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A SIMPLE EXPERIMENT TO EXPOSE MISCONCEPTIONS ABOUT THE BERNOULLI EQUATION

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ABSTRACT
A series of laboratory exercises has been developed to aid in the teaching of thermal and fluid sciences to undergraduate engineers. The exercises use simple hardware and a guided-inquiry approach to expose student misconceptions and to develop deeper understanding of basic concepts. This paper focuses on one of the laboratory exercises, which uses a simple duct with a sudden expansion to demonstrate the error caused by misapplication of the Bernoulli equation. The apparatus and the laboratory exercise are described. Learning gain measurements and results of attitude surveys are presented. The exercise is successful in causing students to confront their misconceptions and lack of understanding. Student attitudes about the usefulness of the exercise correlate with their grade inthe course. The A students have a less favorable opinion than the B and C students.

NOMENCLATURE
A area of duct cross section.
d Duct diameter.
g Acceleration of gravity.
h_L Head loss.
p Static pressure.
R Mean response to Likert scale survey question.
V Average velocity in a duct cross section.
z Elevation above a common datum.
α Cronbach alpha, measure of instrument reliability.
ρ Density of the fluid (air).
$\gamma = \rho g$ Specific weight of the fluid (air).

INTRODUCTION
This paper describes a laboratory exercise that is part of a research project called the *Engineering of Everyday Things* (EET). The goal of the EET project is to develop in-class demonstrations and laboratory-based exercises to improve how engineering students learn core concepts in thermodynamics, fluid mechanics and heat transfer [1, 2]. The laboratory exercises use a guided-inquiry approach that seeks to

- engage students in problem-solving as they conduct experiments, not waiting until they write a lab report;

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- expose and correct misconceptions;
- develop the ability to reason qualitatively.

The "*Everyday Things*" in the title refers to the use of everyday devices – blenders, hair dryers, bicycle pumps, toasters, computer power supplies – as objects of the measurements. In addition to those everyday technologies, the EET project also includes exercises involving fluid mechanics and simple objects that are not consumer products: cylindrical tanks of water, and a duct with an area change. The duct with area change, commonly called a *sudden expansion*, is the subject of this paper.

The guided-inquiry approach in the EET exercises is different from conventional laboratory exercises that have been used in our institutions in the past. We define a conventional exercise as a laboratory-based assignment focused on collection and analysis of data, followed by the written presentation of the results of analyzing the measurements. In a conventional exercise, students spend their time in the laboratory following prescribed steps to record sensor readings while the experiment is running. There is little or no analysis before the students leave the laboratory, and there is little if any engaged problem-solving using the equipment. The bulk of the student effort is spent on data reduction and technical writing. At some other date, typically one week after making the measurements, students turn in a report written in the style of a scientific paper. While there are many variations on laboratory-based exercises, our definition of the conventional exercise is common in many academic settings.

Many conventional exercises are designed to demonstrate a principle that has been discussed in lecture or homework, with the implicit goal of confirming a theory. For example, an exercise to measure the velocity profile in a pipe might be designed to confirm the power law profile for turbulent flow and the quadratic profile for laminar flow. There is value in reinforcing theory with a concrete experience, but students who *only* experience conventional laboratories are given the incorrect impression that the *sole purpose* of laboratory experiments is to set up a compare-and-contrast exercise for testing the agreement between an established theory and a measurement.

Conventional laboratory exercises mimic the way that test engineers, and especially engineers doing research, obtain and report experimental data. The data is systematically recorded. After the measurements are made, the data is reduced with the aid of analytical models and numerical data analysis. The final results are presented in figures, tables, and a narrative report. These are important skills to learn.

However, in many conventional laboratory exercises, students follow *cookbook*-like laboratory procedures that are only slowly changed, if at all, over many generations of students. In order to avoid confusing students or giving them doubts about the relevance of a theory-based coursework, conventional laboratory procedures are usually designed, in conjunction with the apparatus, to give results that agree favorably with established theories. While this helps to reinforce concepts that are new to students, it is not a realistic preparation for the practice of engineering.

The EET laboratory exercises are designed to avoid the highly constrained outcome of a conventional laboratory exercise, while at the same time providing enough structure that students are not left to a completely unspecified laboratory protocal. The approach is called guided-inquiry, or structured inquiry depending on the degree of support students are given in answering the the question posed in the assignment [3, 4]. A distinguishing characteristic of inquiry-based exercises is that the purpose of the assignment is to answer a question, which leads the students to discover new information and/or to develop new skills. In the words of Prince and Felder, inquiry learning exercises are designed to that "as much learning as possible takes place in the context of answering questions and solving problems" [4]. In the EET exercises we attempt to motivate student interest in the measurements with a demonstration of an interesting or surprising observation. For the sudden expansion exercise, the motivating issue is the large discrepancy between the measured pressure difference across the sudden expansion, and the pressure difference predicted by the Bernoulli equation.

We use the term *guided-inquiry* to describe the semi-structured approach to the assignment in the sudden expansion exercise. Students follow instructions on a worksheet that requires them to first make predictions of system behavior, make measurements to confirm or correct the predictions, and then perform additional analysis or comparisons with other measurements. In our guided-inquiry exercises, students perform all measurements, calculations, and written discussion in the laboratory. They are finished with their assignment when the lab period ends.

