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Efficiently Assessing Hands-On Learning in Fluid Mechanics at Varied Bloom's Taxonomy Levels*

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The present study examines the effects of hands-on low-cost desktop learning modules (LCDLMs) in a fluid mechanics class consisting of 27 junior-level chemical engineering students. The LCDLM is a miniaturized venturi meter with standpipes that aid in visualizing pressure trends through the device. Pre- and post-assessment questions were administered to evaluate learning gains across different levels of Bloom's Taxonomy: remember, understand, assess, analyze, and evaluate. Findings show that the LCDLMs produce statistically significant pre/post effects at higher Bloom's level questions compared to the lecture group. Additionally, questions that incorporate the LCDLM design and associated experiments show higher significance in comprehension gain in comparison to questions that are not as closely related. These findings suggest that although the LCDLMs are effective in enhancing student performance at higher Bloom's levels, the design of the assessment questions and how they relate to the LCDLM is an important factor in properly assessing the effects of our novel teaching device on student performance in the fluid mechanics course. Theoretical and practical considerations for these findings and what they mean for future assessments of the LCDLMs are discussed in this manuscript.

Keywords: hands-on learning; active learning; ICAP hypothesis; classroom implementation; fluid mechanics

1. Introduction

Interactive and hands-on learning approaches have been researched extensively to enhance undergraduate engineering education and promote independent, higher-level thinking. As our world advances and is faced with more complex issues, there is an undeniable need for engineers to develop and use skills beyond what the technology we have created can accomplish. A computer, for example, can be used to store information in a database, perform lengthy calculations or analyses, and learn through repetitive inputs. The ability of these devices, however, is dependent on its creator. Although computers are able to analyze data, their aptitude for synthesizing information and making connections among ideas is incomparable to humans – this is what separates engineers from the technology they use on a regular basis. The abilities of a computer, though, sound remarkably similar to today's average engineering student; they store information in their brains, plug-and-chug numbers into equations, and learn through repetition in lecture and coursework. Operating at these low levels of the cognitive domain would not only warrant engineers to be replaced by technology, it could eventually lead to a plateau in technological advancement [1]. What is needed for students is better learning approaches that stimulate independent thinking processes and promote engagement of higher levels of learning. One such approach is hands-on, interactive learning as touted by Prince for its use in promoting student engagement and increasing retention of material [2] and by Freeman et al. because of their meta-analysis of 225 active learning studies showing that "students in traditional lecture courses are 1.5 times more likely to fail than students in courses with active learning" [3]; however, what is of paramount importance is the provision of exercises that promote the associated learning and use of cognitive measurement methods to assess the anticipated impacts of hands-on learning.

A system used to classify depth of knowledge of concepts and material is Bloom's Taxonomy. It is a framework consisting of six levels of mastery that build on each other: remember, understand, apply, analyze, evaluate, and create [4]. These Bloom's levels are referred to in a hierarchical order, and further description on each level based on our interpretation of how each relates to the activities

** Both authors, Kaiphanliam and Nazempour, contributed fairly equally. Nazempour led in the study implementation, question design, and initial analysis, while Kaiphanliam rigorously analyzed the data, wrote the majority of the manuscript, and thoroughly responded to reviewer comments.

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Table 1. Bloom's taxonomy descriptions in our context

Bloom's Level No. and Term	Description
1 – Remember	Recalling basic, fundamental facts without thought
2 – Understand	Relating facts to fundamental concepts
3 – Apply	Utilizing fundamental concepts to solve more complex problems
4 – Analyze	Breaking down technical phenomena in complex problems
5 – Evaluate	Justifying answers to complex problems with sound reasoning
6 – Create	Synthesizing information to contribute to a novel idea

associated with hands-on learning implementation in our own context are outlined in Table 1. Results from previous studies support a premise that traditional lecture approaches are useful for mastering material with learning expectations at the lower Bloom's levels such as remember and understand [5, 6]. However, when it comes to being able to apply, analyze, evaluate, or create, alternative methods such as hands-on, interactive learning are necessary.

Interviews with fluid mechanics professors reveal that many students struggle in describing the true meaning of continuity and the relationship between flow work and kinetic energy, including those who have already completed the course [5]. This suggests a lack of deeper understanding of key concepts in the fluid mechanics curriculum, and acts as the motivation behind rectifying the knowledge gaps maintained after lecture-based instruction.

To bridge the core-concept knowledge gaps persisting in a fluid mechanics classroom after traditional lecture, our group examined hands-on learning tools called low-cost desktop learning modules (LCDLMs) using an interactive group-learning approach to complement standard lecture in an attempt to demonstrate an enhanced learning experience by superimposing the more effective interactive approaches espoused by Felder et al. [7] onto a hands-on learning context. This study required expertise from both engineering and educational psychology, and with our team, we were able to delve into crucial aspects of engineering education implementations. Although in a previous study from our group we showed hands-on learning to have more of an effect at higher Bloom's levels on student comprehension [5], a major limitation in drawing more concrete conclusions was the small number of questions at each Bloom's level; in this study, we produced a 28-question pre- and post-assessment. The reader will find a brief overview of how our LCDLMs are designed and manufactured, the process of identifying common misconceptions to produce valuable pre- and post-assessment questions, and classroom implementation methods. Furthermore, we explore two major hypotheses tested using more comprehensive data from the aforementioned expansion of pre- and post-assessment questions. Succinctly, we predict that: (1) a hands-on learning approach will result in the same outcome as a lecture-based approach at lower levels of Bloom's taxonomy but will result in better outcomes at the higher levels of Bloom's taxonomy; and (2) as a result of using a venturi LCDLM with five standpipes rather than three to better visualize pressure trends, students in the experimental LCDLM group will have a better understanding about the relationship between pressure and velocity through a contraction and expansion than students in a control lecture group. Finally, we situate findings related to Bloom's levels within Chi's and Wiley's *Interactive Constructive Active Passive* (ICAP) framework [8] and Sweller's cognitive load Theory (CLT) [9–11].

2. Concept Design & Theoretical Background

2.1 Identifying Common Misconceptions

In a closely related Washington State University (WSU) study, Brown et al. [12] identified common misconceptions pertaining to open channel flow in a water resources engineering class. This was shown to be a key component in designing an experiential learning model. We then applied this same approach in a chemical engineering fluid mechanics course, i.e., to identify misconceptions related to continuity and Bernoulli principles, core fluid mechanics concepts that can be exhibited in a venturi meter. Students who had already completed a fluid mechanics class and professors who had years of experience in teaching fluid mechanics courses were interviewed, as reported at the American Society for Engineering Education (ASEE) annual meetings [6, 13]. To circumvent the need for the reader to locate documents through the ASEE website, we briefly summarize some of the major conclusions here in this section. The students were asked to briefly explain what each term in the mechanical energy (ME) balance, depicted in Equation (1), means and draw how pressure and velocity change through a venturi nozzle. Professors, on the other hand, were asked to note the misconceptions they have seen displayed amongst students while teaching the ME balance and continuity.

$$\frac{P_1}{\rho} + \frac{\bar{v}_1^2}{2} + g_z H_1 + \eta W_p = \frac{P_2}{\rho} + \frac{\bar{v}_2^2}{2} + g_z H_2 + h_f \quad (1)$$

While we find students capable of performing associated calculations after taking a fluid mechanics course, we still notice persisting misconceptions highlighted below:

- Many often do not have a full understanding of the full meaning of the terms in the energy balance, e.g., the P/ρ term is often thought of as a pressure rather than a flow work term, i.e. the work required to push fluid into or out of a system set apart for study.
- A significant number may continue to think fluid is squeezed by the narrowing diameter as it goes through the throat, resulting in a pressure increase rather than decrease. In a similar manner, they believe this "squeezed" pressure is released as the pipe diameter increases.
- One may continue to think velocity will increase or decrease along the length of a pipe of constant cross-sectional area when one or the other side of the pipe is elevated due to gravity.
- One can think velocity will vary linearly as fluid flows through a constriction whose diameter varies linearly with distance. However, because the variance in the velocity is proportional to the area through which fluid flows it therefore is a function of the square of the ratio of upstream and downstream diameters, i.e. with $(D_1/D_2)^2$.
- One can think pressure will also vary linearly as fluid flows through a linearly decreasing diameter. However, the pressure in the flow work term is related to the kinetic energy, and because kinetic energy is a function of the velocity squared, pressure varies as a fourth-order function decreasing with the ratio of downstream to upstream diameters, i.e. with a term that includes $[1-(D_2/D_1)^4]$.

