Design Philosophy and System Integrity for Propagation of Hands-on Desktop Learning Modules for Fluid Mechanics and Heat Transfer

Negar Beheshti Pour, University of California - Berkeley
David B. Thiessen, Washington State University

David B.Thiessen received his Ph.D. in Chemical Engineering from the University of Colorado in 1992 and has been at Washington State University since 1994. His research interests include fluid physics, acoustics, and engineering education.

Prof. Bernard J. Van Wie, Washington State University

Prof. Bernard J. Van Wie received his B.S., M.S., and Ph.D., and did his postdoctoral work at the University of Oklahoma where he also taught as a visiting lecturer. He has been on the Washington State University (WSU) faculty for 37 years and for the past 23 years has focused on innovative pedagogy research and technical research in biotechnology. His 2007-2008 Fulbright exchange to Nigeria set the stage for him to receive the Marian Smith Award given annually to the most innovative teacher at WSU. He was also the recent recipient of the inaugural 2016 Innovation in Teaching Award given to one WSU faculty member per year.

Kitana Kaiphanliam, Washington State University

Kitana Kaiphanliam is a second-year doctoral student in the Chemical Engineering program at Washington State University (WSU). Her research interests include biomanufacturing for immunotherapy applications and miniaturized hands-on learning devices for engineering education.

Aminul Islam Khan P.E., Washington State University

Aminul Islam Khan PhD Candidate School of Mechanical and Materials Engineering Washington State University, Pullman, WA

Biosketch

Aminul Islam Khan has received BSc/MSc. in Mechanical Engineering from the most regarded and reputed engineering university of Bangladesh, Bangladesh University Engineering and Technology (BUET). In his BSc, he received the Gold medal because of his outstanding results.

Aminul Islam Khan has joined to BUET in 2011 as a Lecturer in Mechanical Engineering Department. Later, in 2015, he has become an Assistant Professor in the same department of BUET. In 2016, he has joined to School of Mechanical and Materials Engineering of WSU as a PhD student. From that time, he has been working as a Research Assistant. As a research assistant, he has been working to improve learning in undergraduate engineering education along with his scientific research.

Aminul Islam Khan is committed to excellence in teaching as well as research and always promotes a student-centered learning environment. He has a keen ability to teach, advise, and recruit students. He has proven himself to be a very effective researcher by publishing several journal articles. His resume has a substantial list of publications, including peer-reviewed articles in national and international journals and conferences. Moreover, he has joined in several reputed conferences, for example American Physical Society (APS), and presented his scholarly works.

Dr. Prashanta Dutta, Washington State University

Prof. Prashanta Dutta has received his PhD degree in Mechanical Engineering from the Texas A&M University in 2001. Since then he has been working as a faculty member in the School of Mechanical and Materials Engineering of Washington State University. He was promoted to the rank of Associate and Full Professor in 2007 and 2013, respectively. Prof. Dutta is an elected Fellow of the American Society of Mechanical Engineers (ASME). He current serves as an Editor for the Electrophoresis.

Mrs. Olivia Reynolds, Washington State University

Second year chemical engineering doctoral student pursuing research on the development and dissemination of low-cost, hands-on learning modules displaying heat and mass transfer concepts in a highly visual, interactive format. Graduated from Washington State University with a B.S. degree in chemical engineering in 2017 and with an M.S. degree in chemical engineering in 2018.

Katelyn Dahlke, University of Wisconsin - Madison

Katelyn Dahlke received her B.S. in chemical engineering from Iowa State University in 2013. She received her M.S. and Ph.D, in chemical engineering from the University of Illinois at Urbana-Champaign in 2019. She completed a postdoc doing hands-on engineering education research at Washington State University. She will be a faculty associate at the University of Wisconsin Madison starting in Summer 2020.

Prof. Olusola Adesope, Washington State University

Dr. Olusola O. Adesope is a Professor of Educational Psychology and a Boeing Distinguished Professor of STEM Education at Washington State University, Pullman. His research is at the intersection of educational psychology, learning sciences, and instructional design and technology. His recent research focuses on the cognitive and pedagogical underpinnings of learning with computer-based multimedia resources; knowledge representation through interactive concept maps; meta-analysis of empirical research, and investigation of instructional principles and assessments in STEM. He is currently a Senior Associate Editor of the Journal of Engineering Education.