In the case of the sudden expansion exercise, a central objective is to show how the Bernoulli equation *does not* apply to the experimental and flow conditions. The Bernoulli equation is used early in the exercise to support qualitatively reasoning about the sign of the pressure change across the expansion, and to make a quantitative prediction about the magnitude of that pressure change. However, quantitative prediction with the Bernoulli equation cannot be reconciled with the measurements because the irreversible head loss violates a central assumption used in deriving the Bernoulli equation. The head loss at the junction between the ducts requires that the steady flow energy equation be used to explain the experimental data.

Misconceptions and Pre-existing knowledge

Students bring prior knowledge and experience to any learning situation [5, 6]. Sometimes this "knowledge" contains incorrect models for, and assumptions about, the behavior of systems. These errors in pre-existing models are called misconceptions, and must be unlearned before deeper conceptual understanding is obtained.

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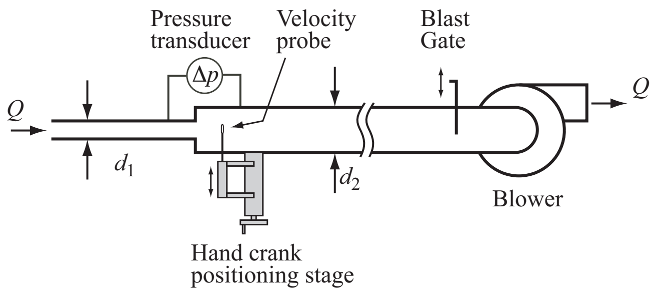

Figure 1. Apparatus for measuring the pressure difference across and the velocity profile downstream of a sudden expansion.

Prince and Vigeant have developed simple experiments to expose and repair misconceptions in fundamental concepts related to heat transfer and thermodynamics [7, 8]. Their work is aimed at concepts such as the nature of temperature and energy, the difference between the rate and amount of heat transfer, the meaning of entropy, the difference between steady-state and equilibrium, and the difference between reaction rate and reaction equilibrium.

The research team that developed the Thermal Transport Concept Inventory identified the Bernoulli equation as a topic that is both important for understanding and difficult for students to learn [9–11]. The sudden expansion exercise provides an opportunity to address two student misconceptions. The first is that fluid pressure must always decrease in the direction of flow. The second is that the Bernoulli equation can always be applied. Students might not espouse these ideas when asked to describe duct flow or the Bernoulli equation. The sudden expansion exercise requires students to apply reasoning to predict system behavior, and these misconceptions, if they are held, are exposed.

The sudden expansion exercise was one of three guided-inquiry laboratory exercises deployed in an introductory fluid mechanics course for third year Mechanical Engineering and Civil Engineering students during Fall 2006, Fall 2007, and Fall 2008. The exercise has been improved each year. Hsieh et. al describe results of a previous testing of the sudden expansion exercise – work that informed changes incorporated into the current form of the exercise [12]. Recktenwald et. al give an overview of several exercises in the EET project and provide some assessment data for the laboratory section required as part of an undergraduate course in fluid mechanics [2].

The remainder of this paper includes a description of the laboratory exercise, and the results of measuring learning gains and attitude change for students performing the exercises during Fall term 2008.

APPARATUS

Figure 1 is a schematic the main components of the laboratory apparatus. Figure 2 is a photograph of the duct area transition, the velocity probe, and the traverse apparatus. A two-speed blower (Dayton 4C566) draws air through a duct constructed from acrylic cylinders of two diameters. The inlet end of the duct has diameter d_1 and length L_1. A longer section of cylinder with diameter $d_2 > d_1$ connects the inlet section to the blast gate, which is just upstream of the blower. The transition from d_1 to d_2 is abrupt. Two functionally identical sudden expansion devices are used in the lab. One device has $d_1/d_2 = 0.64$ and the other has $d_1/d_2 = 0.47$. Students, typically in groups of four, work with one of these two devices.

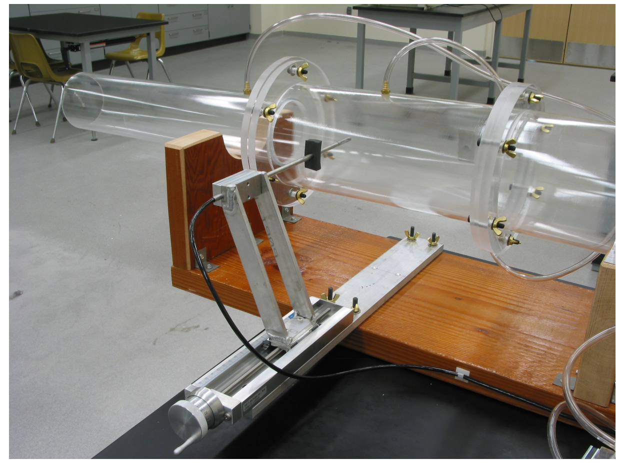

Figure 2. Photograph of the inlet section, traverse mechanism and velocity sensor. Air flows from left to right.

The flow rate through the duct is controlled by adjusting the blower speed switch (either high or low), and the blast gate, which is an inexpensive sliding damper which is sold as part of dust control systems for wood shops. The pressure change across the sudden expansion is measured with a differential pressure transducer (Omega PX653-0.5D5V). The air velocity is measured with a thermal anemometer (TSI Model 8455) mounted on a manual positioning stage (Velmex A2509Q2-2.5) that allows the anemometer to be moved to different radial positions across the larger duct. The velocity sensor is connected to a signal conditioner that produces a 0-5 VDC signal. A data acquisition device (National Instruments USB 6008) digitizes the output of the anemometer and pressure transducer.

