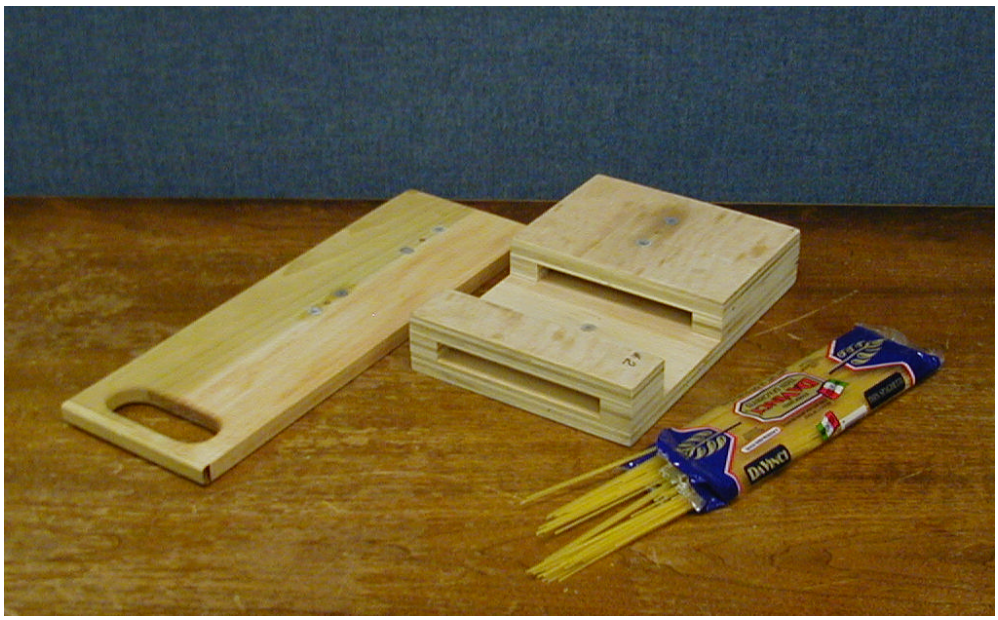

Figure 3: Original Wooden Shear Demonstrator

Following the failure of the wooden device, a very small prototype acrylic device was built and successfully sheared hundreds of strands of dry spaghetti without signs of wear. At this time, a full-sized acrylic demonstrator similar to the one shown in Figure 3 is being constructed. This has been a challenging process, since acrylic sheet tends to be highly variable in thickness (±0.070 in!) and has to be cut down and squared prior to use. The bottom line is that if repeatable, predictable results are desired, a high-precision device is probably required.

Procedure: The use of the device is very straightforward. The students are shown both parts, then a single strand of spaghetti is failed in single shear and the load recorded. Then, a single strand is placed in the double-shear part of the demonstrator, and failed with the load recorded.

Observations: The observed load to fail the specimens in double shear should be twice that observed in single shear. Multiple strands of spaghetti may work once we have finished building the precision device, but the possibility of progressive failure, with its inherent inaccuracy, remains a problem. Students enjoy this demonstration, and it helps to physically reinforce the key concepts of shear strength and shear connections.

Thin-Walled Pressure Vessels

Objective: To show the magnitudes of hoop and longitudinal stresses for a Thin-Walled Pressure Vessel (TWPV). Additionally, we demonstrate that a spherical TWPV has only longitudinal stress, while a cylindrical TWPV has both longitudinal and hoop stress.