Olufunso Oje, Washington State University

Olufunso Oje is a Masters student in the Educational Psychology program at Washington State University. His research interests include learning strategies in engineering education and multimedia learning. He has a Bachelor's degree in Electrical Engineering and a deep background in computing and software programming.

Jacqueline Burgher Gartner, Campbell University

Jacqueline Burgher Gartner is an Assistant Professor at Campbell University in the School of Engineering, which offers a broad BS in engineering with concentrations in chemical and mechanical.

Design Philosophy and System Integrity for Propagation of Hands-on Desktop Learning Modules for Fluid Mechanics and Heat Transfer

Abstract

We focus on a strategy others may use for propagating use of hands-on learning tools, in this case desktop learning modules (DLMs) for fluid mechanics and heat transfer courses. To accomplish this a faculty member needs to pay close attention to several factors broadly categorized under design philosophy, relevance of data procured to industrial equipment, and design for manufacture. In this paper, we will give a historical perspective on how a project like this may be initiated with dresser-sized units, then how one can proceed through a step-by-step process to refine and miniaturize technology, see aspects commercialized to promote adoption, and then further miniaturize the design and prepare it for a larger-scale reproducibility of the associated pedagogy. Hands-on units that are to be used at multiple stations within a classroom need to be low cost, light and simple to build. Such systems need to have maximum visual impact, quantitatively simulate industrial equipment, and be simple to operate by teams of students. We accomplish these goals by using injection molding of see-through plastics and off-the-shelf ancillary componentry to make hydraulic loss, venturi meter, and double-pipe and shell and tube heat exchanger units. Remarkably all of these units behave as anticipated when compared to textbook industrial correlations and representative data will be presented. We will also touch upon relevant factors being used to assess conceptual growth and motivation and to train faculty through a nation-wide hub-and-spoke scheme.

Background and Motivations

Golter et al. [1] first developed a set of hands-on classroom systems consisting of small heat exchangers and fluids systems, rack-mounted with small white boards for modeling equations. The concept was later updated in the form of Desktop Learning Modules or DLMs. Washington State University later joined with Armfield Ltd., a teaching equipment company to produce the final product, a one-cubic-foot unit called the DLMX that can hold seven different interchangeable cartridges, each representing a different miniaturized industrial equipment process including a Fluidized Bed, Orifice Plate, Energy Losses in Hydraulic Systems, Venturi System, Cross Flow Heat Exchanger, Tubular Heat Exchanger, and Shell and Tube Heat Exchanger units. These units are now commercially available from Armfield Ltd. with recommended best practices through use of a university level workbook [2] with exercises that can easily be modified to meet instructor and student needs.

The DLM project was initiated with the goal of transforming the STEM learning environment to make it more effective, exciting and experiential [1]. DLMs can be used to complement lecture-based courses and clarify common misconceptions in the chemical engineering curriculum [3-4]. These hands-on modules foster active, constructive, and interactive forms of engagement far more than lectures do [5] and allow students to see for themselves the real-world effects of the concepts and theories that they are learning in class.

The development of such novel, visual, hands-on learning tools has become increasingly popular [6-10] and data have shown that integration of these modules into the curriculum improves student learning outcomes [11,12], however, a number of factors prevent widespread adoption of these modules including cost, complexity, and size [13]. Thus, the developers of hands-on learning tools should focus on producing modules which are low-cost, miniaturized, and flexible in application and require minimum preparation time from professors for easy adoption.

