DEMONSTRATIONS TO COMPLEMENT A COURSE IN GENERAL ENGINEERING THERMODYNAMICS

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At the University of Washington, the College of Engineering offers a lower-division course in general engineering thermodynamics. The course is part of the core engineering curriculum that students are supposed to take prior to applying for admission to a department. As such, it serves many departments in the College, most of which provide instructors for the course. Chemical and mechanical engineering students take the course in their sophomore year to satisfy departmental admission requirements and to serve as a foundation for further study of advanced thermodynamics in their respective programs. Students from other departments take the course to satisfy specific graduation requirements or to fulfill their elective engineering science credits. These students often do not enroll in the course until late in their senior year; thus the sections usually contain a very broad cross-section of students in various stages of their undergraduate careers.

TABLE 1
Engineering Thermodynamics Schedule and Layout

Week	Topic	Demonstration
1	Basic concepts	Constant-volume thermometry
2	Properties of a pure substance	Critical state of carbon dioxide
3	lst law of thermodynamics (closed systems)	----
4	lst law of thermodynamics (open systems)	Hair dryer
5	2nd law of thermodynamics (closed and open systems)	Heat capacity ratio for air
6-7	Entropy, 2nd law efficiency	Efficiency of a compressor
8-9	Power and refrigeration cycles	Heat pump
10	Instructor's choice	---

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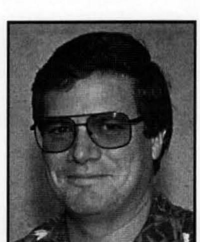

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Engineering thermodynamics is a four-credit course that meets for three 50-minute lectures and one 110-minute quiz section per week. Prerequisites are two quarters of freshman chemistry (general), three quarters of freshman calculus with analytical geometry, and one quarter of freshman physics (mechanics) with a laboratory. The course content, outlined in Table 1, includes

- *Concepts of units and dimensions, pressure, temperature, heat, and work*
- *Macroscopic properties of substances*
- *Principles of first-law analysis for closed systems*
- *Principles of energy analysis for open systems, including flow and shaft work*
- *Concepts of the second law of thermodynamics in its*

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. . . this class ideally should have a laboratory to accompany the lecture material. This would give students hands-on experience with the concepts presented in the lectures and would also expose them to engineering devices. Budget, space, and time considerations prohibit this, but we have found a reasonable substitute in a set of classroom demonstrations that can easily be integrated into the course sequence.

macroscopic form for open and closed systems and engineering devices

- *Power and refrigeration cycles*

The circumstances under which the course is offered make it pedagogically challenging. First, the various departments wish to emphasize topics that are relevant to their own program. For example, one department wants heavy emphasis on thermodynamic cycles, while another wishes to emphasize psychrometrics. As a result, it is difficult to obtain a consensus between the departments on course content, and it is difficult to coordinate among the various instructors to ensure a uniform coverage of the material. Coordination with local community colleges, which also offer the course and from which we receive transfer students, further complicates course administration. Second, there is a universal fear of the course material across the spectrum of students who take the course. Indeed, there are many new and unfamiliar concepts introduced in the course. Terms such as enthalpy and entropy may have been encountered before, but they are usually not well understood and it is difficult for the students to grasp such intangible concepts. This is compounded by the third problem, which is that few of the students have any mechanical skills and most have had very little laboratory experience. Because the material has a strong emphasis on engineering devices, many students find it difficult to comprehend how some of these devices function. Fourth, the course is very crowded and has little room for new material.

To improve comprehension, this class ideally should have a laboratory to accompany the lecture material. This would give students hands-on experience with the concepts presented in the lectures and would also expose them to engineering devices. Budget, space, and time considerations prohibit this, but we have found a reasonable substitute in a set of classroom demonstrations that can easily be integrated into the course sequence. We present below the set of demonstrations that were developed under the auspices of the National Science Foundation's "Engineering Coalition of Schools for Excellence in Education and Leadership" (ECSEL).

The set consists of demonstration hardware, notes for instructors, and student handouts where necessary. The demonstrations were developed with the concept that "seeing is believing" and that some familiarity with engineering devices will improve understanding and comprehension of the lecture material. Our criteria for developing the demonstrations were that they had to be inexpensive, easy to construct, portable, and completable in less than fifteen minutes of class time. In addition, each had to convey several key concepts from the lecture material. In the two years the demonstrations have been used, they have received excellent reviews from students and faculty alike.