The data is displayed on a computer with a virtual instrument (VI) written in LabVIEW. The front panel of the VI is shown in Figure 3. The VI automates the data collection and some of the data analysis. For these laboratory exercises, students are not expected to develop or modify the LabVIEW code, or to physically configure or wire the sensors. The emphasis is on learning about fluid mechanics. Instructors show students the LabVIEW wiring diagram and describe how other classes in their curriculum will provide opportunities to learn about sensors and data acquisition.

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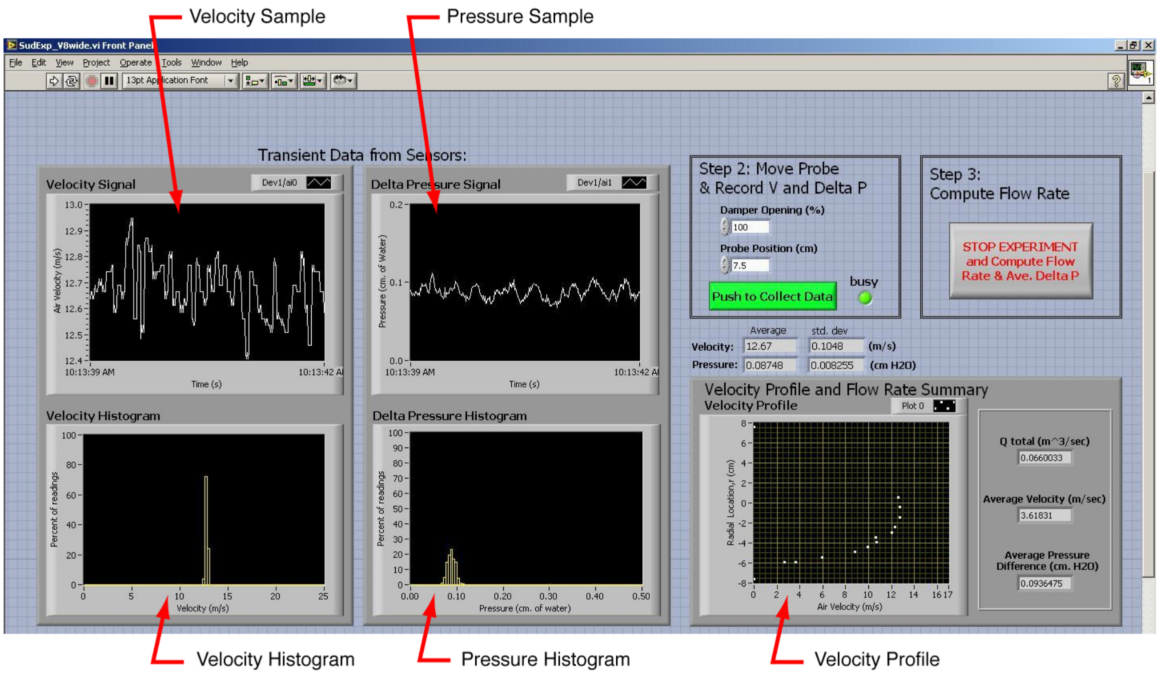

Figure 3. Screenshot of the LabVIEW virtual instrument displaying data during the sudden expansion experiment.

Although the flow through the sudden expansion is nominally steady, the VI updates the display with burst samples of 150 points of velocity and pressure readings taken at 50 Hz. The sample size and rate are adjustable, of course, but we found that exposing these data acquisition parameters to the students was neither necessary nor conducive to their understanding of the basic operation of the equipment. The VI clearly shows the fluctuations in the velocity and pressure, but the sampling rate and sensor bandwidth are not high enough to capture a true turbulent velocity signal.

Each sample from the velocity and pressure sensors is displayed as a function of time and as a histogram. The two leftmost subplots in Figure 3 show the transient velocity signal (above) and the histogram of 150 samples of the velocity (below). An analogous pair of plots near the center of the screen show the transient pressure signal and the histogram of that signal. The histograms provide an opportunity for students to think about the meaning of an average. They can also see how large disturbances to the system, say by suddenly blocking the inlet duct with a hand, will yield a distorted histogram. The display of the histogram allows us to make the point that the average of the samples can always be computed, but the average is not as meaningful when the distribution of values in the samples do not have a strong central tendency. When a sample of 150 readings shows histograms with nicely shaped (normal-like) distributions, the students click a virtual button on the screen to record the data to disk for later processing.

In earlier versions of this exercise, students were asked to numerically integrate the velocity profile to obtain the average velocity [1]. That extra step became a distraction to the larger goal of understanding the relationship between the velocity change and pressure change across the expansion. In the current version of the exercise, the VI computes the average velocity once the students have completed the traverse.

GUIDED-INQUIRY EXERCISE

The primary activity in the laboratory exercise is to relate the measured pressure difference across the sudden expansion to the prediction of the pressure difference by the Bernoulli equation. A secondary activity in the exercise is to measure the velocity profile downstream of the sudden expansion, and to numerically integrate the velocity profile to obtain the volumetric flow rate. The laboratory worksheet can be downloaded from `http://eet.cecs.pdx.edu/expt/suddenExp/`.