To reduce the cost and complexity of such commercial engineering lab equipment, which can be a barrier for some institutions and may limit the number of units that can be deployed in a class, Van Wie and his team developed a manufacturing method that employed 3D printing and vacuum forming [14]. In order to form working flow channels by vacuum forming, 3D models of industrial equipment were designed to have a vertical symmetry plane such that two mirror-symmetric halves could be vacuum formed and joined by adhesive. The vacuum-forming molds of the two symmetric halves were made by 3D printing. The availability of low-cost vacuum forming equipment and 3D printing of CAD designs allows for rapid prototyping of designs. We have fabricated numerous inexpensive thermal-fluids experiments using this technique including a hydraulic loss pipe system, a venturi meter, a double-pipe and a shell and a tube heat exchanger [11,13]. We call these vacuum-formed affordable units Low-Cost Desktop Learning Modules or LC-DLMs or Affordable Transport Equipment (ATE). Engineering students can manipulate these modules to master concepts in thermodynamics, fluid mechanics and heat transfer.

The main draw backs of these vacuum-formed cartridges are that they often break when dropped on the floor and the difficult assembly procedure leads to a high failure rate when cartridges are tested for leaks. The two-part, transparent adhesive used for the vacuum-formed LC-DLMs has a very short working time of approximately five minutes. For more complex modules such as the double-pipe and shell and tube heat exchangers containing both plastic shells and metal tubes, applying the required adhesive to all portions of the module within the adhesive working time is difficult and even experienced assemblers often apply an incomplete layer of adhesive, leading to leaks [15].

We were able to improve the manufacturing process by redesigning the LC-DLM kits. The new design makes use of injection-molded polycarbonate parts and UV-cured adhesives. The use of injection molding allows for much tighter tolerances in the dimensions compared to vacuum-forming, which sometimes results in deformed plastic shells due to varying vacuum pressure along the length of the mold. Accurate knowledge of critical dimensions, such as a venturi throat diameter, is important for comparing measurements to theory. Additionally, the use of UV-cured adhesives allows unlimited time to apply the adhesive before curing via UV light. The selected adhesive also fluoresces under UV light, allowing assemblers to identify any gaps in the adhesive coating before curing. The consistent dimensions of injected-molded parts allows adhesive application to be automated with a programmable robotic applicator, saving considerable labor and nearly eliminating leaks in the completed cartridges. The new design is far more robust and also reduces the amount of pre-class preparation time to less than a half hour. Qualitative destructive testing of the injection-molded cartridges show that they don't break when dropped on a hard floor and are hard to break when thrown forcefully against a hard surface [15]. Figure 1 represents the timeline of DLMs development; from machined DLMs to low-cost DLMs.

In the next section, we will discuss several factors broadly categorized under design philosophy and design for manufacture that are essential for successful implementation and propagation of DLMs.

