ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education
JUNE 22 - 26, 2020 #ASEEVC
Paper ID #30087

Work in Progress: Using Jupyter Notebooks to Climb Bloom's Taxonomy in Thermodynamics

Prof. Bryan Weber, University of Connecticut

Dr. Weber joined the UConn Department of Mechanical Engineering faculty in 2014 and is currently an Assistant Professor in Residence and Director of Undergraduate Studies for Mechanical Engineering. He received his B.S.E. in Aerospace Engineering from Case Western Reserve University in 2009, and his M.S. and Ph.D. from the University of Connecticut in 2010 and 2014, respectively. Dr. Weber's research interests are in the development of software for combustion and thermodynamic analysis, as well as improving engineering education by integration of software to the classroom.

Work-In-Progress: Using Jupyter Notebooks to Climb Bloom’s Taxonomy in Thermodynamics

Introduction

To be effective engineers in the 21st century, students need a holistic understanding of the challenges that they face in a given project. This includes ethical, economic, social, and environmental aspects of a design, in addition to the technical aspects. Traditional engineering education focuses primarily on the latter of these, usually leaving the other aspects to the later stages of a student’s educational program, e.g., capstone projects.

However, students would benefit from, and are interested in, integrating holistic education throughout the curriculum. Moreover, university engineering programs that are accredited by ABET are required to meet these objectives. In their recent redevelopment of the student outcomes criteria, ABET [1], [2] identified seven primary outcomes for students. Of these, items two and four focus on holistic engineering, emphasizing global cultural, social, environmental, and economic factors.

To address all of the critical aspects of engineering projects, students must successfully analyze the requirements, synthesize information, and evaluate several design options for a given problem. These cognitive skills match well with Bloom’s Taxonomy [3], [4], which identifies six levels of learning. From lowest to highest these are: 1. Remember 2. Comprehend 3. Apply 4. Analyze 5. Synthesize 6. Evaluate

Achieving analysis, synthesis, and evaluation requires active participation from the students. Research shows that student outcomes are improved by engaging in active learning [5], [6]. This includes not only higher grades in courses, but also greater “mastery of higher- versus lower-level cognitive skills” [6].

The present work describes the application of active learning of holistic engineering practice in a sophomore-level thermodynamics course sequence. First, the motivation for pursuing these changes is discussed, followed by a description of the technologies the author has integrated into the course. Then, preliminary analysis of course outcome data is presented and several lessons-learned are included.

Motivation

The motivation and approach for this work are described in detail in the author’s previous work [7], [8]. A brief description is included here for completeness.

Many traditional thermodynamics classes and textbooks rely on tables of properties for simple compressible systems that students use to solve problems. The arithmetic required to perform linear interpolation in these tables impedes understanding of underlying physical principles in a problem and increases the chances for a trivial error to creep into a problem solution. Moreover, the time that students are required to spend on interpolation prohibits the study of a range of conditions for a given physical system.

The combination of these two factors limits the available problems that instructors can assign to problems that generally have one correct solution. However, “real” problems have multiple feasible solutions that require engineers to synthesize knowledge, evaluate outcomes, and analyze results. Problems of this sort require higher levels of thinking on Bloom’s Taxonomy. Lifting

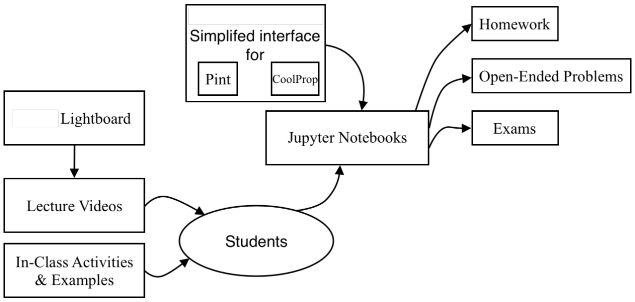

Figure 1: Overview of the interaction between elements of the approach used to engage active learning and move higher on Bloom's taxonomy in the author's thermodynamics courses.

students to higher levels of learning on Bloom's Taxonomy is an effective method to prepare them to be engineers in the 21st century. Achieving this goal via active learning engages students in their own education and improves their outcomes in the course [6].