► Constant-Volume Thermometry ◄

This classic apparatus may be used to demonstrate the absolute temperature scale and the ideal gas law. The constant-volume thermometer is based on Gay-Lussac's law (1802) that the temperature of a gas is proportional to its pressure at constant volume. Gay-Lussac's law is, of course, a special case of the ideal gas law. The goals of this demonstration are to illustrate Gay-Lussac's law and to estimate the value of the temperature at zero pressure, *i.e.,* the absolute zero of temperature.

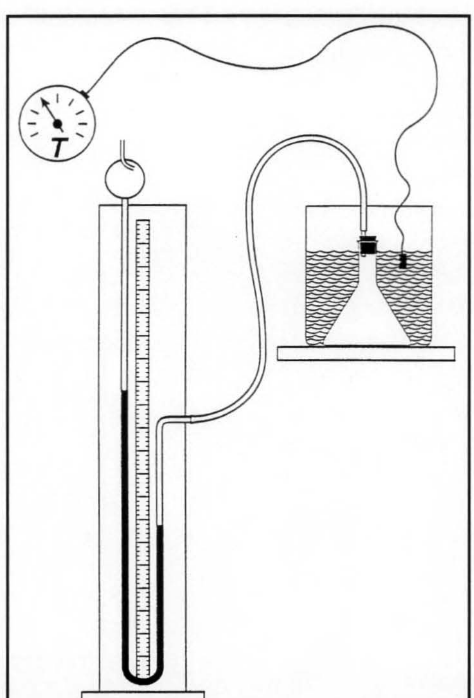

***Figure 1.** Schematic diagram of the constant-volume thermometer.*

The apparatus (see Figure 1) consists of a thin-tube water manometer, a stoppered 125-ml Erlenmeyer flask, a 1000-ml beaker, a digital thermometer, and a supporting stand. One end of the manometer is open to atmosphere and the other is connected to the flask through a short piece of Tygon® tube. For best results, it is important to use a thin-tube manometer (diameter less than 5 mm) and a short piece of tube to connect the manometer to the flask to minimize the volume of air that is not in the water bath. In addition to the apparatus, the instructor must supply approximately 2000 g of ice.

In order to establish the P-T proportionality, at least three data points are required, although it is easy enough to acquire more points. For the first point, the beaker is filled with room-temperature water and the flask is immersed in the beaker. After allowing the system to come to equilibrium, the pressure on the manometer and the temperature of the water bath are measured. For additional points, ice is added to cool the water to a lower temperature (it is usually necessary to pour off excess water). The final data point is obtained using a saturated ice/water solution (273 K, approximately 0°C). Of course, the system is not at constant temperature except at the end points of 273 K (0°C) and room temperature (approximately 295 K). But the change in temperature is sufficiently slow that its contribution to experimental error is negligible.

Gay-Lussac's law may be expressed as T = a + bP, where a and b are constants. Thus, a plot of the P-T data should give a linear result. Extrapolation to P = 0 gives a measure of absolute zero. With our system, using the procedure outlined above, consistently we have been able to come within 20 K of the true value, which is remarkable due to the simplicity of the apparatus and the large extrapolation involved. The demonstration also illustrates the use of a manometer to measure pressure and the concepts of differential, absolute, and gauge pressures.

► *Critical State of Carbon Dioxide* ◄

This demonstration allows a pure, two-phase mixture to be observed as it passes through the critical point. The apparatus was developed in 1959 by an undergraduate student at the University of Washington's Department of Mechanical Engineering;[1] we merely added it to the current package of demonstrations. It consists of a sealed quartz tube containing a two-phase mixture of carbon dioxide (CO_2). The mixture is sealed into the tube at the critical molar volume (0.0943 m^3/kmol), and when the contents are heated from room temperature (state 1) to a higher temperature (state 2), the mixture passes through the critical point (304.2 K, 7.39 MPa) as shown on the property diagram depicted in Figure 2. The meniscus is observed to pass into critical opalescence, then to disappear.