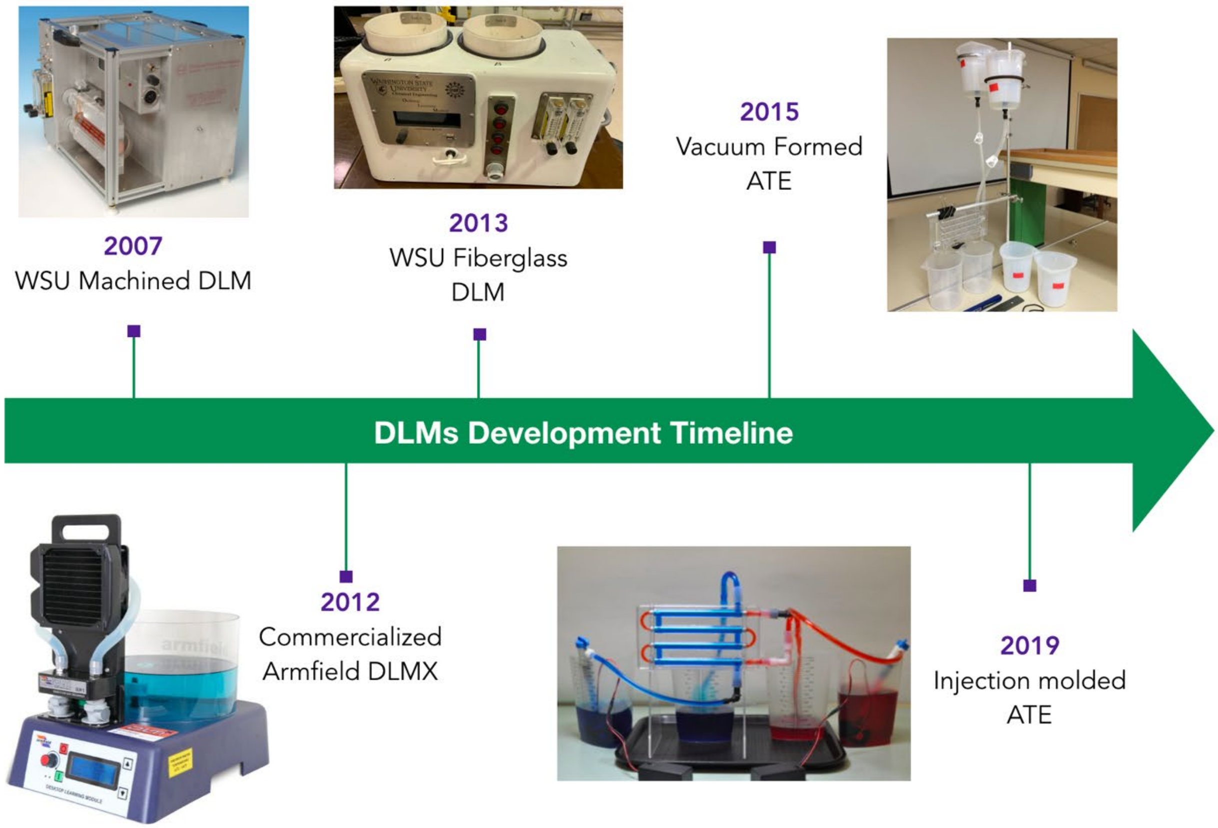


Figure 1. LC-DLMs development timeline from the rack-mounted units to the low-cost modules made through injection molding.

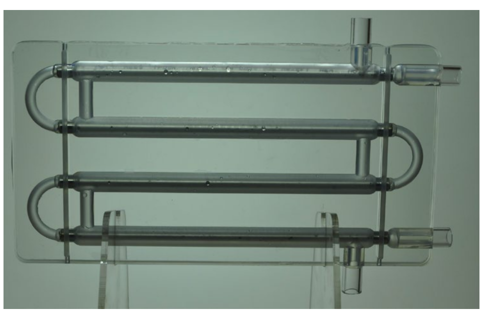
Design Goals

A number of requirements are essential for successful implementation and propagation of LC-DLM approaches. In order to enable wide-spread adoption of such experiments, the hands-on apparatuses need to be:

1) <u>Low-cost but robust</u>: Experiments must be inexpensive to buy and inexpensive to run. We use mostly off-the shelf parts and try to design kit components in a way that they can be used interchangeably between different units, however, at the same time, modules must be sturdy to prevent breakage. They should be able to withstand normal handling and even occasional mishandling. Any broken parts should be easy to replace quickly, easily, and cheaply. Our injection-molded LC-DLMs have been tested and results show they do not break even when dropped from 20

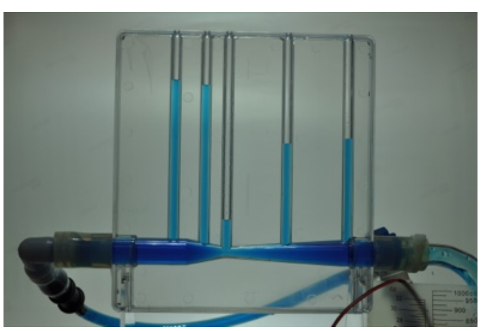
ft. With the new injection-molded design, the fluid mechanics kit including the venturi and hydraulic loss cartridges plus pump, beakers, etc. costs ~ $170 if ancillary components are used for both units and one limits use to one type of cartridge at a time. The heat transfer kit including the double-pipe and shell and tube heat exchanger cartridges plus pumps, beakers, thermometer, etc. costs ~ $225. A combined fluid mechanics and heat transfer kit with all four cartridges and pumps, beakers, tubing, etc. costs ~$346.