Methods

The strategies discussed in this manuscript have been applied to two thermodynamics courses in the Department of Mechanical Engineering at the University of Connecticut. Typical enrollment in these courses is approximately 150–180 students per semester, usually split into several lecture periods. The courses cover the first and second laws of thermodynamics, applications to open and closed systems, evaluation of properties of pure fluids, cycle analysis (Brayton, Rankine, etc.), and psychrometry.

Figure 1 shows an overview of the elements the author has developed to engage students in active learning and shift them higher on Bloom's Taxonomy. Prior to class time, students watch lecture videos posted to an online video platform. The videos are also embedded in an online quiz that reinforces conceptual content. These videos and the quiz broadly accomplish the first two levels of Bloom's Taxonomy, that is, remembering and comprehending.

During class time, students apply the knowledge from the lecture videos during guided in-class activities and examples. These activities are designed to accomplish the third level of Bloom's Taxonomy. Outside of class, students further cement their application skills by using open-source web-based software (Jupyter Notebooks and ThermoState) to solve homework problems and take exams. Finally, students use the same software to conduct analysis for their open-ended problems and reports. This leads them to the three highest levels of Bloom's Taxonomy: analysis, synthesis, and evaluation.

Problem-Based Learning

The overall approach taken in this work is to incorporate problem-based learning (PBL) into the thermodynamics courses. According to Tatar and Oktay [9], PBL satisfies the criteria identified for implementation of active learning and the higher-level learning on Bloom's Taxonomy identified above. Thus, PBL seems to be an ideal approach to achieve the objectives of this work.

Each PBL problem statement should incorporate some aspect of holistic engineering practice. Students employ higher-level learning concepts on these problems, especially by including a stage where students *recommend* a final decision, supported by their design and analysis.

In the author's thermodynamics courses, PBL is typically applied to more advanced concepts, such as cycle analysis. These concepts provide an excellent gateway to considering the broader impacts of an engineering design. An example problem statement is included below.

> Select a developing region of the world with limited electrical power. Identify the region's population, economic base, natural resources, and potential demand for electricity. **Recommend** a source of energy (i.e., $\dot{Q}_{in}$) for the electric generation appropriate for the region and **propose** a power plant configuration operating on the superheated Rankine cycle to meet the anticipated power need. Include a thermodynamic analysis of the cycle and **estimate** the power output from the cycle and the annual revenue generated from the sale of electricity. Write a report summarizing your design, and especially discuss the assumptions you make.

Incorporation Of Computation

In addition to the PBL approach, the author has incorporated modern open-source software and Web-based technologies into the class. This replaces the use of static tables and shifts course content online to reserve face-to-face time for active learning practice, as discussed previously.

The primary piece of software in use is the Jupyter Notebook [10], [11]. Jupyter Notebooks are an open-source browser-based literate programming platform that allow users to combine prose, equations, multimedia content, and executable code *in the same document*. Jupyter Notebooks serve as an interface to a Python library that simplifies calculations of thermodynamic properties for simple compressible systems by eliminating table lookups and interpolation. This library, called ThermoState [12], provides a simplified interface to the CoolProp [13] library and uses the Pint [14] library to handle units.

There are several other software packages that provide similar replacement of tabular data, including TEST [15], EES [16], and Interactive Thermodynamics [17]. Unfortunately, these software packages are either commercially licensed, not open source, or cannot be integrated with Jupyter Notebooks.

Flipping The Classroom

The last aspect of the approach to active learning in the author's thermodynamics classes is "flipping the classroom" (FTC). FTC shifts most presentation of fundamental course content outside of the classroom, so students engage in the lower levels of Bloom's Taxonomy (remembering, comprehending, applying) on their own. This frees class time with the instructor to focus on the higher levels of learning. FTC has also been shown to be effective in increasing student engagement with the course material [18].

In practice, this means pre-recording lecture content videos. These videos are uploaded to an online video platform and embedded in an online quiz that reinforces the concepts from the videos. Students complete the quiz prior to attending lecture.

Data Collection

To evaluate the effectiveness of this approach, the author conducted an ad-hoc experiment over two semesters. In Fall 2018, the author recorded the lecture videos and used Jupyter Notebooks for student assignments. In Fall 2019, the author re-used the pre-recorded videos, but did not use

Jupyter Notebooks for assignments. The primary reason for the switch was administrative constraints on the course in Fall 2019.

Both classes were offerings of *Thermodynamic Principles*, which did not include problem-based learning activities. Nonetheless, the approaches of flipping the classroom and engaging students with active learning were pursued in both semesters.