For the above set of misconceptions, a series of questions was devised. Questions were developed to evaluate understanding at different Bloom's levels so we could assess where the learning innovation and its implementation, described later, were most effective.

2.2 Designing Questions at Varied Bloom's Taxonomy Levels

As noted by Nasr and Ramadan, there is a tendency for engineering students to plug values into models and equations without a deeper understanding of the terms, which led them to implement a problem-based learning approach in an engineering thermodynamics course [14]. A lack of conceptual understanding of fundamentals can make it difficult for students to deal with new problems and limits them in reaching higher levels of learning associated with the framework in Bloom's taxonomy [4]. Dealing with new situations and applying a fundamental understanding of phenomena in new contexts, however, are inseparable parts of engineering careers and are critical in promoting creativity in solving problems [15, 16]. As a result, proper assessment of learning regardless of teaching approach is vital to engineering education.

As in our previous papers [5, 6], we used pre-and post-assessment models to check the efficacy of the implementation in reducing pre-identified misconceptions. To have well-distributed questions, from simple to complex, we developed pre-and post-assessments based on the revised version of Bloom's taxonomy [4], which consists of six main categories defined by verbs in the cognitive domain of learning as described in the introduction. Our goal was to include questions from each level of the taxonomy in our pre-/post-assessments. To do so, we first came up with the pool of questions regarding continuity, Bernoulli's principle, and head loss. Then, using a mini-Delphi method [17, 18] with a post-doctoral fellow, two professors from the Voiland School of Chemical Engineering and Bioengineering, and one professor from the College of Education on the panel, we discussed and decided the Bloom's level of each of the proposed questions. Each member on the panel was provided with a copy of Bloom's taxonomy. Having one question per Bloom's level leaves the risk of students not understanding the question. To make results more reliable, multiple questions from each Bloom's level where considered for pre-/post-assessments.

The post-assessment consisted of 28 questions, each belonging to a particular Bloom's level; the questions asked are included in the Appendix along with a detailed rating rubric for assigning scores. Two questions at Bloom's Level 3 were omitted from pre- to post-assessment in the process of fine-tuning the assessment methods. Because the pre-assessment is treated as a covariate in the statistical analysis, all questions from the posttest were evaluated whether or not it was included in the pre-test. Statistics were performed on SPSS using either the analysis of variance (ANOVA) or analysis of covariance (ANCOVA) methods – the latter used when the question appeared in both pre- and post-assessments.

The outcome of a Bloom's Level 1 question is to recall basic facts. To assess students at this level, they were given a set of multiple-choice questions to define each term in the Bernoulli equation: P/ρ, $\bar{v}^2/2$, $g_z H$, h_f, and ηW_p. Additionally, they were asked to write the equation for velocity as a function of mass flow rate. At the second Bloom's level, understand, students should be able to identify and describe basic concepts. To assess students at this level, they were asked to select the correct description for three basic concepts.

At Bloom's Level 3, students are expected to be able to apply their knowledge to scenarios they may have not seen before. To assess students at this level, they were asked to select the correct option for pressure, velocity, and flow rate between two points in the pipe. These questions were not included in the pre-test and were therefore analyzed using the ANOVA method.

By Bloom's Levels 4 and 5 – analyze and evaluate, respectively – students are able to break down technical phenomena in complex problems and explain or justify the solution to those problems. Many of the questions to assess comprehension at the higher Bloom's levels were grouped together in a single question with two parts. For example, students were asked to select the correct graph for velocity verses distance in a venturi meter, and in the second part, were asked to justify their answer whether that be through equations or words. Although some of the questions were thought to identify as Bloom's Level 6, create, when the authors first started analyzing data, it was decided that those questions did not reach the expectations for how we describe this highest level in Table 1.

2.3 Theoretical Underpinnings

Chi and Wiley's ICAP hypothesis is critical in shaping our hypotheses on the effectiveness of the LCDLMs on student comprehension and in designing the LCDLM experiments and associated worksheets to further amplify the potential cognitive gains. ICAP is an acronym that stands for *interactive*, *constructive*, *active*, and *passive* modes of learning. The hypothesis is used to extend beyond the binary *active* or *passive* descriptors for learning approaches, allowing us to further categorize the level of interaction with material students experience across the different forms of active learning, such as the difference between conducting an experiment alone versus conducting an experiment in a group [8]. In a 2013 Chi associated study, Menekse et al. report on applying the ICAP hypothesis within an engineering context – for the first time since Chi developed ICAP – to assess comprehension gains in an introductory materials science engineering course before and after different types of in-class experiments. From the results of the short-term assessments, the researchers found that the ICAP hypothesis proved to be true, where the *interactive* experiments were more effective in producing comprehension gains than the *constructive* experiments and the *constructive* experiments were more effective than the *active* experiments [19]. The LCDLM activities are inherently designed to be *constructive* because they are experiment-based, but the associated worksheets with thought-provoking questions where students are required to collaborate and exchange ideas makes the implementation of the LCDLMs *interactive*. The results from Menekse et al. studying the ICAP hypothesis in an engineering context further contributes to our hypothesis that students who use the LCDLMs will outperform those in the traditional lecture group because it is an *interactive* implementation.

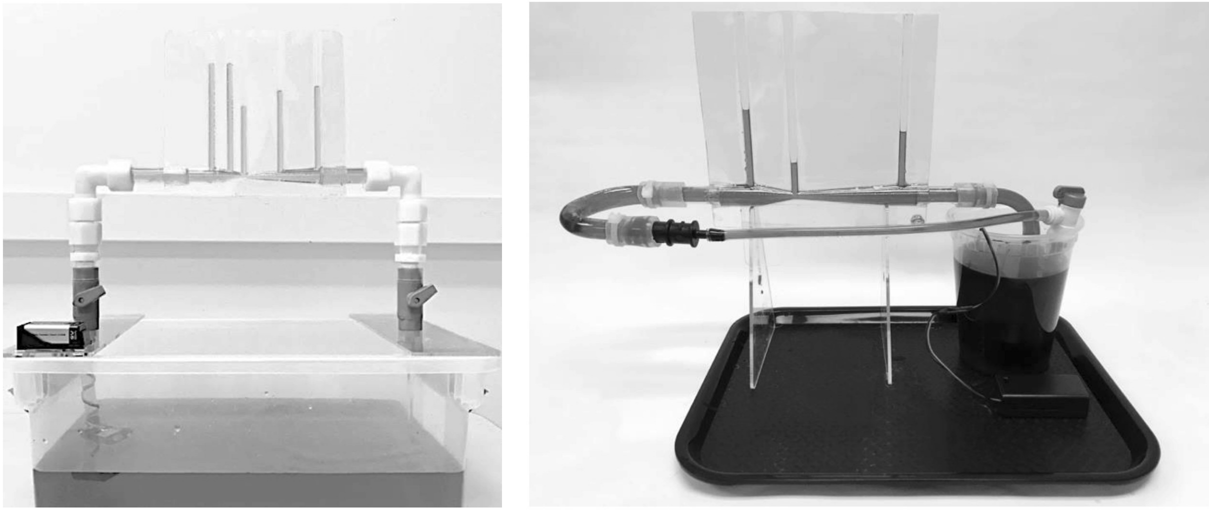
Sweller's CLT is another major notion in educational psychology that provides us a framework for analyzing the varied Bloom's level questions in our assessment to determine the effectiveness of the LCDLMs on student comprehension gains. The CLT takes into account how the number of conceptual elements associated with new material affects the transition from working memory to long-term memory in learners processing new information [9–11]. In other work by Sweller's group, Kalyuga et al. outline how the level of the learner in a particular domain is a critical factor in the ability of the learner to use information stored in the long-term memory to reduce the working memory load when presented with new material within the same domain [20], which will be useful in the analysis of our results because we are assessing junior-level students. General CLT and how the level of learner affects cognitive load in the working memory will be used to help explain student response results in relation to the hands-on learning context for the various Bloom's level questions in the assessment.

3. Experimental Design and Assessment Methods

3.1 Venturi LCDLM Manufacturing

To minimize common misconceptions related to continuity and the ME balance, a venturi meter was considered as an ideal engineering tool for use in the classroom. The venturi meter provides a consistent means of visualizing phenomena demonstrating both continuity and ME principles, along with the ability to fit on top of a classroom desk. Based on these criteria, an ultra-low-cost venturi meter was designed and developed – the manufacturing process is further explained in a former paper [21]. To describe fabrication briefly, two separate halves of the venturi meter are 3D printed using acrylonitrile butadiene styrene (ABS) and we vacuum form polyethylene terephthalate glycol-modified (PETG) thermoplastic sheets over the top of the 3D-printed structure. The two halves are then joint together using SciGrip's Weld-On 3 Acrylic Glue. The whole venturi with all accessories including the pump, batteries, and tubing costs on the order of \$50 to \$100 to manufacture – around the cost of, if not lower than, an average engineering textbook making it reasonable for purchase.