2) Designed to resemble industrial equipment: There are several examples of low-cost fluid mechanics and heat transfer desktop experiments in the literature that may be used to teach the fundamentals of fluid mechanics and heat transfer through hands-on activities [6,9], but these experiments do not attempt to look like miniaturized industrial process equipment. One of the advantages of LC-DLMs compared to other inexpensive learning tools is that LC-DLMs are designed based on industrial equipment. In Figures 2(a) and 2(b) we contrast the design of the double-pipe heat exchanger LC-DLM with a stacked industrial double-pipe heat exchanger used for heating sludge [16]. Figure 2(c) and 2(d) compare the venturi meter desktop learning module to a municipal venturi unit [17].



(a)

(b)

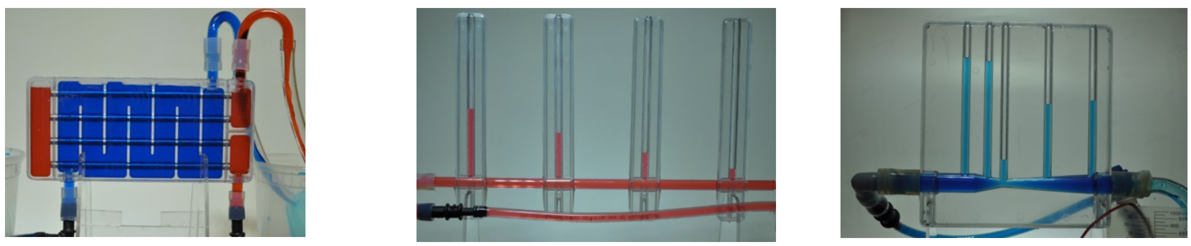


(c)

(d)

Figure 2. LC-DLMs designs resemble large scale industrial equipment.

3) Maximized for visual observation of phenomena: Clear plastic casing allows students to directly observe the fluid flow arrangement and meaning behind the various pitches, tubes sizes, spacing, turns and basic geometry that encompass typical equipment, and are used in mathematical modeling of heat transfer in a heat exchanger system or the pressure profile in a hydraulic loss or venturi unit. A close-up of the shell & tube heat exchanger, the hydraulic loss, and the venturi modules enhanced with food coloring are shown in Figure 3(a), 3(b), and 3(c) respectively.



(a) (b) (c)

Figure 3. A close-up of the shell and tube heat exchanger (a), the hydraulic loss module (b), and the venturi meter unit with food coloring to help students visualize flow patterns and pressure profiles.

4) Simple to set up and operate: Experiments must be fast and simple, requiring as little preparation by the instructor as possible. Students should feel comfortable manipulating hardware with minimal instruction. For this we demonstrate one-minute online tutorial videos to show students how to set up each module in less than five minutes. This approach will reduce the time and workload of implementation for the instructor or teaching assistants (TAs). These tutorial videos can be found under our website: https://labs.wsu.edu/educ-ate/tutorial-videos/

5) Suitable for use in any classroom: Our new LC-DLMs may be used in any classroom. So far, we have implemented them in a standard classroom with tablet-arm desks, a collaborative learning space (studio-type class) and rooms with tables in rows (see Figure 4).

6) Light weight and bulk of equipment: The overall weight for our DLMs ~ 2 lb, which is less than a textbook. Setups for a class of 48 students includes 12 kits to be used by groups of four students. These can be easily transported a classroom using one utility cart.

7) Designed to facilitate flexibility in implementation: With our new LC-DLMs instructors have flexibility in how they implement the modules, e.g., they can be implemented in a standard classroom with an instructor or TA transporting materials to the room. Alternatively, instructors can have teams or individuals pick up materials outside of class and bring them to class for common activities. Teams or individuals can pick up materials in or out of class for activities done outside of class. With the

simplicity of the new kits, students are able to set up the modules on their own in less than five minutes, and the compactness of the design increases application flexibility by allowing students to fit the LC-DLMs in their backpacks so they can be used outside the classroom. The other option is to set up LC-DLMs in a student space within the department for activities done outside of class. LC-DLMs can even be mailed to distance education students in standard medium-sized mailer boxes enabling instruction for place-bound students. In a national dissemination effort, we have begun distributing existing LC-DLM cartridges to institutions nationwide [15].