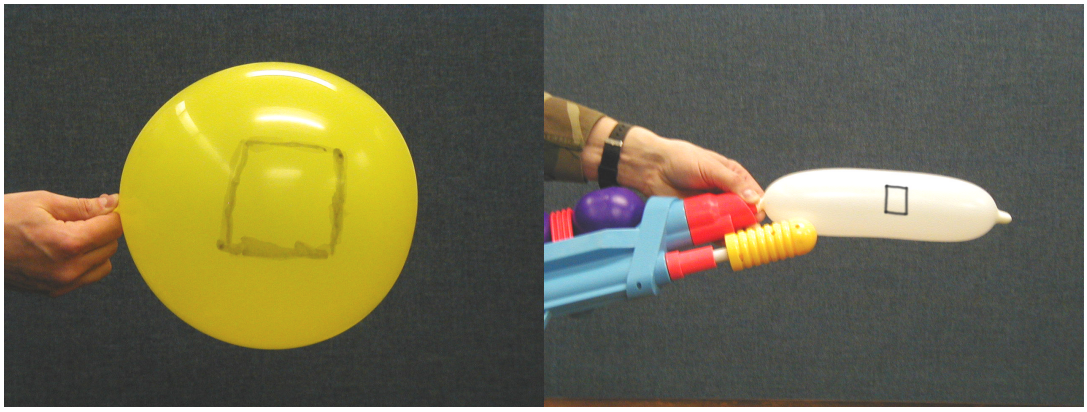

Figure 4: Balloons for the Demonstration of Hoop and Longitudinal Stress

Equipment: Two types of balloons, shown in Figure 4, are needed for this demonstration. The spherical balloon should be quite large, with the square stress block drawn centered on the side of the balloon when the balloon is flat. The cylindrical balloon should be at least 5 times longer than its diameter, the larger the ratio of the length to diameter, the better. The stress block should be drawn midway down its length to negate the effects of the ends. Be careful drawing the square, ensuring the sides are even length with 90° corners, and the lines are very bold. If the lines are not dark enough, they will be very hard to see after the balloon is inflated, as they become faded as they stretch. Regular ink pens work well for drawing the stress block.

Procedure: We typically have fun with the demonstration and play it up. Several balloons of each type are prepared with stress blocks already drawn on the balloons. First, show the square stress block to the students on the deflated balloons. Ask the students what shape the square will be after the balloon is inflated for each balloon type. Will the sides be the same length? The corners still 90°? We then ask for student volunteers to blow up the balloons, having purchased balloons that were difficult to inflate. The students have always succeeded in blowing up the balloons, although usually only after multiple attempts. We then ask the students

if they'd like to see us blow up the balloon. The students are usually quite eager to see what shade of red the instructors face will turn during the attempt, and are surprised when we pull out a Super Soaker water gun prepositioned fully charged with air, and easily inflate the balloon. Two embedded lessons within this demonstration are the spherical pressure vessels on the Super Soaker (why did they choose spheres?) and the fact that pre-yielding the latex balloons by stretching significantly weakens them and allows for easy inflation.

Observations: The student should observe that on a spherical balloon, the stress block remains square, with all 90° corners. This demonstrates that the magnitude of the stress in both the longitudinal (along the length of the balloon) direction and in the direction about the circumference (hoop) are the same. On the cylindrical balloon, the student should observe that the initially square stress block has deformed into a rectangle, with the longitudinal deformation being half as large as in the hoop direction. This demonstrates that the magnitude of the hoop stress is twice that of the longitudinal stress. For both balloons, the 90° corners demonstrate that there is no shear stress acting on the stress block. The lack of any shear deformation shows that the stress blocks are oriented to show the principal stresses in both cases.

Statically Indeterminate Systems; "The Compression Cadet"

Objective: Demonstrate the key concepts related to the solution of statically indeterminate problems.