As mentioned previously, students tend to think pressure increases at the throat of a venturi because



(a) (b)

Fig. 1. (a) Venturi LCDLM with additional standpipes to better indicate hydrostatic pressures and (b) an older model of the venturi LCDLM with only three standpipes.

fluid would have to "squeeze" to pass the smaller area. To reduce this conceptual misunderstanding, vertical standpipes included for visualizing static heads at the inlet, throat, and outlet of the venturi were expected to be of help. In the hands-on section, each group of students was provided with the system shown in Fig. 1a. Moreover, based on our previous results with an older model (Fig. 1b), we had noticed that students believed pressure linearly changes through the venturi. To reduce the prevalence of this conceptual difficulty, we made a venturi meter with two additional standpipes, one between the inlet and the throat and another between the throat and the outlet.

3.2 Course Implementation

In a junior-level, 3-credit Fluid Mechanics and Heat Transfer (ChE 332) course at WSU, students were split into two sections. The group receiving lecture on the venturi meter consisted of 35 students; the venturi LCDLM group consisted of 27 students. All were allowed to self-select into one of the two sections. Both groups met together on Mondays and Wednesdays in a large lecture hall. On Fridays they were split into two groups that met in a smaller room with tables that could accommodate the miniature hands-on equipment. Both groups had prior hands-on activities in the use of a hydraulic loss system. Both had an initial Wednesday lecture on flow measurement using orifice and venturi meters, and other flow measurement systems. On the subsequent Friday, both had additional exposure to concepts related to the venturi meter, one through an LCDLM venturi hands-on, interactive session and the lecture group through a lecture covering the same content. To counterbalance exposure and ensure fairness of success in the course between the two groups, the venturi LCDLM section received lecture on heat exchanger concepts while the venturi lecture section received a heat exchanger LCDLM.

Even though both venturi lecture and LCDLM groups received a nearly identical worksheet, the lessons for each group were taught differently. In the lecture group, the instructor walked students through the fill-in-the-blank worksheet exercise solutions. In the LCDLM group, the instructor prompted the students with each successive question, allowed students to discuss solutions in teams of three or four, volunteer group answers, and briefly correct any misconceptions with professor input via document camera. The only difference in the worksheets was for tabulated data. The lecture group was given reservoir volumes, liquid collection times and static manometer heights to enter into a table. They were then shown, step-by-step, how to calculate volumetric flow rates and pressure drops. The LCDLM group was given a brief set of experimental procedures, and they used the venturi LCDLM to collect and obtain such data. In the hands-on section, to encourage students to actively take part in teamwork and make them think and analyze what they had just observed, we made sure each student team member had a role, as suggested in Oakley et al. [22], i.e., an equipment manipulator who controls the flow valve and holds the measuring cup, a moderator/facilitator who leads group discussion following the worksheet prompts, a summarizer/recorder who writes out group answers and data collected, and a reflector who works closely with the moderator/facilitator to answer thought questions more in depth.

3.3 Worksheet Principles

The main purpose of our venturi meter worksheet, briefly, is to provide students with various exercises and problems to assist them in learning targeted concepts related to continuity, the ME balance, and head loss. A full eight-page worksheet similar to that used in this implementation can be downloaded from our website (https://labs.wsu.edu/educ-ate/worksheets-2/). Based on the interview results, students struggled to understand energy balance or continuity between two distinct points in a system. We believe such misconceptions arise from the fact that students have a hard time in defining a closed-system and designating its border. As a result, we started the worksheet with a preparatory thought section, in which we asked students to apply continuity to different points in pipe flow and discuss how velocity changes in a pipe with a constant diameter. One of the main reasons we chose pipe flow as an example was that students tend to think pipe friction causes liquid to slow down as it travels down the pipe. We hoped having this example would reduce the prevalence of this misconception and help students understand that mass for any open or closed system, with no nuclear reaction, is conserved. We continued by providing the ME equation and asking students to reduce it between the points for which they had applied continuity. The reason behind this is students have difficulty in correlating velocity and pressure changes as fluid flows through a given system.

The worksheet continued with a blank table with spaces for collected volumes and times to determine flow rates, and corresponding manometer heights for the venturi inlet, throat and exit, from which one can determine pressure drops for two regions of the venturi, between the inlet and throat and between the inlet and outlet. The worksheet continues with exercises for applying the continuity equation to these two regions as well as the mechanical energy

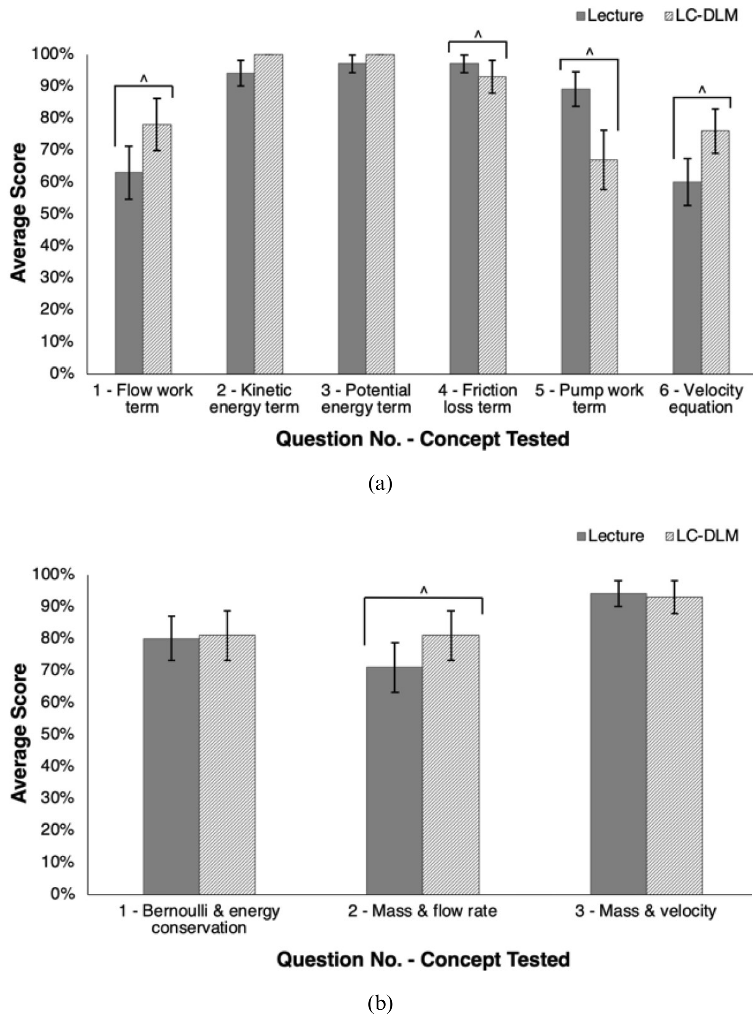


Fig. 2. Comparison of average posttest scores for Bloom's Levels 1 (a) and 2 (b) questions between the LCDLM and lecture groups using an ANCOVA analysis, treating the pre-test as the covariate. (^ small effect size).

balance and then continues with questions on how velocity and pressure vary within these regions, as well as why one will not see full recovery of the initial inlet pressure at the venturi outlet. Next there is space for showing how to combine continuity and energy balance relationships so that the throat velocity can be determined. Following is a section on why a venturi coefficient, C_v, is needed and how to determine it graphically from the data. The worksheet is followed by homework exercises to write a summary on what was learned under each objective and submission of a note set with all the associated calculations and percent deviation from venturi meter equation calculated volumetric flow rate to that determined experimentally.

3.4 Data Analysis

An ANCOVA statistical analysis was performed using SPSS to examine variances in understanding between pre- and post-assessments between the lecture and LCDLM groups with the pre-assessment as the covariate and post-assessment as the dependent variable. Two assumptions were tested prior to running statistics that: (1) values of the covariate cannot vary significantly across groups; and (2) for each independent variable, the relationship between the dependent variable and the covariate must be linear, also known as homogeneity of regression. P-values and partial eta squared η^2, small, 0.01–0.09, medium, 0.09–0.25, and large, >0.25, effect sizes are reported [23].