The tube is conveniently heated by placing it in a fixture that fits into the focal point of a surplus 35-mm film strip projector. Heat from the 150-W projection bulb raises the temperature of the mixture such that it reaches the critical state in about ten minutes. The optics of the projector are used to focus the meniscus onto a screen for viewing by the entire class. Similar designs have been reported recently in this journal.[2] This demonstration illustrates the critical properties of a pure substance, the structure of property and phase diagrams, and the concept of quality for a two-phase mixture.

Because the sealed quartz tube contains a fluid at very high pressure, this demonstration poses a significant explosion hazard, so appropriate safety procedures should be observed. As a minimum, the instructor should wear safety glasses, transport the tube in a shielded case, and quickly mount the tube into the projector (preferably before students are present). Once the tube is mounted, the geometry of the projector provides a blast shield against the effects of an accidental explosion. We suggest that before preparing a tube for this demonstration, interested readers should consult relevant literature[2] and select a fluid with a lower critical pressure.

► *First Law for an Open System* ◄

This demonstration is the realization of a problem from the Çengel and Boles' textbook, *Thermodynamics: An Engineering Approach,* which is currently used for the course.[3,4] The first law is used to determine the mass flow rate of air exiting a hair dryer. The apparatus consists of a hand-held hair dryer mounted on a stand and a Chromel-Alumel (type-K) thermocouple with an attached digital thermometer. The thermocouple tip should be located approximately 7-8 cm from the dryer exit and in the middle of the flow (radially). The tip should be no closer to the dryer exit since the temperature distribution of the air nearer the exit is not uniform and radiative heating of the thermocouple by the dryer's hot filament becomes a problem. The hair dryer is operated for two or three minutes to reach steady state, and the outlet (T_2) and inlet (T_1) temperatures are measured.

This is a simple application of the first law

$$\dot{Q} - \dot{W} = \dot{m}(\Delta h + \Delta ke + \Delta pe) \tag{1}$$

where

$\dot{Q}$, $\dot{W}$ rate of heat transfer and work, respectively

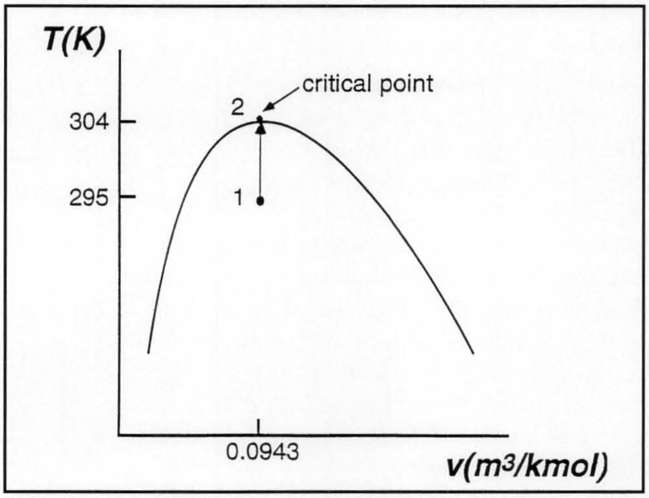

Figure 2. *The T-v property diagram for CO_2.*

$\dot{m}$	mass flow rate
$\Delta h, \Delta ke, \Delta pe$	change in specific enthalpy, kinetic energy, and potential energy, respectively

We make a number of assumptions for the analysis: negligible heat loss through the dryer's walls, negligible changes in kinetic and potential energy, steady state and uniform flow, that air is an ideal gas under these conditions, and that its heat capacity is constant over the measured temperature range. This gives