Data was collected in the form of pre- and post-quizzes. The pre-quiz was given at the start of the semester to determine prior knowledge of thermodynamics concepts and the post-quiz was given at the end of the semester. Ideally, the pre- and post-quiz would contain the same questions. However, due to changes in the course format, the number and formatting of the questions differed in both semesters from pre- to post-quiz.

Finally, data was collected from the standard end-of-semester evaluations completed by the students. Students are asked to rank the course and the instructor on a scale of 1 to 5. These surveys are identical between the two semesters and are administered by the University.

Results and Discussion

Summary statistics for the two courses and the pre- and post- quizzes and student surveys are presented in Table 1. Recall that the Fall 2018 semester used Jupyter Notebooks and the Fall 2019 semester did not. Conducting a Student's t-test on the difference from pre- to post-quiz finds that the difference is significantly higher in Fall 2019 than in Fall 2018. Moreover, the mean pre-quiz score is significantly higher in Fall 2018 than in Fall 2019.

Despite the statistical significance of the results, there are likely to be several confounding factors that influence the result. First, the pre- and post-quizzes do not directly address the learning outcomes on Bloom's Taxonomy. In fact, the nature of the quizzes primarily focuses on the first three levels of the Taxonomy, rather than the three higher levels. Relatedly, the *Thermodynamics Principles* course did not address any problem-based learning objectives, which the author typically uses in the *Applied Thermodynamics* course. Unfortunately, comparison data between using and not using the Jupyter Notebook are not yet available for *Applied Thermodynamics*.

Second, the Fall 2018 semester was the first time the author used the flipped classroom technique. Responding to feedback from the students, the author improved the utility of contact hours in the Fall 2019 semester. Appropriately using contact hours when sections of the course have more than 80 students is an ongoing challenge, as discussed below. Improvements in the utilization of contact

Table 1: Summary statistics for two *Thermodynamic Principles* courses.

	Fall 2018	Fall 2019
Number of Students	148	155
Mean Final Grade	0.839	0.876
Mean Pre-Quiz Score	0.517	0.480
Mean Post-Quiz Score	0.585	0.727
Mean Score Difference	0.069	0.247
Student Median Rating of Course	4.0	4.0
Student Median Rating of Instructor	4.0	5.0

hours are supported by the median rating of the instructor, which increased from 4.0 to 5.0 from Fall 2018 to Fall 2019.

Third, the author changed the format of the pre- and post-quizzes between the semesters, and even within the Fall 2018 semester. These changes were driven by limitations in the course. Moreover, the questions on the pre- and post-quizzes were developed by the author. Since developing the quizzes, the author has learned about the PhysPort Conceptual Inventory and several of the resources located there [19], [20]. In the future, the author hopes to collect further data using a consistent format using questions that have been validated to evaluate thermodynamics instruction.

Aside from the statistical analysis, the author has collected responses from students on the standard end-of-semester evaluation forms. These comments, in addition to the high median rating of the course shown in Table 1, indicates students are generally in favor of the use of Jupyter Notebooks. Moreover, the author is aware of several students who have continued to use Notebooks to complete other coursework, e.g., data analysis for their laboratory courses.

Lessons Learned

The author has gradually incorporated more of the elements of the approach described above over the last several semesters. The following discussion is an account of some of the "lessons-learned" from the approach described in the previous section and future directions to be explored.

Lesson 1: Students Are Worried About Programming

In the Mechanical Engineering program at the University of Connecticut, students take a general "Introduction to Programming" course in their first year, so they have some experience with Python prior to taking *Thermodynamic Principles*. Nonetheless, they are often worried about applying programming to solve practical problems. The author finds a three-pronged approach works well to make sure that students can engage with the portions of the material that require programming.

First, it is crucial for students to recognize that some experience with programming will benefit their careers. As more and more design tasks are accomplished in software, the ability to automate simple tasks (e.g., report generation from a data table) or the ability to script within another application (e.g., to perform a parameter sweep in a design software) will be an important differentiator in their careers.