The activities during the exercise support the following learning objectives. After completing the lab exercise students will be able to

- Sketch the velocity profile downstream of a sudden expansion;
- Sketch the velocity profile at two flow rates;
- Apply mass conservation to a measurement of velocity profile in a duct;
- Use the conservation of mass to calculate the inlet velocity from the measured velocity downstream of the sudden ex-

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pansion;
- Explain why or why not the Bernoulli equation can be used to compute to the pressure change across the sudden expansion;
- Apply the Energy Equations to calculate the head loss across a sudden expansion.

The timing of this exercise with the material covered in lecture is important. We recommend that the students perform experiment *before* the instructor has extensively discussed minor losses in ducts. The guided inquiry experience is designed to motivate student interest in understanding minor losses.

Before turning on the blower and recording any data, students are asked to predict the sign of the pressure difference: does the pressure increase or decrease in the flow direction? Many students, without analyzing the flow, think the pressure must decrease in the flow direction, as it does for steady flow through a duct of constant cross sectional area.

After making their predictions about the sign of the pressure change, and completing a preliminary analysis, students turn on the apparatus and get immediate confirmation of their prediction (or error in prediction) for the direction of the pressure change. Students are encouraged to perform additional measurements and debugging tests to determine whether the equipment is correctly configured and functioning. For example, students can switch connections of the tubing that connect the pressure taps to the pressure transducer and inclined manometer. The pressure difference is low enough that incorrectly configured pressure signals will not damage the transducers.

The guided-inquiry worksheet asks students to develop or use an engineering model that explains the results. The "answer" to that step in the exercise is to combine the Bernoulli equation, $p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}\rho V_2^2$, with the mass conservation principle, $V_1 A_1 = V_2 A_2$, to obtain a formula that predicts the pressure change from the upstream to the downstream side of the sudden expansion

$$p_2 - p_1 = \frac{1}{2}\rho V_1^2 \left[1 - \left(\frac{A_1}{A_2}\right)^2\right] \tag{1}$$

For all cases, $A_1/A_2 < 1$, so $p_2 - p_1 > 0$. In words: when flow losses are neglected, the Bernoulli equation predicts that the pressure increases as the air moves downstream from the smaller duct to the larger duct.

From the flow rate obtained by numerically integrating the measured velocity profile, students are asked to use the Bernoulli equation to compute the pressure rise across the sudden expansion. Comparison between the theoretical data and the experimental data is startling: the measured pressure rise is several hundred percent smaller in magnitude than the pressure rise predicted by the Bernoulli equation. This creates a context for a discussion of the applicability of the Bernoulli equation. What could explain the large discrepancy? What physical effects are not captured by the model? Is there a model that better explains the data?

Even more confounding to the students, the sign of the measured pressure change for the apparatus with $d_1/d_2 = 0.47$ is negative, whereas the sign of the pressure change for the apparatus with $d_1/d_2 = 0.64$ is positive. In a typical laboratory exercise, at least two separate groups of students are working on copies of the apparatus with different d_1/d_2 ratios. The contradictory results allow the groups to interact and develop shared or competing strategies for resolving the discrepancy.

To resolve the difference between the two different sudden expansion devices, the concept of head loss must be introduced. The students see that the Bernoulli equation does not apply because the existence of head loss violates one of the key assumptions in deriving the Bernoulli equation. For these concepts to be understood correctly, we have found it important to have oversight by the lab instructor. With inadequate instructor involvment, students can become confused as they try to manipulate the Bernoulli equation so that it fits the data. Another bad outcome is that students will make a false generalization: because the Bernoulli equation does not match the measured data, the Bernoulli equation is never useful.

TYPICAL RESULTS

Figure 4 shows a velocity profile obtained from the apparatus when careful attention is paid to spacing between the sample points and when the system is allowed to stabilize each time the velocity probe is moved. More typical results from students are not as clean because the data is taken in haste. Regardless of how clean the profile looks, the LabVIEW VI integrates the velocity profile to obtain the volumetric flow rate and average velocity in the duct.

After the velocity profile is obtained for one flow rate, students are asked to predict how the profile will look at higher and lower flow rates. Many students describe the profile as "parabolic", the only shape of a velocity profile that they seem to retain from their study of fluid mechanics. At this point the instructor can point out the inflection in the profile, and other features that are different from the iconic fully-developed profile for laminar duct flow.

With the measured velocity and the measured duct diameters, students compare the pressure change predicted by the Bernoulli equation, with the pressure change from direct measurement. In all cases, the Bernoulli equation predicts that the pressure should rise as the fluid slows. As indicated above, the static pressure change is positive (pressure rises) for the apparatus with $d_1/d_2 = 0.64$, but it is negative (pressure decreases) for the apparatus with $d_1/d_2 = 0.47$. This behavior can be understood by application of the steady flow energy equation.

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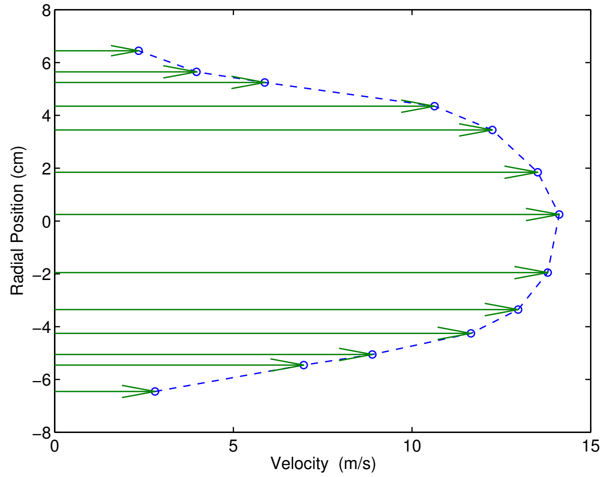

Figure 4. Typical velocity profile downstream of the sudden expansion.