$$-\dot{W} = \dot{m}\Delta h = \dot{m}C_p(T_2 - T_1) \qquad (2)$$

or, on rearranging,

$$\dot{m} = \frac{-\dot{W}}{C_p(T_2 - T_1)} \qquad (3)$$

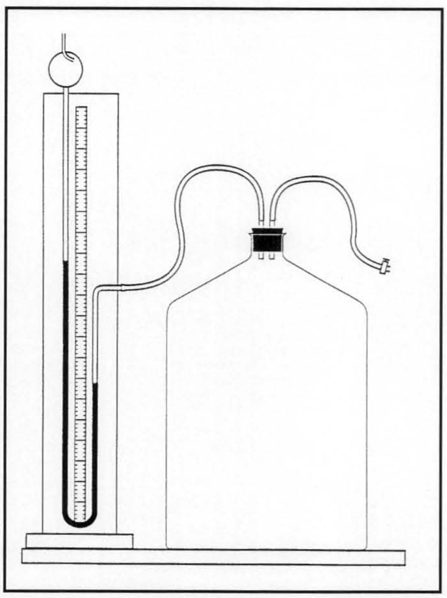

Figure 3. *Apparatus for measuring the heat capacity ratio of air.*

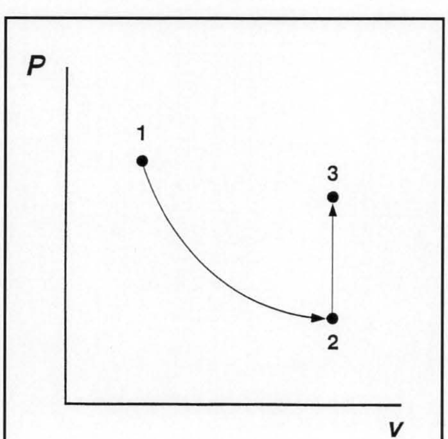

Figure 4. *Pressure-volume diagram for the heat capacity ratio experiment.*

where C_p is the heat capacity of air.

We further assume that negligible electric energy is consumed by the dryer's fan so the power delivered to the air is the electric power into the dryer, which was measured as 1176 W (±5%) out of class using a voltmeter and a clip-on ammeter. Typical temperatures measured are

$$T_1 = 22°C\ (295K) \quad \text{and} \quad T_2 = 72°C\ (345K)$$

so that the mass flow rate works out to

$$\dot{m} \approx 0.023\ kg/s$$

This value is within 4% of the mass flow rate measured with a velometer. Because the cross-sectional area of the exit can be measured, the mass flow rate can easily be manipulated to give the average gas velocity and the volumetric flow rate to illustrate the relationship between these quantities, in addition to illustrating the first law. The principles and operation of a thermocouple are also shown, and if the thermocouple at the exit is moved radially, the assumption of uniform flow used in Eq. (1) can be relaxed and nonuniform flow can be demonstrated.

► *Heat Capacity Ratio for Air* ◄

This demonstration is a simplified version of an experiment given by Shoemaker, *et al.*[5] The goal is to determine the heat capacity ratio

$$\gamma \equiv \frac{C_p}{C_v}$$

for air near standard temperature and pressure. The demonstration gives students experience with properties of an ideal gas, adiabatic processes, and the first law. It also illustrates how P-V-T data are used to measure other thermodynamic properties and how to measure differential pressure using a manometer.

The apparatus is illustrated in Figure 3 and consists of a stoppered, 19-liter (five-gallon) carboy and an open-tube, water-filled manometer. The carboy stopper is punctured by two pieces of glass tubing for connection to Tygon® tubing. One piece of tubing connects the carboy to the manometer, while the other is used to pressurize the carboy through a hose clamp. The water in the manometer is tinted with food coloring for better viewing.

The experiment involves a two-step process (see Figure 4):

Process 1-2: Expand the gas in the carboy adiabatically and reversibly from P_1 to P_2.

Process 2-3: At constant volume, allow the gas to return to thermal equilibrium as its pressure changes to P_3.

The system is initialized by opening the vent clamp, blowing into the carboy, and then closing the vent. An initial pressure of 16-18 inches H_2O (6.4 to 7.2 x 10^{-2} Pa) is generally sufficient. The system is then allowed to reach thermal equilibrium (about fifteen minutes). This preparation may be done outside of the actual class time since it is not a part of the process outlined above.

For the demonstration, the initial pressure P_1 is read on the manometer. The carboy is momentarily unstoppered and then the stopper is replaced. This allows the gas in the carboy to expand as the pressure drops to atmospheric (P_2). Note that this expansion is approximately adiabatic and reversible.[5] After 10 to 15 minutes, the system returns to thermal equilibrium once again and the final pressure P_3 is read on the manometer.