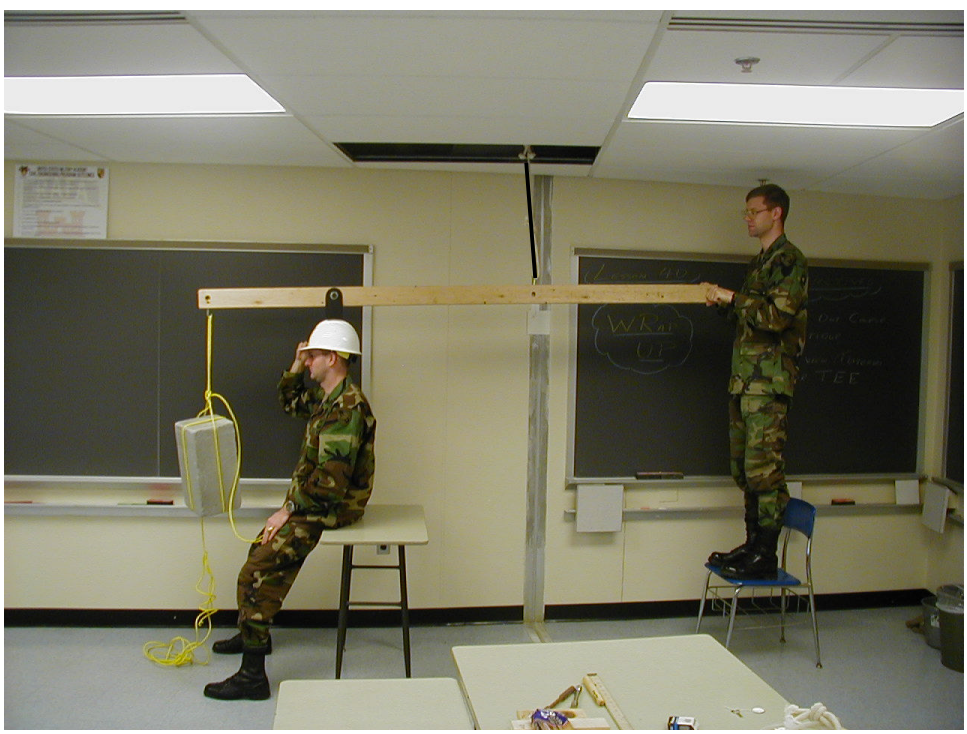

Figure 5: Demonstration of Statically Indeterminate Systems; "The Compression Cadet"

Equipment: Figure shows the equipment required for this demonstration. The total cost for the materials is approximately $30. The apparatus consists of an eight-foot long 2x4, a hardhat with a steel bracket attached, a bungee strap, and a weight. Make a three-quarter inch

hole at one end of the 2x4 for a ten-inch long pin, and another three-quarter inch hole approximately six-feet along the 2x4 where the hardhat will attach. Place two j- hooks, one about three-feet from the pinned end, and the other on the far end of the 2x4. Use a one to two-foot piece of surgical tubing or bungee cord hung from a ceiling or other convenient point and attached to the middle J-hook.

For the hardhat support, we used a U-shaped bracket made out of sheet metal that had a two-inch wide opening and was three inches wide and six inches tall. We made a 5/16 inch hole in the top of the hardhat and bolted the bracket onto the hardhat, and then pinned the bracket to the 2x4 about six feet from the pin end. Any object between about five and twenty-five pounds can be used as a weight, depending on the strength and tolerance of the student. We have used a light weight piece of concrete (heavy) or a bucket of water (light) for the weight.

Procedure: Two students are needed to participate in the demonstration. Have one student stand on a chair and hold on to the pin. Ask the student what motion a pin allows and what motion it prevents. Attach the bungee cord to a support in the ceiling, and hook in on to the first j-hook. Have the second student put on the hardhat attached to the 2x4 as shown in Figure 5. Now add the weight at the end. Lightweight concrete has worked best, because it looks impressive, while weighting less than 20 pounds. Be careful not to have too heavy a weight, or the student wearing the hardhat might be injured. Have the student wearing the hardhat squat down several inches to allow for observable deformation of the bungee.

Observations: The students should observe that the bungee cord is in tension, the student wearing the hardhat is in compression, and that there is a compatibility relationship between the deformation of the bungee cord and the student wearing the hardhat. Point out that this is a statically indeterminate problem.

Assessment

Lowman (1995) contends that demonstrations, which he calls lecture-demonstration classes, are essential in engineering and science courses. The authors of this paper couldn't agree more, and both anecdotal and statistical data support this contention. First, student response during the demonstrations is always strong, and inspires a high volume of questions, a clear sign of student engagement. Second, most of the demonstrations described here were put into use in the Fall of 2001, and were not used in the Fall of 2000. For the authors, who taught Mechanics both terms, semester-end survey questions related to visual connection showed a strong upward trend between the two semesters (see Figure 6). This is significant because the instructors, course content and student population composition remained fairly constant between those two terms. Third, in speaking with students in the semester following the Mechanics courses, most of the strongest recollections are of the physical demonstrations rather than equations or even general concepts. Speaking with former students follows a predictable path, when you remind the student of the demonstration, you get a strong recollection of the physical demonstration which usually leads to a recollection of the physical phenomenon.