Listing 1: ThermoState code example demonstrating the output from an impossible unit conversion. The input syntax is from the IPython interactive terminal.

```
In [1]: from thermostate import Q_
In [2]: Q_(100.0, "degC").to("kg")
---------------------------------------------------------------
DimensionalityError Traceback (most recent call last)
<ipython-input-2-4110b6cbb00c> in <module>
----> 1 Q_(100.0, "degC").to("kg")

DimensionalityError: Cannot convert from 'degC' ([temperature]) to '
   ↪ kilogram' ([mass])
```

Second, make it as easy as possible for the students to get started. The Jupyter Notebook service runs on a University-owned web server and students log in using their University credentials in their web browser. Students do not need to install anything on their computers and they can start working immediately after logging in. This ensures that every student is working with the same version of the software and eliminates individual installation troubleshooting.

Third, make it as easy as possible for students to find and correct mistakes. This is done in the software by providing useful and actionable error messages. For instance, one of the most common errors students encounter using ThermoState is a `DimensionalityError`. This error message clearly states that the student is attempting to convert between units with incompatible dimensions, as shown in Listing 1.

Lesson 2: Get Regular Feedback From Students

If active learning is to improve student outcomes, then it stands to reason that students must be engaged with the learning. However, students may feel uncomfortable if it is their first time participating in active learning–doing something new is often uncomfortable. This may cause student engagement to lag and expected outcomes may not be achieved. Other students have pre-conceived, and in the author's anecdotal experience, mostly negative feelings about flipping the classroom.

The author has found that asking students about their expectations and asking them for feedback during the class is an effective method to engage with students and determine where and why they may feel uncomfortable. Listening to this feedback and making changes when it is reasonable to do so indicates to the student a good-faith effort on the part of the instructor to improve; this, in turn, may help the student feel more comfortable and much more willing to engage with the material.

Lesson 3: It Won't Work Perfectly The First Time

The author's experience is that faculty expect that trying a new technique in the classroom should yield perfect results on the first try. Perhaps we worry that students do not maximize their learning in a semester; perhaps we worry about perceptions of our colleagues or even our students if a technique is not very successful.

Frankly, in the experience and opinion of the author, these fears are overblown. First, students rarely maximize the amount they learn anyways. Thus, focusing on the volume of material the students are exposed to seems to be an inappropriate metric. We should instead be focusing on helping student to retain the most important concepts and reinforcing the importance of lifelong learning.

In addition, making incremental improvements is critical to ensuring that any new technique will be a success. It is not necessary to wait for the end of the term to solicit feedback (see Lesson 2). Using active learning techniques even for a single module in a course can improve outcomes for students and engage them with new material.

Future Directions

After implementing the approach described above over several semesters, the author has identified a number of future improvements and ongoing challenges with implementing active learning in their thermodynamic classes. First, evaluating the performance of individual students is challenging. Exams given in an online environment increase the chances for academic misconduct, particularly in large classes. The author has used a mix of take-home and in-class assessments, but this issue largely remains unresolved.

Second, further quantitative data should be collected to compare the efficacy of the approach described in the previous sections. This quantitative data can help inform which in-class activities are helpful and the impact on physical understanding when tabular property evaluation is replaced with a software-based process.

Conclusion

This manuscript presented an approach to implement active learning in engineering courses. The author applied this approach to two thermodynamics courses in the Department of Mechanical Engineering at the University of Connecticut over several semesters.

To assist students with problem-based active learning, the author uses Jupyter Notebooks paired with the Python-based ThermoState library. Together, these give students the tools to analyze and evaluate systems at a range of conditions that would not be possible with traditional table-based methods. In addition, most content is delivered in online video lectures. Contact hours are focused on activities that promote problem solving and conceptual understanding.

Data on the efficacy of this approach are limited by the informality of the experiments. Nonetheless, this approach has generally met with with overall student approval, judged by responses on the end-of-semester student course evaluations. Future steps involve continuing refinement of the in-class activities and procedures for handling assessments.

References

[1] *ABET | ABET accreditation*. [Online]. Available: `https://www.abet.org/`.

[2] *Criteria for Accrediting Engineering Programs, 2019 – 2020 | ABET*, en-US. [Online]. Available: `https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/`.

[3] N. E. Adams, “Bloom’s taxonomy of cognitive learning objectives,” *Journal of the Medical Library Association : JMLA*, vol. 103, no. 3, pp. 152–153, Jul. 2015, ISSN: 1536-5050. DOI: `10.3163/1536-5050.103.3.010`.

[4] B. S. Bloom, *Taxonomy of Educational Objectives: The Classification of Educational Goals*, 1st ed. Longman, 1956.