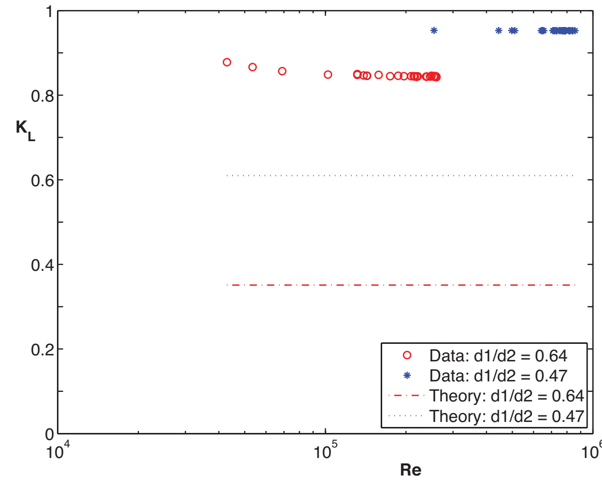

Figure 5. Computed loss coefficient for the sudden expansion with two different diameter ratios.

In the absence of a pump or turbine, the steady flow energy equation between two stations is [13]

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L \qquad (2)$$

where p is the static pressure, $\gamma = \rho g$ is the specific weight of the fluid, V is the average velocity at a given station, g is the acceleration of gravity, z is the elevation, and h_L is the head loss. For duct components such as elbows, junctions, and changes in duct area, the head loss is typically correlated by

$$h_L = K_L \frac{V^2}{2g} \qquad (3)$$

where K_L is the so-called minor loss coefficient, and V is a characteristic velocity. For a sudden expansion, the V in Equation (3) is the upstream average velocity. Combining mass conservation $V_1A_1 = V_2A_2$ with Equations (2) and Equation (3) gives

$$K_L = \frac{2(p_1 - p_2)}{\rho V_1^2} + \left(1 - \frac{d_1^4}{d_2^4}\right) \qquad (4)$$

where $A_1^2/A_2^2 = d_1^4/d_2^4$ for round ducts.

Figure 5 shows some typical data for head loss versus Reynolds number for the two diameter ratios. The Reynolds number is based on the average velocity and the diameter in the upstream (smaller) duct. Also shown are the K_L values from the standard design formula for head loss in a sudden expansion [13]

$$K_{L,\mathrm{std}} = \left(1 - \frac{d_1^2}{d_2^2}\right)^2 \qquad (5)$$

The measured head loss is higher than the prediction of the standard design formula, but the trend with the d_1/d_2 ratio is correct: K_L increases as d_1/d_2 decreases.

ASSESSMENT

In surveys of student attitude from Fall 2007, some students complained that the experiments showed that the theory did not work. For example, in the open response part of the survey one student wrote

> [The] sudden expansion, was poorly designed and did not reinforce concepts. It showed us where the theory does not work. However, we were still struggling to understand the basic concept. 4000% only confused us. Move the end pressure sensor! I want results that confirm theory, not contradict it!

The point of the exercise was to show a practical situation where the Bernoulli equation does not apply. However, as this student makes clear, the disagreement between theory and measurements can also lead to more confusion.

The exercise was redesigned for Fall 2008 to provide more structure and guidance to the student, i.e., the pure inquiry component was decreased. The goal was to allow the students to experience the disagreement between the Bernoulli equation and the measurements without becoming totally confused, or without concluding that both theory and experiment were useless. The guided-inquiry worksheet was rewritten and graphical “stop signs” were added to key points in the laboratory exercise. At the stop signs, students are expected to show their worksheets to the instructor before moving on to the next step. This provides an opportunity to do a cursory inspection of the written answers on the worksheet, and to check that students are not compounding

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Table 1. Laboratory exercises in EAS 361 during Fall 2008. Only the guided-inquiry exercises (1, 5, and 7) were part of the EET research project.

	Exercise	Type
1	Tank filling	guided-inquiry
2	Viscometer	Conventional
3	Pressure gages	Conventional
4	Hydrostatics	Conventional
5	Tank draining	guided-inquiry
6	Jet impact	Conventional
7	Sudden expansion	guided-inquiry

any pre-existing conceptual errors with new errors in reasoning. The open-ended responses to surveys at the end of Fall 2008 had no complaints about the contradiction between experimental results and the predictions obtained with the Bernoulli equation.

In Fall 2008, 137 students enrolled in one of two lecture sections of EAS 361, *Fluid Mechanics* a required course in the undergraduate Civil Engineering and Mechanical Engineering programs (ABET accredited BSCE and BSME). One section consisted of 84 students, predominantly in the Civil Engineering program. The other section consisted of 57 students, predominantly in the Mechanical Engineering program. Students from either lecture section were free to enroll in any of six laboratory sections that met weekly during the ten-week academic term. All students were required to complete the seven exercises listed in Table 1. Three of the seven experiments used the guided-inquiry approach.Additional information on the EET exercises listed in Table 1 is presented in companion papers [2, 14].