4. Results

Although easier to design, lower Bloom's level questions do not have positive gains nor losses in testing the effects of using LCDLMs on student comprehension. For Bloom's Level 1, we asked students to define each term in the ME balance equation, and for Bloom's Level 2, we asked students about the relationship between velocity, flow rate, and mass conservation – see Appendix for the exact questions asked.

As shown in Fig. 2a four of the six questions under the Bloom's Level 1 category show small effect sizes, two positive and two negative; however, when comparing the difference in magnitude of the posttest averages, none of the differences are statistically significant at a 95% confidence level. Similar results appear in Fig. 2 for the Bloom's Level 2 questions, where one of the three shows a small effect size, yet none show statistically significance differences. In other words, there is no apparent cognitive gain at these lower levels in conceptual understanding while using the LCDLMs. More importantly, there is no loss in understanding; therefore, if analyses at the higher Bloom's level questions show significant differential gains, there is considerable benefit in using LCDLMs.

At a mid-level, Bloom's Level 3, we begin to see in Fig. 3 an impact on student performance when using LCDLMs *interactively*. Although the first question shows no statistically significant difference between posttest scores, the second shows a statistically significant increase at the 95% confidence level ($p = 0.01$) and a medium effect size with a partial η^2 of 0.104 for the LCDLM over the lecture groups.

For the statistically significant question, we asked students to apply continuity and the mechanical energy balance to two points, both after a pump, to decide how flow rate, velocity, and pressure vary between the points (see Appendix). We developed this type of question because, based on the interviews with professors [6], many students have a misconception that fluid velocity at an upstream location is higher than that at a point

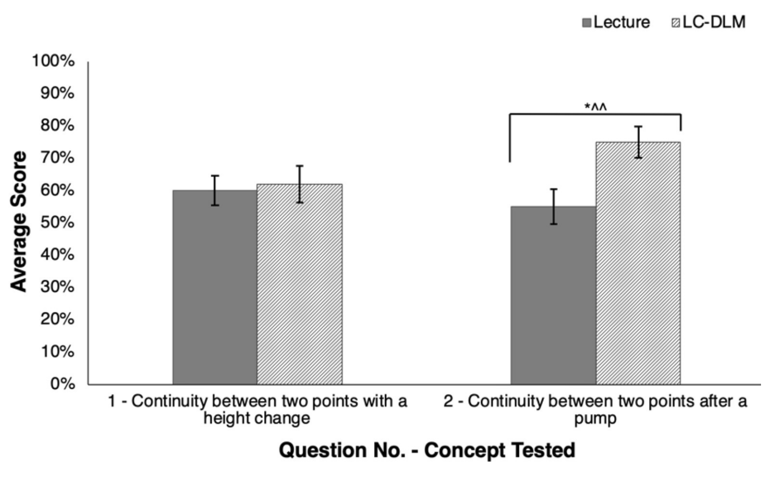
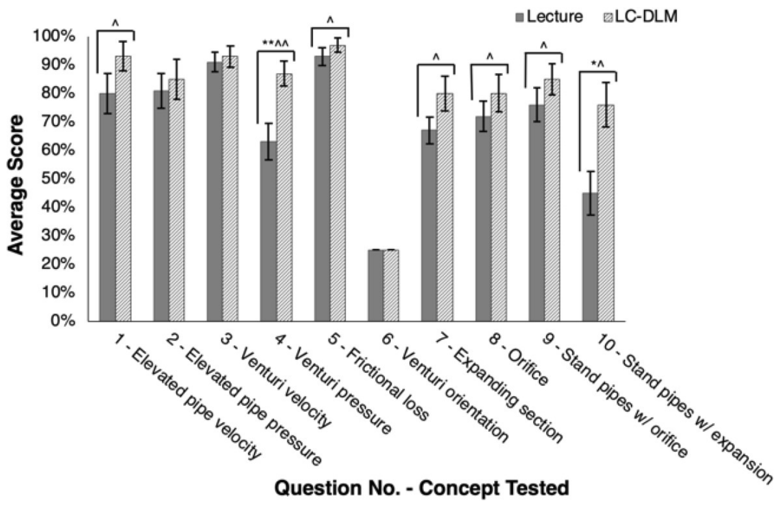
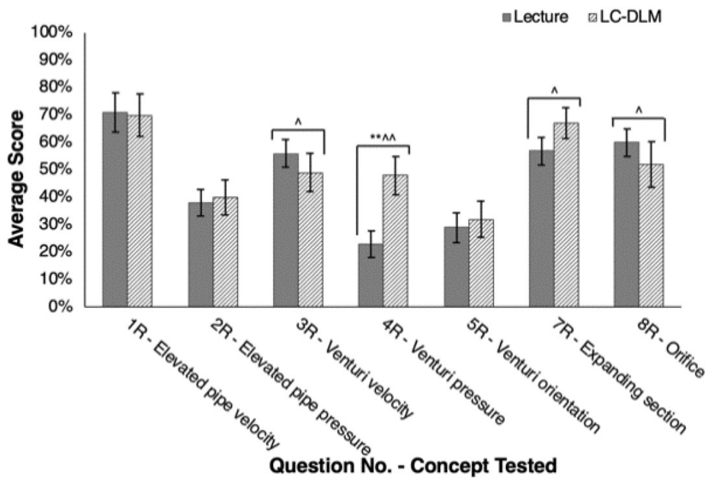


Fig. 3. Comparison of average posttest scores for Bloom's Level 3 questions between the lecture and experimental groups using ANOVA analysis. No pre-test scores are available to treat as a covariate. (* p < 0.05; ^^ medium effect size).



(a)



(b)

Fig. 4. Comparison of average posttest scores for Bloom's Levels 4 (a) and 5 (b) questions between the lecture and LCDLM groups using ANCOVA analysis, treating the pre-test as the covariate. Questions labeled "#R" in (b) are the reasoning or explanation portion of the Bloom's Level 4 question, hence making it Bloom's Level 5. (*p < 0.05, **p < 0.01; ^ small effect size, ^^ medium effect size).

further downstream despite the pipe having constant diameter. Rationale for the misconception is based on the incorrect thought that wall friction slows down the flow. While higher friction downregulates the flow rate at all locations between two points, the flowrate still remains constant and the previously mentioned misconception defies continuity; the correct conceptual understanding is that mass input and output flow rates are constant in a steady-state process, and, therefore, velocities are constant if the cross-sectional areas are equal. We surmise that the LCDLM group significantly outperformed the lecture group on the particular question discussed due to the *constructive* nature of the LCDLM itself, where students had the opportunity to set-up a basic pump system as part of the module, in conjunction with the *interactive* approach of the LCDLM implementation with the complementary worksheet and group experiments.

Now considering Bloom's Levels 4 and 5, we see an increase in the number of questions with statistically significant differences between the LCDLM and lecture groups and notable effect sizes in Fig. 4. The three questions that stand out in this data set are 4, 4R, and 10. Questions 4 and 4R have p-values of 0.003 and 0.002, respectively, and their effect sizes are both in the medium range (partial η^2 = 0.143 and 0.164, respectively). In this two-part question, we asked students to select the correct graph for pressure versus distance in a venturi, then we asked them to justify their choice by explaining the energy transitions with a summary of the two questions and graphical choices for the first question illustrated in Fig. 5. For the same reason as to

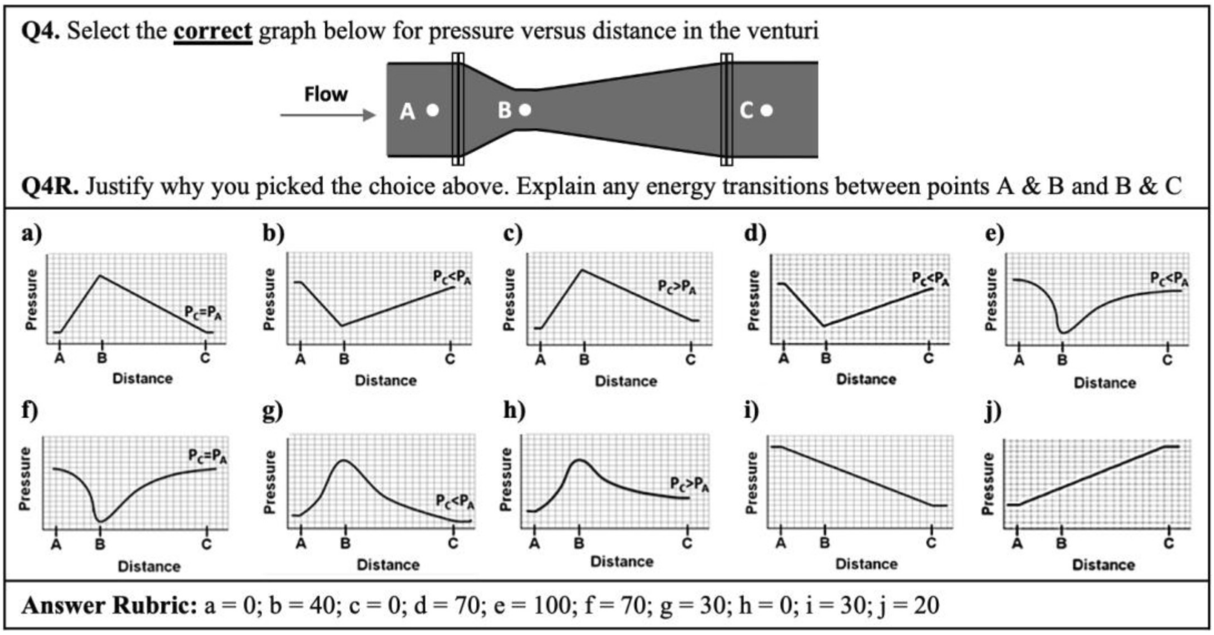


Fig. 5. Joint Bloom's Levels 4 and 5 question on pressure versus distance in a venturi with statistical significance.