Student comments also supported the use of demonstrations, though usually not in a direct way. In general, students were very positive about how the course related to real-world

applications and physical understanding, which the demonstrations have a clear impact on. A few examples of positive student comments related to the use of demonstrations are as follows:

- "The instructor uses extremely effective learning tools in class, and they really helped me to better understand the material presented."
- "This has been my favorite class…(cut). Even though it was more work than any other class, it really stimulated my learning and excitement of being a Civil major."
- "Good visual aids"
- Q: Strengths of course. A: "The instructor demos and visual aids", "Practical applications", "Interesting material, vital to Civil and Mechanical majors", "Made difficult concepts easy and applicable"; "Relevance to practical applications/life"; "very practical material".

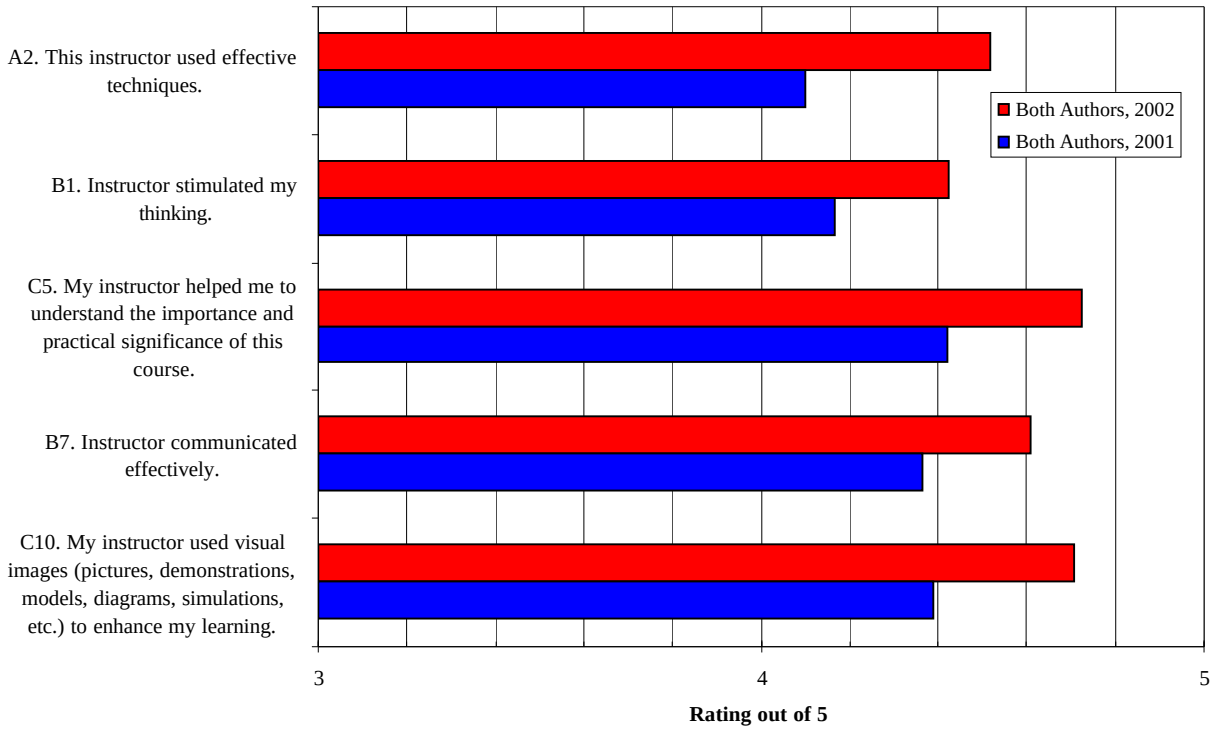

Figure 6: Assessment Data for Fall 2001 and Fall 2002

Conclusions

This paper presents a number of low-cost, effective classroom demonstrations in elementary mechanics. The reader is encouraged to both try out the demonstrations given here and to develop new demonstrations. Course-end assessment by students here at West Point has consistently shown a highly positive student response to the demonstrations used, and they tend to form the core of what students recall even years later.

Acknowledgements
The authors wish to acknowledge the efforts of Colonel Steve Ressler, who had the original idea for the compression cadet. The rest of the demonstrations depicted are not his fault, so don't blame him.

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