Of the 137 students enrolled in EAS 361, 118 volunteered to participate the research study by completing a background survey, and two attitude surveys: one at the beginning and one at the end of the term. For the volunteers, scores in the lab exercises and other measures of performance were recorded and correlated with demographic data. All participants were assigned a randomized numerical code to prevent any personally identifying information from being kept in the research database.

Learning Gains

Learning gains from the EET exercises were measured with a pretest/posttest design. For the sudden expansion exercise, the pretest and posttest consist of the same two multiple-choice questions and one short answer question. The pre/post test questions are in the Appendix. At the start of the lab meeting, students were asked to complete the pretest. The students were told that neither pretest nor the posttest count toward their grades. Students who volunteered to participate in the study identified their work by writing their unique numeric code on their pretest and posttest. Students who did not volunteer to participate in the research study could choose to take the pretest and posttest if they wished, but they did not identify themselves. The posttest was administered immediately after the students completed the lab exercise.

A total of 113 students completed the pretest and posttest. The average score increased from 38.9 percent on the pretest to 64.2 percent on the posttest. The Cronbach alpha, a common reliability indicator for testing, was very low: $\alpha = 0.07$ for the pretest, and $\alpha = 0.29$ for the posttest. The standard threshold for a reliable assessment instrument is $\alpha = 0.7$; instruments with lower α should not be considered indicative of student understanding [15].

The low α is most likely caused by student fatigue and disinterest in the pretest and posttest. The sudden expansion exercise took all of the 1.5 hour lab period and many student groups were frustrated at the intellectual effort and the amount of time taken by the exercise. The sudden expansion exercise also occurred at the end of the term, when the pretest/posttest were no longer novel or interesting. In addition, the small number of questions makes it difficult to obtain a large α. We believe that the sudden expansion exercise results in significant student learning. However, the procedure for measuring learning gains needs to be revised.

Attitude Toward Laboratory Exercises

Surveys administered at the start and end of the Fall 2008 term were used to measure student attitude toward the laboratory exercises. Fifteen questions on the pre-course and post-course survey were the same. The *change* in survey responses for those common questions shows that student attitude toward laboratory exercises was less favorable at the end than at the beginning of the course [2]. More detailed analysis of the changes in survey responses reveals that attitude toward the exercises correlated with the grade that students obtained in the class. Students who achieved grades of A tended to be be more negative than students who achieved grades of B and C. This pattern is discussed below in the analysis of post-course survey responses. The reliability of the pre-course survey responses, as measured by the Cronbach alpha, was low. In particular, the questions common to the pre-course and post-course surveys had $\alpha = 0.35$, so the responses cannot be considered a reliable indicator of student attitude change.

The post-course survey had 14 questions that were not common to the pre-course survey. Those questions and the mean student response are listed in Table 2. The Cronbach alpha for this set of questions was 0.84, with a 95 percent confidence interval of 0.80 to 0.89 [16]. Thus, the post-course survey instrument has good reliability for the students who volunteered to participate in the EET research project in Fall 2008.

The pre-course and post-course survey responses used a 5 point Likert scale. A response value of 1 indicates *strongly disagree*, a response of 5 indicates *strongly agree*, and response of

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Table 2. Mean response, R, to post-course survey questions at the end of Fall 2008.

Survey Statement	R
46. The inquiry-based laboratory exercises have increased my curiosity about the application of engineering principles to the machines and gadgets I use every day.	3.43
47. The inquiry-based laboratory exercises have increased my interest in laboratory work.	3.09
48. The inquiry-based laboratory exercises have increased my understanding of course material.	3.59
49. The inquiry-based laboratory exercises helped me understand the practical need for laboratory measurements.	3.54
50. I would like to have a data acquisition system to use with my personal computer.	3.39
51. The EET experiments and demonstrations have improved my ability to apply my engineering knowledge to practical problems.	3.34
52. The EET laboratory exercises have increased my ability to reason about the First Law of Thermodynamics.	3.23
53. The EET laboratory exercises have increased my ability to reason about the Bernoulli equation.	3.52
54. The EET laboratory exercises increased my confidence that I can correctly apply fundamental equations like the First Law of Thermodynamics and the Bernoulli equation.	3.36
55. I decided to participate in the EET project because an in-class demonstration of an EET experiment made me curious.	2.59
56. I decided to participate in the EET project because I am willing to try anything that might help me get a better grade.	3.23
57. I would recommend the EET exercises to a friend.	3.44
58. I would recommend the EET exercises to a friend who wants to learn more about core concepts in fluid mechanics, thermodynamics, or heat transfer.	3.51
59. I would recommend the EET exercises to a friend who is interested in improving his/her grade.	3.27

3 indicates *neutral*, neither agreement nor disagreement. A sixth choice, *No opinion* was provided, and empty responses were also accepted. The mean response, R, was computed as a weighted average of all responses in the range of 1 to 5, i.e., all responses that were not empty or not "no-opinion". Mean responses greater than 3 indicate agreement with the given statement in the survey question. Mean responses less than 3 indicate disagreement.

Table 3. Grade distributions students in EAS 361 during Fall 2008.