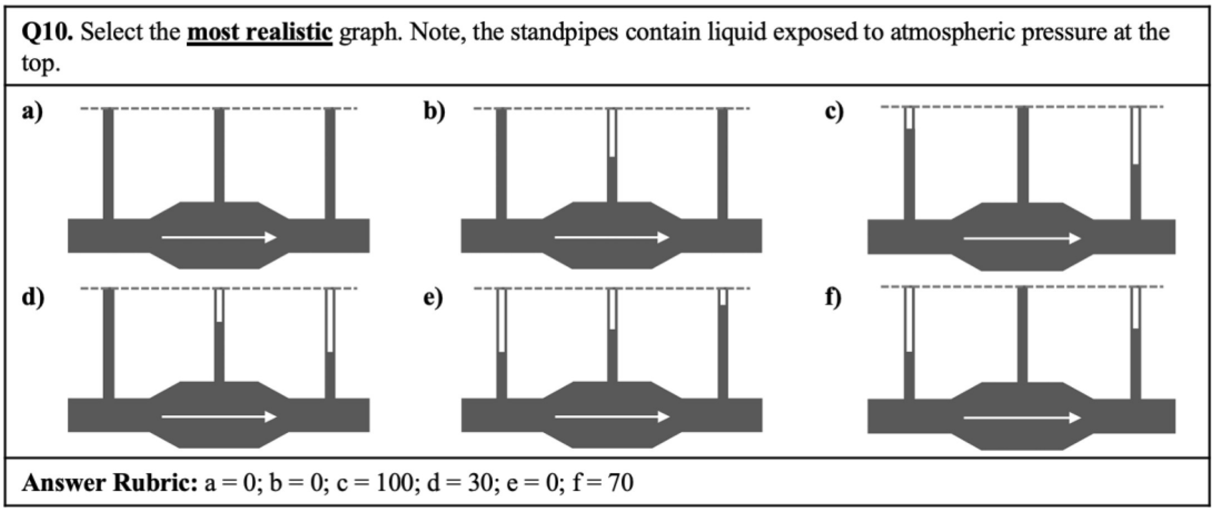


Fig. 6. Bloom's levels 4 question on pressure versus distance in an inverse venturi, or expansion in a flow system, with statistical significance.

why we developed the statistically significant Bloom's Level 3 question, this question is used to test a common misconception in the fluid mechanics classroom related to pressure versus distance in a venturi. As mentioned in section 2.1, students typically believe the pressure increases through the throat of a venturi because the fluid has to "squeeze" through a narrower section of tubing. The other statistically significant question, 10, is used to test the same concept, but in an opposite scenario – an expansion versus a contraction as shown in Fig. 6. The p-value for this question is 0.02, with a small effect size of 0.083.

From the aforementioned results, we can see a clear increase in statistically significant differences between the LCDLM and control groups with increasing Bloom's level. An additional finding we did not expect to see within each set of Bloom's questions, however, is the type of questions that show statistical significance at the higher Bloom's levels and that the nature of the question and its relation to the physical LCDLM may be another factor in showing significant differences between the two groups. In the following section, the reader will find how we relate our results to comparative literature and theoretical underpinnings and how our findings in addition to others' affects future hands-on implementations and assessments.

5. Discussion

5.1 Lower Bloom's Levels: 1 & 2

The lack of statistical significant between the LCDLM and lecture groups at lower Bloom's levels is not unexpected, as previous work by Burgher et al. [5] shows that out of five Bloom's Level 1 and 2 questions, none were significant at a 95% confidence level between control and experimental groups, and the research suggests that an *interactive* approach may not be more effective than a *passive* approach – terms derived from the ICAP hypothesis proposed by Chi and Wiley [8] – when testing students at these lower cognitive levels. The results at Levels 1 and 2 are consistent with what one would expect based on cognitive load theory (CTL). Each concept has a number of elements associated with it, and element interactivity is a measure of how each element within that concept relate to one another. Concepts with high element interactivity require comprehension of more information, while the opposite is true for concepts with low element interactivity. For example, the concept of velocity alone is easy for students to grasp, but the concept of velocity changes in a venturi requires students to integrate the knowledge they have of velocity with cross-sectional area changes in a venturi, hence higher element interactivity exists.

In CLT, higher levels of element interactivity in concepts add to the foundational *intrinsic cognitive load* [9–11], i.e. that which is inherent in the material and cannot be altered by variations in teaching approaches. Because lower Bloom's level questions are used to test concepts with low element interactivity, such as defining each term in the mechanical energy balance equation, they can be assimilated as easily through lecture and note-taking, and this low level of element interactivity may be one reason for the lack of significant difference between the two groups. Additionally, as outlined in the Theoretical Underpinnings, the foundation of knowledge the learner already has is a critical factor in using long-term memory to reduce working memory load when presented with new information in a domain with which the learner is familiar [20]. Because the students in this study are juniors and had taken an introductory transport phenomena class the semester prior, both groups most likely already had the basic concepts tested at the lower Bloom's levels stored in their long-term memory; therefore, the use of the LCDLM did not enhance the transition of such information from the working memory to the long-term memory for the students in the LCDLM group because they may have been spending the capacity of their working memory to learn concepts not already in their long-term memory.

Due to the lack of statistical significance, these lower Bloom's level questions may not be necessary for studying the effect of LCDLMs on performance and comprehension in junior- or senior-level courses, and there is support for removing them from pre- and post-assessments to focus valuable class time on more important assessments. Such questions may be more suitable in assessing the effectiveness of the LCDLMs on first- and second-year students, as they have not been presented with enough material from the domains being tested that they would not have a long-term memory base to pull from to reduce their working memory load. If there is time in the higher-level courses, though, the lower-level questions could be used as a control in the pre-assessment to determine if the lecture and experimental groups are starting at the same pre-knowledge level and are roughly equal in their ability to learn. Based on theory, we expect at higher Bloom's levels corresponding to higher element interactivity, having hands-on systems in front of students will reduce the cognitive load of information in the working memory.

5.2 Mid Bloom's Level: 3

As seen in the results, out of the two Bloom's Level 3 questions, the LCDLM group significantly outperformed the lecture group on a question (see in Appendix Bloom's Level 3 Q2) about whether velocity changes between two successive points after a pump; this may be due to the *interactive* learning experience, as the lecture group did not have the same experience of assembling and using the LCDLM in a team-setting. During the LCDLM experiment, the students followed the corresponding worksheet in their groups to assemble the hands-on learning module, making this an *interactive* or *constructive* form of engagement within the ICAP framework depending on whether the student was conversing with a peer to put the module together. In addition to assembling the LCDLM, students were required to collect flow rate data at four different valve positions. Because the valve on the LCDLM is placed just after the pump but upstream from the pressure standpipes, students may have realized that lower flow rates are correlated to the additional frictional losses introduced by the partial closing of the valve rather than incorrectly thinking that flow is faster just after a pump, and then slows down due to friction in the pipe; this may partially account for the statistical significance for the second Bloom's Level 3 question with the pump scenario.