(a) (b) (c)

Figure 4. WSU Students working with different LC-DLMs in different types of classrooms; (a) a studio-type class, (b) a standard classroom with tablet-arm desks, and (c) a classroom with tables in rows.

8) Ability to make quantitative measurements: Results have shown that LC-DLMs can be used to validate textbook correlations and equations. For instance, Meng et al. [13] reported that mechanical engineering students used the low-cost air venturi nozzle and were able to validate the Bernoulli equation within experimental uncertainty, with fairly low scatter in the measurements. Beheshti Pour et al. [11] showed students can take reasonable data with the shell and tube LC-DLM in a 50-minute class period. Collective student group data illustrate the linear relationship between heat duty and the log mean temperature difference, as well as energy conservation principles. More importantly, these low-cost apparatuses provide quality data that are in excellent agreement with correlations developed for industrial scale heat exchangers.

Conclusions

Commercially available engineering lab equipment for thermal-fluids activities are typically expensive and generally require a dedicated lab space. For this reason, hands-on experimentation is often restricted to specific lab courses. Many of the concepts we teach in engineering science courses would benefit from a timely experiential component that can be brought into the classroom. We have developed low-cost, lightweight, easy and safe-to-use desktop experiments which replicate industrial equipment on a small scale and can be used in traditional classroom settings to display fundamental mass and heat transfer concepts in a highly visual manner. With a target cost comparable to a textbook, these experiments make it possible for teams of students to pursue their own investigations of fluid flow and heat transfer phenomena. These kinds of learning modules are also amenable for student-led design and construction activities as many universities have a maker space facility. In this paper, we gave a historical perspective on how the DLM project was initiated and evolved throughout the years. We also discussed a number of design goals that are essential for wide-spread adoption of LC-DLM. Studies with existing LC-DLMs show their use fosters deeper conceptual understanding. Studies are underway on transference of new LC-DLM technology and accompanying pedagogy to a variety of institutions.

Acknowledgements

The authors are grateful for support through the years that enabled design, development, assessment and commercialization and dissemination of DLMs through NSF grants DUE 0618872, 1023121, 1432674, 1546979, 1601404, and 1821578, the Norcliffe Foundation, Teaching and Learning Grants and the Washington State University Voiland School of Chemical Engineering & Bioengineering Teaching Fellow Program. Furthermore, we recognize collaborators along the way, Prof. Bob Richards who spearheaded the vacuum forming initiative, Prof. Jeff Laube who implemented and Kenai Peninsula College, assessed and provided design feedback for a 2-year Process Technology program, MS Andrew Easley, Profs. Jennifer Adam and Shane Brown who spearheaded efforts to create open channel flow DLM technology and refined assessment approaches, Dr. Gary Brown whose mentoring enhanced implementation efforts, Dr. Paul Golter whose MS, PhD and postdoctoral work laid the foundation for the longstanding effort, Voiland College of Engineering and Architecture machinist Gary Held who manufactured various versions of the DLMs and who with Machine Shop Director Miles Pepper proposed solutions for manufacturing DLM systems, Dr. Clint Cole and Scott Hanson of Digilent who designed digital displays, former Armfield CEO Chris Addis and Ted Sansom who had the vision for and designed the DLMX and Phillip Scuderi of the WSU Center for Teaching and Learning who mentored Prof. Van Wie during the initial implementations of the DLMs. We are thankful for the numerous undergraduate research assistants who have worked on the project and students and professors who have learned through and implemented the learning pedagogy. The NSF-IGERT grant 0903714 provided companion support for one of the co-authors and Prof. Van Wie received partial salary support from USDA NIFA Hatch Project WNP00807.