	Overall		Grade				
	GPA	N	A	B	C	D	F
Study Group	2.79	84	10	50	22	0	2
EAS 361 Overall	2.74	137	21	69	40	4	7

The mean responses in Table 2 tend toward agreement with the given statement for almost all questions. The strongest agreement value of 3.59 is for statement 48: *The inquiry-based laboratory exercises have increased my understanding of course material.* The strongest disagreement value of 2.59 is for statement 55: *I decided to participate in the EET project because an in-class demonstration of an EET experiment made me curious.* Question 55 is not applicable to students enrolled in the *Fluid Mechanics* lab because the EET exercises in the lab were required and did not have corresponding in-class demonstrations. Other EET exercises during Fall 2008 were introduced with in-class demonstrations [2]. With the exception of Question 55, all responses indicated a positive student response to the EET exercises.

The mean responses to the survey questions hide features of student opinions. We have analyzed subgroups of students by gender, age, previous engineering experience, and academic major. An interesting way to categorize student responses is by the final grade earned in EAS 361.

Table 3 shows the distributions of the grades for all 137 students in the class, and the 84 students in the *Study Group* who completed all survey instruments. The GPA of the class as a whole and of students who volunteered to participate in the research are nearly identical. When student responses were binned by grade, the data was simplified by ignoring the $+/-$ modifiers to the letter grade. Thus, an A^- was grouped with the A grades, a B^+ was grouped with the B grades, and so on.

Figure 6 and Figure 7 show the distributions of responses to

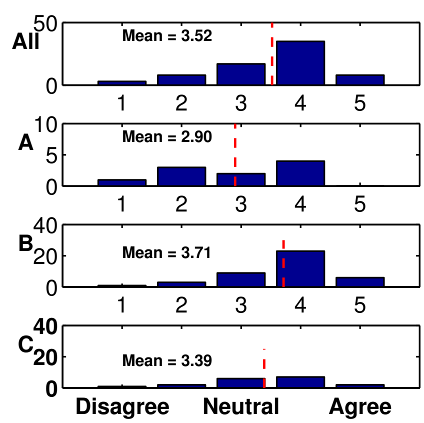

Figure 6. Responses to question 53: *The EET laboratory exercises have increased my ability to reason about the Bernoulli equation.*

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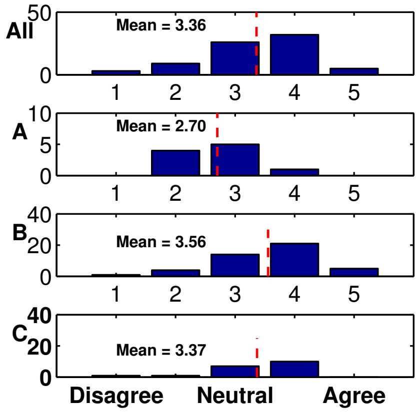

Figure 7. Responses to question 54: *The EET laboratory exercises increased my confidence that I can correctly apply fundamental equations like the First Law of Thermodynamics and the Bernoulli equation.*

questions 53 and 54 in Table 2. The top histogram in these Figures is the overall distribution of responses on the Likert scale. For both question 53 and question 54, the dominant response was "Agree" (numerical value of 4), though the strength of agreement for question 53 is stronger than question 54.

The bottom three histograms in Figure 6 and Figure 7 are the distribution of responses for students earning grades of A, B, and C, respectively. For Question 53 and Question 54, the B students had more favorable responses than the A students. The C students were also favorable, but not as strong as the B students. Also note from Table 3 that there were substantially more B grades than A grades, so the mean response is dominanted by the response of the B students.

The correlation of survey response with grade leads to further research questions. One hypothesis is that successful students, i.e., the A students, are less receptive to the guided-inquiry exercises because it requires them to work harder in the lab without increasing their understanding. The guided-inquiry exercises also introduce a new and unfamiliar mode of coursework, which increases the percieved risk of a lower grade. These hypotheses will be explored in continuing research on the EET project.

CONCLUSION

The sudden expansion exercise requires students to reason about the Bernoulli equation and to realize that it does not apply to flow through a sudden expansion. The exercise is challenging because the Bernoulli equation can be difficult to master when it *does* apply.

The assessment of learning gains is inconclusive. Student scores increased from the pre-lab quiz to the post-lab quiz, but the reliability of the quiz, as indicated by the Cronbach alpha, is too low. The reliability of the post-course survey response is very good.

Student survey responses are correlated with the final grade obtained in the course. The B students believed that the exercise improved their understanding of the Bernoulli equation, whereas the A students did not think the exercise was helpful. The C students also had a positive opinion of the exercise.

The sudden expansion exercise has undergone three cycles of deployment, assessment, and revision. Instructors interested in using this material are encouraged to visit and download the worksheet and fabrication information from the web site for the EET project, `eet.cecs.pdx.edu`. We will continue to make minor improvements to the worksheet and the LabVIEW VI, and post updates to the web site.

In the future, we will improve the pre/post test instrument. We will also provide more information before the lab so that students have some familiarity with the apparatus and purpose of the exercise.

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REFERENCES

[1] Recktenwald, G., and Edwards, R., 2007. "Using simple experiments to teach core concepts in the thermal and fluid sciences". In 2007 ASEE Annual Conference & Exposition, American Society for Engineering Education. paper no. AC 2007-2294.

[2] Recktenwald, G., Edwards, R., Howe, D., Faulkner, J., and Hsieh, C., 2009. "The engineeering of everyday things: Simple experiments in the thermal and fluid science". In 2009 ASEE Annual Conference & Exposition, American Society for Engineering Education. paper no. AC 2009-704.