The analysis, which comes directly from Shoemaker, *et al.*,[5] is lengthy but straightforward, and a handout is provided for the students. It will not be repeated here, but starting with the first law and the assumption of ideal gas behavior, the heat capacity ratio may be related to the measured pressures

$$\gamma \equiv \frac{C_p}{C_v} = \frac{\ell n\, P_1 - \ell n\, P_2}{\ell n\, P_1 - \ell n\, P_3} \tag{4}$$

Although our apparatus is crude in comparison to that detailed by Shoemaker, consistently we are able to determine γ for air to within 5% of the reported value of 1.40.[3]

► *Efficiency of a Compressor* ◄

The goal of this demonstration is to determine the second-law efficiency of a small compressor. Discussion may also center around the operation of a compressor (actually a pump, in our case), a Bourdon pressure gauge, and/or a gas flow meter.

The apparatus, shown schematically in Figure 5, consists of a 40-W reciprocating-piston pump that compresses air into a 3.5-liter tank. (The type of compressor is not important; any suitable compressor available from the university salvage pool will work.) The gas flow rate of the air exiting the tank is measured by a rotameter and controlled by a valve on the rotameter; this valve also controls the pressure in the tank. The tank pressure is measured with a Bourdon gauge, and a digital thermometer is used to measure the temperature both inside the tank and in the external environment.

In our apparatus, the pump generates pressures from 0 to 6 psig (101 to 142 kPa) and mass flow rates of air from 0 to 0.33 g/s, drawing approximately 40 W electrical power for any setting. The power consumption was measured (outside of class) to ±5% using a wattmeter. Operating at steady state, we observe no significant change in temperature between the inlet and the tank, indicating that this system is essentially isothermal.