Regarding comparative literature, we note a pre- to post-assessment comparison conducted by Ferri et al. [24] that falls in line with the ICAP framework, on the effects of an *interactive*, team-based, hands-on circuit board learning environment in a junior-level class on student performance. Though they did not have a lecture group, they found similarly, that "A" and "B" GPA-level students, who comprise 72% of the students in the study, performed statistically better by 14.2% on average on what we determined to be Bloom's Level 3 questions that related more closely to the hands-on experiment over performance on control questions they used. We note that while the comparative study questions are not explicitly defined as being at Bloom's Level 3 we deemed them to be based on a sample question presented by the authors where students were asked what the time constant is for a given plot of an output for a circuit; therefore, students had to apply their knowledge base to a new scenario that is still similar to the hands-on circuit board experiment. Based on the results of the current study at this mid-Bloom's Level 3 and comparative literature, we expect to see at the higher Bloom's Levels 4 and 5 that questions relating more closely to the LCDLM and complementary materials will show statistical significance more frequently compared to those that do not.

5.3 Higher Bloom's Levels: 4 & 5

As seen in our results across Bloom's Levels 3, 4, and 5 and comparative Bloom's Level 3 results from Ferri et al. [24], Cirenza et al. [25] also found that student test results showed statistically significant differences on questions that correlate more closely with activities performed in a workshop, where the researchers studied the effect of hands-on, computer-based workshops to assist in student understanding of heat transfer concepts. For example, the experimental group conducted a hands-on experiment by feeling two separate heating plates of different material at the same temperature, and scored significantly higher by 26.1% compared to the control group when tested on the concept of radiation for different emissivity and reflectivity values of two different surfaces at the same temperature. Relating back to the CLT and ICAP hypothesis, *interactive* or *constructive* modes of learning with a physical or *interactive* learning device may prove more effective than *active* or *passive* modes for higher Bloom's level questions. This is because the visualization provided by interaction with the device leads to storage of a mental image upon which conceptual understanding can be superimposed. Therefore, one does not need to store the physical geometric elements, especially in the LCDLM case, as they are easily viewed in front of students or by a mental image of the device available on instant recall. This lowers the demand on working memory and allows the student to focus on the more difficult conceptual elements as they relate to the geometrical system.

Constructive exercises are different from *interactive* ones, however, because the *interactive* level requires the exchange of ideas between two or more parties. Our current LCDLM experiments are *interactive* because we require the students to work in groups to conduct mini-experiments for data collection and discuss results led by a group-designated facilitator as they fill out the worksheet together. Similar group-approaches were also used in studies by Ferri et al., where students worked in pairs to complete a worksheet corresponding to the hands-on activity with instructor guidance [24], and Cirenza et al., where students were split into groups of two or three in challenge-based instruction to promote team discussions [25]. It may not be necessary, however, for the students to work together to learn at these higher Bloom's levels; the questions from Bloom's Levels 4 and 5 with statistical significance can also be answered by direct visual observations, or straight-forward applications, of what is seen during the LCDLM experiment. Finding studies to prove such a point on significant increase in performance at only a *constructive* mode of activity, though, has proven difficult, as most hands-on activities are performed in group settings for a number of reasons such as the cost of learning devices, space in a classroom setting, and time available.

The question about velocity in a venturi, on the other hand, did not show a statistically significant difference between the LCDLM and lecture control groups; however, both groups performed well, with average scores above 90%. Perhaps this is attributable to the fact that many times within the course, students need to determine velocity from a flow rate as a function of cross-sectional area, and that by the time of the posttest, this understanding has been cemented into their thinking. One can, however, make the LCDLM velocity profile more visual by introducing velocity tracers. This was actually done in an in-front-of-class demonstration using a document camera and overhead screen during the class by inserting small alginate beads for the LCDLM group, and could offer some explanation for the 6% increase in scores for the LCDLM group while the lecture group remained at 91%, but again, given the high scores and associated standard deviations for both groups, a much larger sample size would be needed in future studies to determine if this truly has an effect.

6. Implications, Conclusions, and Future Work

Although the 28-question pre- and post-assessments took an entire lecture period each, they served as a valuable means for assessing what types of questions at each Bloom's level are more appropriate for testing comprehension gains with a hands-on learning approach. Supporting our first hypothesis, lower Bloom's level questions do not show significant differences in growth between the lecture and LCDLM groups in the junior-level course, and in this circumstance, would only be necessary if the implementer has the time and is interested in using it as a control. Lower Bloom's level questions may be more suitable in assessing the effectiveness of the LCDLMs on first- and second-year students, as their long-term memory base is not as developed as junior-level students. It is also shown collectively across Bloom's Levels 3, 4, and 5 that the design of questions and their correlation to the LCDLMs is an important factor in assessing statistical significance between the lecture and LCDLM groups, further aligning with our hypothesis and what the ICAP framework would predict based on the *interactive/constructive/active* nature of the LCDLM and its corresponding activities. The second hypothesis is also well supported as conceptual understanding of flow and pressure profiles is aided by the visualization afforded by additional standpipes thereby reducing cognitive load as a mental image of the process is readily stored aligning with the old adage that "a picture (in this case a physical image) paints a thousand words."

We also find that there is the potential that students could simply see the LCDLM in a lecture demonstration and still outperform traditional lecture students on visual, higher-Bloom's-level questions; although, there are more important benefits to having students work in groups. Working in groups promotes growth in communication skills, an important skill for working on typical engineering projects that is normally lacking amongst engineering students. It is important to note the potential ability for students to still outperform a lecture group by just seeing the LCDLM at the *constructive* level, though, because this means the application of the learning device can extend to institutions who may not have the resources to purchase enough LCDLMs for their students to form groups of four or five.

The potential to enhance comprehension of engineering concepts just through the visual aide of the LCDLMs can also be useful in instances where distance-learning is necessary. Currently, in the time frame of writing this paper, we are faced with the coronavirus pandemic (COVID-19), which has caused universities to switch to online lectures. During this time, to follow-up with the idea that the LCDLMs can still increase performance at the *constructive* or *active* learning levels of Chi's theory, we are implementing the modules via step-by-step videos that the students can watch of the implementation and fill out the worksheet as they typically would. In the virtual LCDLM implementations, we expect the students will significantly outperform the virtual lecture group due to the ability of the LCDLMs to reduce working memory load when learning new material not already stored in the long-term memory, as seen in the results of this study relating to CLT.

Because we have developed a better understanding of question quality in assessing the effectiveness of our novel hands-on learning tool, a major implication from this study is pre- and post-assessments can be shortened significantly to only include questions that directly correspond to key concepts learned through use of the LCDLMs. So rather than the 28-question test used in the present study, though beneficial in elucidating which concepts are best learned in our approach, we can improve classroom efficiency by eliminating questions that are ineffective in assessing conceptual growth, or those at lower Bloom's levels where our results support that lecture is just as effective as the hands-on activities. New pre- and post-assessments consisting of 4 to 6 questions have been designed for our ongoing implementations and will provide data for future studies.

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References

1. R. W. Lucky, Are engineers designing their robotic replacements?, IEEE Spectrum, http://spectrum.ieee.org/at-work/tech-careers/are-engineers-designing-their-robotic-replacements, Accessed 5 December 2019.
2. M. Prince, Does *Active* Learning Work? A Review of the Research, *Journal of Engineering Education*, **93**(3), pp. 223–231, 2004.
3. S. Freeman, S. L. Eddy, M. McDonough, M. K. Smith, N. Okoroafor, H. Jordt and M. P. Wenderoth, *Active* learning increases student performance in science, engineering, and mathematics, *Proceedings of the National Academy of Sciences of the United States of America*, **111**(23), pp. 8410–8415, 2014.
4. D. R. Krathwohl, A revision of Bloom's taxonomy: an overview, *Theory Into Practice*, **41**(4), pp. 212–218, 2002.
5. J. K. Burgher, D. M. Finkel, O. O. Adesope and B. J. Van Wie, Implementing and assessing *interactive* physical models in the fluid mechanics classroom, *International Journal of Engineering Education*, **32**(6), pp. 2501–2516, 2016.