[3] Staver, J. R., and Bay, M., 1987. "Analysis of the project synthesis goal cluster orientation and inquiry emphasis of elementary science textbooks". Journal of Research in Science Teaching, **24** (7) , pp. 629–643. Cited by Prince and Felder as a source of definitions for structured inquiry and guided inquiry.

[4] Prince, M. J., and Felder, R. M., 2006. "Inductive teaching and learning methods: Definitions, comparisons, and

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research bases". Journal of Engineering Education, **95** (2) , pp. 123–138.

[5] Bransford, J. D., Brown, A. L., and Cocking, R. R., Eds., 2000. *How People Learn: Brain, Mind, Experience, and School*. National Academy Press, Washington, DC.

[6] Svinicki, M. D., 2004. *Learning and Motivation in the Postsecondary Classroom*. Anker Publishing Company.

[7] Prince, M. J., and Vigeant, M., 2006. "Using inquiry-based activities to promote understand of crticial engineering concepts". In Proceedings of the ASEE Annual Conference and Exposition, American Society for Engineering Education. paper no. AC 2006-1379.

[8] Vigeant, M., Prince, M., and Nottis, K., 2009. "Using inquiry-based activities to repair misconceptions in thermodynamics and heat transfer". In 2009 ASEE Annual Conference & Exposition, American Society for Engineering Education. paper no. AC 2009-2039.

[9] Sreveler, R. A., Olds, B. M., Miller, R. L., and Nelson, M. A., 2003. "Using a delphi study to indentify the most difficult concepts for students to master in thermal and transport science". In 2003 ASEE Annual Conference and Exposition. paper no. AC 2007-2294.

[10] Streveler, R. A., Nelson, M. A., Miller, R. L., Olds, B. M., Evans, D., Mitchell, J., and Martin, J., 2004. "Investigating the conceptual understanding of engineering students". In Annual Conference of the American Educational Research Association.

[11] Sreveler, R. A., Miller, R. L., Nelson, M. A., Geist, M. R., and Olds, B. M., 2007. "Development and psychometric analysis o the thermal and transport concept inventory". In First International Confrence on Research in Engineering Education.

[12] Hsieh, C., Recktenwald, G., and Edwards, R., 2008. "Implementing inquiry-based experiments in a fluid science laboratory class". In 2008 ASEE Annual Conference & Exposition, American Society for Engineering Education. paper no. 2008-1351.

[13] Munson, B. R., Young, D. F., and Okiishi, T. H., 2006. *Fundamentals of Fluid Mechanics*, fifth ed. Wiley, New York.

[14] Edwards, R., Recktenwald, G., and Benini, B., 2008. "A laboratory exercise to teach the hydrostatic principle as a core concept in fluid mechanics". In 2009 ASEE Annual Conference & Exposition, American Society for Engineeering Education. paper no. AC 2009-251.

[15] Allen, K., Reed-Rhoads, T., Terry, R. A., Murphy, T. J., and Stone, A., 2008. "Coefficient alpha: An engineer's interpretation of test reliability". Journal of Engineering Education, **97** (1) January , pp. 87–94.

[16] Iacobucci, D., and Duhachek, A., 2003. "Advancing alpha: meausring reliability with confidence". Journal of Consumer Psychology, **13** (4) , pp. 478–487.

Appendix: Pre/Post Quiz

The following text was used as a pre-lab and post-lab quiz to measure student learning gains. Only the first and third questions were used to measure learning gain.

The schematic in Figure 8 depicts flow through a duct with a sudden change in cross sectional area. Assume that the flow is steady and incompressible.

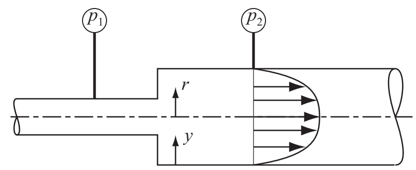
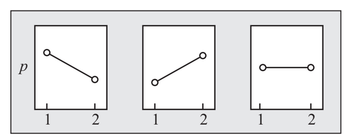
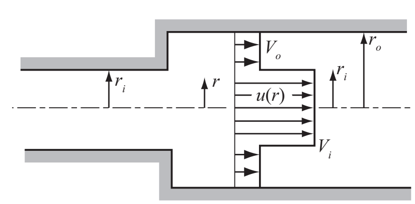


Figure 8. Flow through an abrupt expansion in a duct.

1. Assume that there are *no losses* and that the flow is from left to right, i.e., from the small duct to the large duct. Circle the graph that is most likely to agree with the trend in measured pressure values at stations 1 and 2. The plots are meant to indicate the *trend in the pressure*, not the exact variation in pressure across the step change in duct area.



2. Use an equation (or equations) or a physical reason to justify your answer to the previous problem.
3. The schematic depicts a simplified view of the velocity profile downstream of a sudden expansion. Which of the following expressions gives volumetric flow rate of the fluid that is passing through the sudden expansion?
   a. $\frac{1}{2}(V_o + V_i)\pi r_o^2$
   b. $\frac{1}{2}(V_o + V_i)\pi(r_o^2 + r_i^2)$
   c. $V_i \pi r_i^2 + V_o \pi(r_o^2 - r_i^2)$
   d. $\frac{1}{2}(V_o - V_i)\pi(r_o^2 + r_i^2)$
   e. $\frac{1}{2}(V_o \pi r_o^2 + V_i \pi r_i^2)$
   f. None of the above.



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