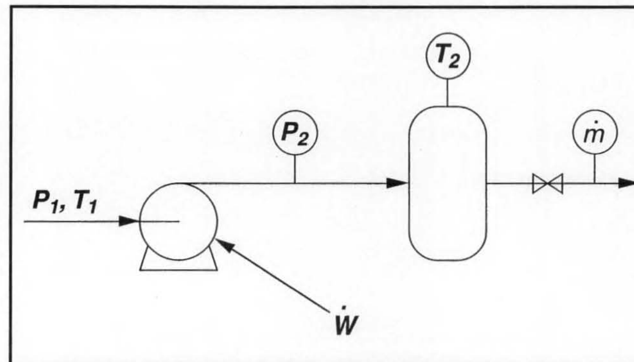

***Figure 5.** Schematic diagram of the apparatus for measuring the efficiency of a compressor (pump).*

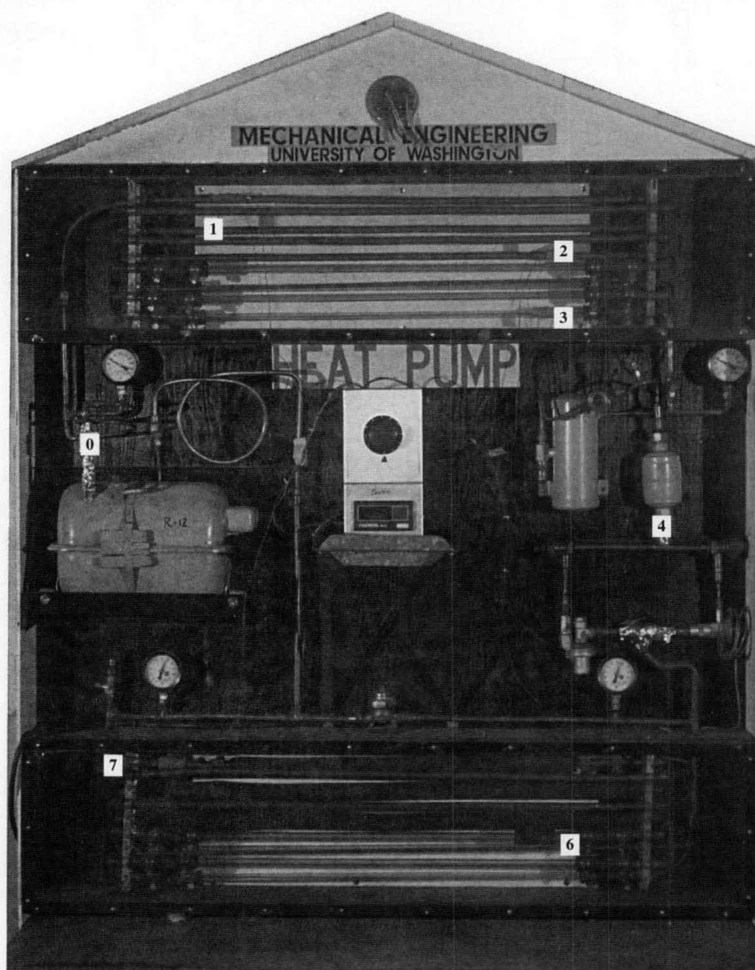

***Figure 6.** Photograph of the heat pump system showing (0) the compressor, (1,2,3) the condenser, (4) the dryer and expansion valve, and (6,7) the evaporator.*

For purposes of analysis, the compressor comprises the thermodynamic system (control volume) and the working fluid is air. The second-law efficiency for a compressor is the ratio of the reversible work to the actual work

$$\eta_c = \frac{\dot{W}_{rev}}{\dot{W}} \quad (5)$$

The actual work, $\dot{W}$, we know to be -40 W. To obtain the reversible work, we start with the first law for a steady-flow system

$$\dot{Q} - \dot{W}_{rev} = \dot{m}(\Delta h + \Delta ke + \Delta pe) \quad (6)$$

and the second law for a reversible steady-flow system ($\dot{S}_{gen} = 0$)

$$\dot{m}\Delta s = \frac{\dot{Q}}{T_o} \quad (7)$$

These expressions are combined to eliminate $\dot{Q}$. Neglecting changes in kinetic and potential energy, we arrive at the following expression relating the reversible work to changes in enthalpy and entropy:

$$\dot{W}_{rev} = \dot{m}\left(T_o\Delta s - \Delta h\right) \quad (8)$$

If we assume an ideal gas, then the changes in enthalpy and entropy are easily calculated from the heat capacity of air and the measured temperature and pressure. Thus, the reversible work and the second-law efficiency of the compressor may be calculated. Typical values for our setup are $\dot{W}_{rev} \approx -6W$ giving $\eta_c \approx 0.15$. This is one of the few demonstrations that conveniently allows students to observe and quantify a change in entropy.

► *Heat Pump* ◄

Power and refrigeration cycles are an important topic of this course, and we have a working heat-pump cycle demonstration to illustrate the main principles of thermodynamic cycles. The heat pump was fabricated from a surplus refrigerator compressor, two cross-flow, air heat exchangers, and an expansion valve (see Figure 6). The heat-exchanger compartments of the condenser and evaporator are covered with Plexiglas® and several of the heat-exchanger tubes are constructed from glass to observe the changes in phase of the working fluid, refrigerant-12 (R-12) as it transits the cycle. Pressure gauges and thermocouples are included between processes in the cycle so that students can observe pressure drop and temperature changes associated with each process and compare it with property changes predicted from the property diagram of the refrigerant.

During operation, the evaporator operates at a pressure of 586 kPa (85 psia), the condenser pressure is 974 kPa (141 psia), and the temperature exiting the compressor is 357 K (183°F). From these values and the R-12 property tables or diagrams, the students can calculate the coefficient of performance for the heat pump, the work supplied to the compressor assuming isentropic operation, the irreversibility associated with the expansion valve, etc. Discussion can also center around changes in expected performance if R-12 is replaced by the more environmentally friendly refrigerant-134a (R-134a), assuming the same amount of work is supplied to the compressor.

This demonstration does not fit in the same category as those discussed above; it is portable (but not small) and inexpensive, but relatively complicated to construct. It was constructed several years ago in the Department of Mechanical Engineering and was available for use in this class, so we have included it to round out the demonstration set.

EVALUATION

The demonstrations were designed to supplement each of the major sections of the course as shown in Table 1. The addition of the demonstration set to the lecture material was evaluated by two sections of students who took our offering of the course. The evaluation took the form of a set of questions prepared by the UW Office of Educational Assessment and the ECSEL assessment team. The students were asked to respond to four or five questions concerning the demonstrations and how helpful they had been in enhancing their understanding of the underlying thermodynamic concepts. On a scale of 0 to 5, the pooled average and standard deviation were 3.76 and 1.01, respectively, with 53 students responding. Verbal feedback from faculty who used the demonstrations has been uniformly positive.

ACKNOWLEDGMENTS

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