Bibliography

1. Golter, P., Van Wie, B., Windsor, J., Held, G., Practical Considerations for Miniaturized Hands-on Learning Stations. in 2006 Annual Conference & Exposition, Chicago, Illinois. https://peer.asee.org/1084.
2. Burgher, J., Thiessen, D., Van Wie, B., Arasteh, A., Finkel, D., Abdul, B., Eaton, B., Desktop learning modules for fluid mechanics and heat transfer classroom workbook: User's manual, worksheet exercises and assessments, 2013, WSU Publications, Pullman, WA.
3. Beheshti Pour, N., Thiessen, D., Van Wie, B., Implementation of an Ultra-low Cost Heat Exchanger Learning Module to Address Energy Balance Concepts. in 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana.
4. Beheshti Pour, N., Thiessen, D., Van Wie, B. (2018). Improving Student Understanding and Motivation in Learning Heat Transfer by Visualizing Thermal Boundary Layers, International Journal of Engineering Education, 34(2A), 514-526.
5. Adesope, O., Beheshti Pour, N., Van Wie, B., Thiessen, D., Work in Progress: Fostering Cognitive Engagement with Hands-on Learning Pedagogy. in 2019 ASEE Annual Conference & Exposition , Tampa, Florida. https://peer.asee.org/33622
6. Recktenwald, G., Edwards, R., Howe, D., Faulkner, J., Hsieh, C., The engineering of everyday things: Simple experiments in the thermal and fluid sciences, in 2009 ASEE Annual Conference and Exposition Proceedings, Austin, Texas.
7. Moor, S., and Piergiovanni, P., Experiments in the classroom: Examples of inductive learning with classroom friendly laboratory kits, in 2003 ASEE Annual Conference and Exposition Proceedings, Nashville, Tennessee.
8. Connor, J., Goff, R., Assessment of providing in-class, hands-on, activities to Virginia Tech's first year engineering students, in 2001 ASEE Annual Conference and Exposition Proceedings. Albuquerque, New Mexico.
9. Garrison, L., Garrison, T., A demo every day: Bringing fluid mechanics to life, in 2015 ASEE Annual Conference and Exposition Proceedings, Seattle, Washington.
10. Minerick, A., Schulz, K., Freshman chemical engineering experiment: Charged up on electrophoresis & brewing with bioreactors, in 2005 ASEE Annual Conference and Exposition Proceedings, Portland, Oregon.
11. Beheshti Pour, N., Thiessen, D., Richards, R., Van Wie, B., Ultra-Low-Cost Vacuum Formed Shell and Tube Heat Exchanger Learning Module, International Journal of Engineering Education, 33, 2(A), 723–740, 2017

12. Nazempour, A., Golter, P., Richards, C., Richards, R., Van Wie, B., Assessments of Ultra-Low-Cost Venturi Nozzle in Undergraduate Engineering Classes, in 2015 ASEE Annual Conference & Exposition, Seattle, Washington.
13. Meng , F., Van Wie, B., Thiessen D., Richards R., Design and fabrication of very-low-cost engineering experiments via 3-D printing and vacuum forming, International Journal of Mechanical Engineering Education, 47(3) 246–274, 2019,
14. Richards, R., Meng, F., Van Wie, B., Spadoni, F., Ivory, A., MAKER: Very Low-cost Experiments via 3-D Printing and Vacuum Forming, in 2015 ASEE Annual Conference & Exposition, Seattle, Washington.
15. Reynolds, O., Kaiphanliam, K., Khan, A. , Beheshti Pour, N., Dahlke, K., Thiessen, D., Gartner, J., Adesope, O., Dutta, P., Van Wie, B., Board 131: Nationwide Dissemination and Critical Assessment of Low-cost Desktop Learning Modules for Engineering: A Systematic, Supported Approach, in 2019 ASEE Annual Conference & Exposition , Tampa, Florida. https://peer.asee.org/32236
16. Kinam Engineering Industries. https://www.kinam.in/gallery.php# (accessed Feb 3, 2020).
17. Primary Flow Signal. https://www.primaryflowsignal.com/products/venturi-flow-meters/hvt-ci-cast-iron-hvt-di-ductile-venturi/ (accessed Feb 3, 2020).