[5] C. C. Bonwell and J. A. Eison, *Active Learning: Creating Excitement in the Classroom*, ser. ASHE-ERIC Higher Education Report 1, 1991. Washington, DC: School of Education and Human Development, George Washington University, 1991, ISBN: 978-1-878380-08-1.

[6] 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,” en, *Proceedings of the National Academy of Sciences*, vol. 111, no. 23, pp. 8410–8415, Jun. 2014, ISSN: 0027-8424, 1091-6490. DOI: `10.1073/pnas.1319030111`.

[7] B. W. Weber, “Climbing Bloom’s Taxonomy With Jupyter Notebooks: Experiences in Mechanical Engineering,” in *Volume 5: Engineering Education*, American Society of Mechanical Engineers, Nov. 2019, V005T07A022. DOI: `10.1115/IMECE2019-10615`.

[8] ——, *Climbing Bloom's Taxonomy With Jupyter Notebooks: Experiences in Mechanical Engineering*, Mar. 2020. DOI: `10.31224/osf.io/cxema`. [Online]. Available: `https://engrxiv.org/cxema`.

[9] E. Tatar and M. Oktay, "The effectiveness of problem-based learning on teaching the first law of thermodynamics," en, *Research in Science & Technological Education*, vol. 29, no. 3, pp. 315–332, Nov. 2011, ISSN: 0263-5143, 1470-1138. DOI: `10.1080/02635143.2011.599318`.

[10] T. Kluyver, B. Ragan-Kelley, F. Pérez, B. Granger, M. Bussonnier, J. Frederic, K. Kelley, J. Hamrick, J. Grout, S. Corlay, P. Ivanov, D. Avila, S. Abdalla, and C. Willing, "Jupyter Notebooks – a publishing format for reproducible computational workflows," in *Positioning and Power in Academic Publishing: Players, Agents and Agendas*, F. Loizides and B. Schmidt, Eds., 2016, pp. 87–90. DOI: `10.3233/978-1-61499-649-1-87`.

[11] L. A. Barba, L. J. Barker, D. S. Blank, J. Brown, A. B. Downey, T. George, L. J. Heagy, K. T. Mandli, J. K. Moore, D. Lippert, K. E. Niemeyer, R. R. Watkins, R. H. West, E. Wickes, C. Willing, and M. Zingale, *Teaching and Learning with Jupyter*. May 2019. [Online]. Available: `https://jupyter4edu.github.io/jupyter-edu-book/`.

[12] B. Weber, "ThermoState: A state manager for thermodynamics courses," *Journal of Open Source Education*, vol. 1, no. 8, p. 33, Oct. 2018. DOI: `10.21105/jose.00033`.

[13] I. H. Bell, J. Wronski, S. Quoilin, and V. Lemort, "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp," *Industrial & Engineering Chemistry Research*, vol. 53, no. 6, pp. 2498–2508, 2014. DOI: `10.1021/ie4033999`.

[14] *Pint: Makes units easy — pint 0.9 documentation*. [Online]. Available: `https://pint.readthedocs.io/en/0.9/`.

[15] S. Bhattacharjee, *TEST: The Expert System for Thermodynamics - A Comprehensive Thermodynamic Web Portal*, Apr. 2019. [Online]. Available: `https://energy.sdsu.edu/testhome/index.html`.

[16] *EES: Engineering Equation Solver | F-Chart Software : Engineering Software*. [Online]. Available: `http://www.fchart.com/ees/`.

[17] M. J. Moran and H. N. Shapiro, "A review of "IT: Interactive Thermodynamics" Third Edition," en, *European Journal of Engineering Education*, vol. 21, no. 4, pp. 450–451, Dec. 1996, ISSN: 0304-3797, 1469-5898. DOI: `10.1080/03043799608913034`.

[18] C. Brame, *Flipping the Classroom*, en, Jan. 2013. [Online]. Available: `https://wp0.vanderbilt.edu/cft/guides-sub-pages/flipping-the-classroom/`.

[19] B. Brown, "Developing and assessing research-based tools for teaching quantum mechanics and thermodynamics," University of Pittsburgh, Jul. 2015.

[20] P. Wattanakasiwich, P. Taleab, M. Sharma, and I. Johnston, "Development and implementation of a conceptual survey in thermodynamics," *Int. J. Innov. Sci. Math. Educ.*, vol. 21, no. 1, pp. 29–53, Jan. 2013.