6. A. Nazempour, P. B. Golter, C. D. Richards, R. F. Richards and B. J. Van Wie, Assessments of ultra-low-cost venturi nozzle in undergraduate engineering classes, *American Society for Engineering Education*, Seattle, WA, 14–17 June, pp. 26.266.1–12, 2015.
7. R. M. Felder, D. R. Woods, J. E. Stice and A. Rugarcia, The future of engineering education II teaching methods that work, *Chemical Engineering Education*, **34**(1), pp. 26–39, 2000.
8. M. Chi and R. Wylie, The ICAP framework: Linking cognitive engagement to *active* learning outcomes, *Educational Psychologist*, **49**(4), pp. 219–243, 2014.
9. F. Paas, A. Renkl and J. Sweller, Cognitive load theory and instructional design: Recent developments, *Educational Psychologist*, **38**(1), pp. 1–4, 2003.
10. J. Sweller, J. P. Mestre and B. H. Ross, "*Cognitive Load Theory* " in *The psychology of learning and motivation: Cognition in education*, vol. 55, (*The psychology of learning and motivation*: Elsevier Academic Press, ch. 2, pp. 37–76, 2011.
11. J. Sweller, Element interactivity and intrinsic, extraneous, and germane cognitive load, *Educational Psychology Review*, **22**(2), pp. 123–138, 2010.
12. S. A. Brown, A. Easley, D. Montfort, J. Adam, B. J. Van Wie, O. O. Adesope, C. Poor, C. Tobin and A. Flatt, Effectiveness of an interactive learning environment utilizing a physical model, *Journal of Professional Issues in Engineering Education and Practice*, **140**(3), pp. 04014001.1-10, 2014.
13. J. K. Burgher, D. M. Finkel, B. J. Van Wie, O. O. Adesope, S. A. Brown and J. W. Atkinson, New hands-on fluid mechanics cartridges and pedagogical assessment, *American Society for Engineering Education*, Atlanta, GA, 23–26 June, pp. 23.927.1-17, 2013.
14. K. J. Nasr and B. Ramadan, Implementation of problem-based learning into engineering thermodynamics, *American Society for Engineering Education*, Anaheim, CA, 12–15 June, pp. 10.722.1 – 10.722.17, 2005.
15. M. Ogot and G. E. Okudan, Integrating systematic creativity into first-year engineering design curriculum, *International Journal of Engineering Education*, **22**(1), pp. 109–115, 2006.
16. C. S. Wasson, 1.2.1 System engineering competency the missing element in engineering education, *INCOSE International Symposium*, Chicago, IL, 12-15 July, **20**(1), pp. 21–36, 2010.
17. S. Q. Pan, M. Vega, A. J. Vella, B. H. Archer and G. R. Parlett, Mini-delphi approach: an improvement on single round techniques, *Progress in Tourism and Hospitality Research*, **2**(1), pp. 27–39, 1996.
18. P. Tugwell, C. Sitthi-Amorn, J. Hatcher-Roberts, V. Neufeld, P. Makara, F. Munoz, P. Czerny, V. Robinson, Y. Nuyens and D. Okello, Health research profile to assess the capacity of low and middle income countries for equity-oriented research, *BMC Public Health*, **6**(151), pp. 151.1-13, 2006.
19. M. Menekse, G. S. Stump, S. Krause and M. T. H. Chi, Differentiated overt learning activities for effective instruction in engineering classrooms: Differentiated overt learning activities, *Journal of Engineering Education*, **102**(3), pp. 346–374, 2013.
20. S. Kalyuga, P. Ayres, P. Chandler and J. Sweller, The expertise reversal effect, *Educational Psychologist*, **38**(1), pp. 23–31, 2003.
21. R. F. Richards, F. S. Meng, B. J. Van Wie, F. L. Spadoni and A. L. Ivory, MAKER: Very low-cost experiments via 3-D printing and vacuum forming, *American Society for Engineering Education*, Seattle, WA, 14–17 June, pp. 26.1121.1-14, 2015.
22. B. Oakley, R. Brent, R. Felder and I. Elhajj, Turning student groups into effective teams, *Journal of Student Centered Learning*, **2**(1), pp. 9–34, 2004.
23. P. Watson, Rules of thumb on magnitudes of effect sizes, University of Cambridge. http://imaging.mrc-cbu.cam.ac.uk/statswiki/FAQ/effectSize, Accessed 11 August 2019.
24. B. H. Ferri, A. A. Ferri, D. M. Majerich and A. G. Madden, Effects of in-class hands-on laboratories in a large enrollment multiple section blended linear circuits course, *Advances in Engineering Education*, **5**(3), pp. 1–27, 2016.
25. C. F. Cirenza, T. E. Diller and C. B. Williams, Hands-on workshops to assist in students' conceptual understanding of heat transfer, *Journal of Heat Transfer – ASME*, **140**(9), pp. 092001.1-10, 2018.

Appendix: Full Set of Pre- and Post-Assessment Questions and Scoring Rubric

Bloom's Level 1:

Choose the best definition for each term in the mechanical energy balance:

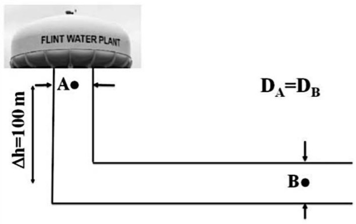
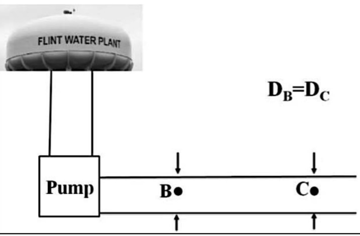
$$\frac{P_1}{\rho} + \frac{\bar{v}_1^2}{2} + g_z H_1 + \eta W_p = \frac{P_2}{\rho} + \frac{\bar{v}_2^2}{2} + g_z H_2 + h_f$$

Question	Choices	Rubric
Q1: $\frac{P}{\rho}$	a) Pressure drop b) Physical energy of the fluid c) Flow work	a = 0 pts b = 0 pts c = 100 pts
Q2: $\frac{\bar{v}^2}{2}$	a) Average velocity term b) Kinetic energy c) Momentum	a = 0 pts b = 100 pts c = 0 pts
Q3: $g_z H$	a) Enthalpy b) Potential energy c) Height change energy	a = 0 pts b = 100 pts c = 0 pts
Q4: h_f	a) Height b) Enthalpy c) Energy losses due to friction	a = 0 pts b = 0 pts c = 100 pts
Q5: ηW_p	a) Power needed to flow fluid through a piping system b) Pump work multiplied by the efficiency c) Pressure work	a = 0 pts b = 100 pts c = 0 pts
Q6: What is the equation for velocity as a function of mass flow rate?	Open-ended	$\dot{m} = \rho \dot{V}$ $(50\ pts)$ $\dot{V} = \bar{v}_A A_X$ $(50\ pts)$

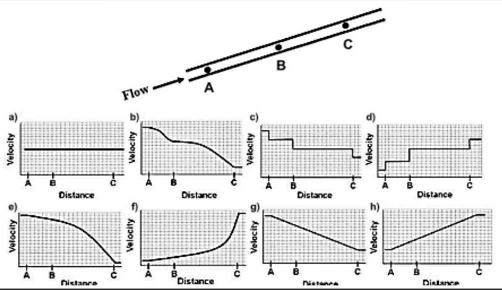
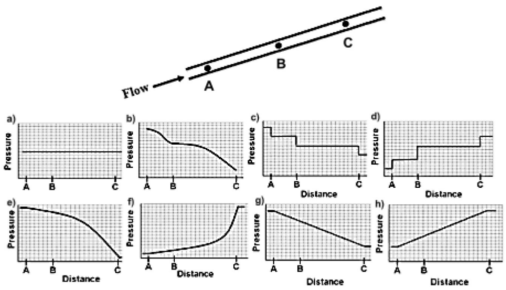
Bloom's Level 2:

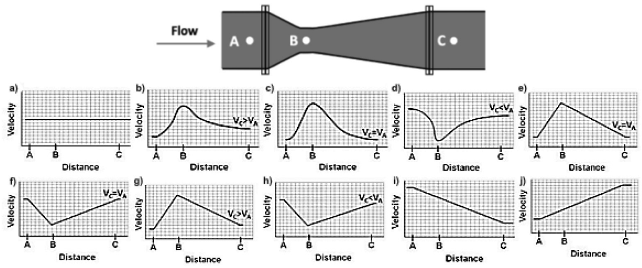
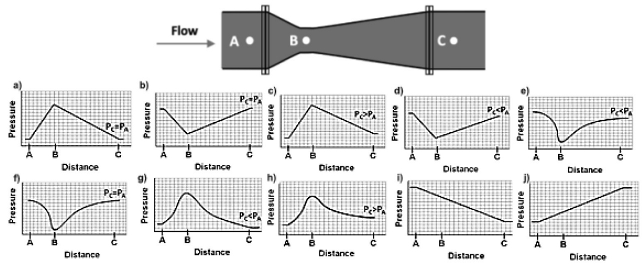
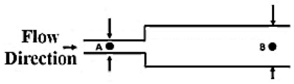
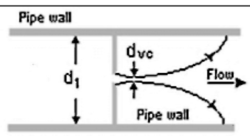
Question	Choices	Rubric
Q1: Bernoulli's equation tells us that along a streamline...	a) Energy is conserved b) Mass is conserved c) Pressure is constant d) Kinetic energy is constant	a = 100 b = 30 c = 0 c = 0
Q2: If mass is conserved, the volumetric flow rate of a constant density fluid in an expanding cross section...	a) Is constant b) Decreases c) Increases	a = 100 pts b = 0 pts c = 0 pts
Q3: If mass is conserved, average velocity of a constant density fluid in a decreasing cross section...	a) Is constant b) Decreases c) Increases	a = 0 pts b = 0 pts c = 100 pts

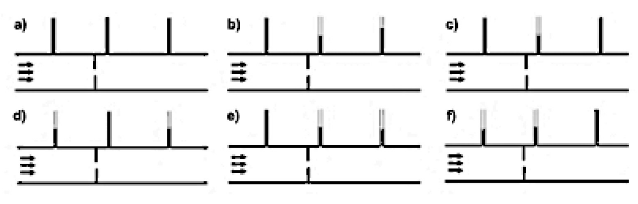
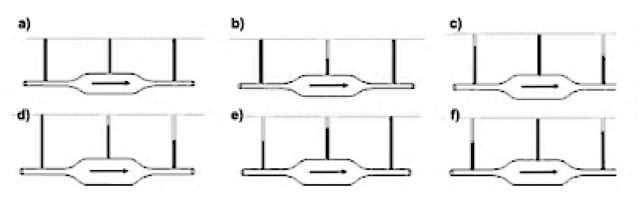
Bloom's Level 3:

Apply continuity and the M.E. balance between two points specified for the systems shown below and decide how volumetric flow rate, velocity, and pressure are different between these two points:		
Question	**Choices**	**Rubric**
Q1:  	Open-ended	$\dot{m}: Constant;\ \rho\bar{v}_A A_A = \rho\bar{v}_B A_B$ $(30\ pts)$ $A_A = A_B \Rightarrow\ \bar{v}_A = \bar{v}_B$ $(30\ pts)$ M.E. Balance: $\frac{P_A - P_B}{\rho} = g_z(H_B - H_A) + h_f$ Equation shows it could be either $P_A > P_B$ $(20\ pts)$ or $P_B > P_A$ $(20\ pts)$
Q2:  	Open-ended	$\dot{m}: Constant;\ \rho\bar{v}_B A_B = \rho\bar{v}_C A_C$ $(30\ pts)$ $A_B = A_C \Rightarrow\ \bar{v}_B = \bar{v}_C (30\ pts)$ M.E. Balance: $\frac{P_B - P_C}{\rho} = h_f$ $(20\ pts)$ $P_C < P_B$ $(20\ pts)$

Bloom's Levels 4 and 5:

Question	Choices	Rubric
Q1: Select the correct graph for **velocity** versus length in the pipe shown.	 	a = 100 pts b-h = 0 pts
Q1R: Justify why you picked the choice above. Explain why you see the velocity trend you selected for flow from A to B and B to C.		$\dot{m} = \rho\dot{V} = \rho\bar{v}_A A_A$ is constant (50 pts); ρ & A are constant ⇒ velocity is constant (50 pts)
Q2: Select the correct graph for **pressure** versus length for the pipe shown.	 	g = 100 pts b, e = 50 pts c = 25 pts a, d, f, h = 0 pts
Q2R: Justify why you picked the choice above.		Flow work to raise fluid (25) and overcome friction (25). Height varies linearly with length (25) and velocity is constant thus head loss is a function of length (25).

Q3: Select the most realistic graph for **velocity** versus distance in the venturi shown.		c = 100 pts b, e = 70 pts g = 40 pts f = 30 pts j = 20 pts a, d, h, i = 0 pts
Q3R: Justify why you picked the choice above. Explain why you see velocity changes between A & B and B & C.		Conservation of mass (30). Relation between flow rate and cross-sectional area (20). Relation between area and D^2 (20). $\bar{v}_A = \bar{v}_B$ (30).
Q4: Select the correct graph for **pressure** versus distance in the venturi.		e = 100 pts d, f = 70 pts b = 40 pts g, I = 30 pts j = 20 pts a, c, h = 0 pts
Q4R: Justify why you picked the choice above. Explain energy transitions between A & B and B & C.		Flow work converted to kinetic energy (40). Relation between V, P, and cross-sectional area (20) and D^{-4} (10). Frictional losses (30).
Q5: In the venturi above, what happens to pressure relative to point A when fluid reaches the end of the venturi meter at point C?	a) $P_C > P_A$ because of frictional drag build up along the way. b) $P_C > P_A$ because pressure at point B increases significantly due to a squeezing effect and the accumulated pressure will not disappear by point C. c) P_C returns to the exact value at P_A because of continuity and conservation of energy. d) P_C nearly to P_A because of continuity and conservation of energy; however, there is some conversion of energy associated with flow work to thermal energy due to friction. e) P_C falls significantly over the full length of the venturi meter due to frictional drag	a = 0 pts b = 0 pts c = 40 pts d = 100 pts e = 30 pts
Q6: One of the applications of a venturi is to measure flow rate. To do so, the venturi should be installed in...	a) Horizontal line b) Vertical line c) Inclined line with flow upward d) Inclined line with flow downward e) In any orientation	a – d = 25 pts e = 100 pts
Q6R: Justify why you picked the choice above.		Flow work depends on kinetic energy that is a function of throat diameter not venturi orientation (70). A non-vertical orientation introduces a height change effect but can be accounted for in analysis (30).
Q7: For the system shown, circle the right answer considering **$D_B = 100D_A$**.	 Choices include all 27 conditions possible for the combination of: $\dot{V}_A$ equal, higher, or less than $\dot{V}_B$ $\bar{v}_A$ equal, higher, or less than $\bar{v}_B$ P_A equal, higher, or less than P_B	$\dot{m}$: constant (30); $\rho\bar{v}_A A_A = \rho\bar{v}_B A_B$; $A_A \ll A_B \Rightarrow$ $\bar{v}_A > \bar{v}_B$ (30); M.E. balance: $P_A<P_B$ (40)
Q7R: Justify why you picked the choice above.		
Q8: For the orifice plate shown, choose the right answer considering **$d_1>d_{VC}$**.	 Choices include all 27 conditions possible for the combination of: $\dot{V}_1$ equal, higher, or less than $\dot{V}_{VC}$ $\bar{v}_1$ equal, higher, or less than $\bar{v}_{VC}$ P_1 equal, higher, or less than P_{VC}	$\dot{m}$: constant (30); $\rho\bar{v}_1 A_1 = \rho\bar{v}_{VC} A_{VC}$; $A_{VC} < A_1 \Rightarrow$ $\bar{v}_{VC} > \bar{v}_1$ (30); M.E. balance: $P_1>P_{VC}$ (40)
Q8R: Justify why you picked the choice above.		

Q9: Select the **most realistic** graph. Note, the standpipes contain liquid exposed to atmospheric pressure at the top.		$D \downarrow \Rightarrow A \downarrow \Rightarrow \bar{v}_A \uparrow \Rightarrow P \downarrow$ (40) $D \uparrow \Rightarrow A \uparrow \Rightarrow \bar{v}_A \downarrow \Rightarrow P \uparrow$ (40) Full pressure recovery does not happen because of frictional losses (20)
Q10: Select the **most realistic** graph. Note, the standpipes contain liquid exposed to atmospheric pressure at the top.		$D \uparrow \Rightarrow A \uparrow \Rightarrow \bar{v}_A \downarrow \Rightarrow P \uparrow$ (40) $D \downarrow \Rightarrow A \downarrow \Rightarrow \bar{v}_A \uparrow \Rightarrow P \downarrow$ (40) Full pressure recovery does not happen because of frictional losses (20)

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Olusola O. Adesope is a Boeing Distinguished Professor of STEM Education and a Professor of Educational Psychology at Washington State University-Pullman. Dr. Adesope's current research focuses on the use of systematic reviews and meta-analyses for evidence-based practices, cognitive and pedagogical underpinnings of learning with computer-based multimedia resources, and investigation of instructional principles and assessments in STEM education. Dr. Adesope's research is mostly funded by the National Science Foundation and published in top peer-reviewed journals. Dr. Adesope has over 100 published journal papers, book chapters and proceedings and presented over 80 conference papers in national and international conferences. Dr. Adesope is an Associate Editor of the Journal of Educational Psychology and a Senior Associate Editor for the Journal of Engineering Education and sits on the editorial boards of several top-tier journals including the Review of Educational Research, Contemporary Educational Psychology, and Educational Psychology Review. He is a recipient of several awards including the American Educational Research Association's early career research award.