

Climbing Bloom's Taxonomy With Jupyter Notebooks: Experiences In Mechanical Engineering

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Abstract

Active learning techniques are well known to improve student outcomes and shift their thinking higher on Bloom's Taxonomy. In this paper, I will present experiences from my implementation of active learning in sophomore-level Mechanical Engineering thermodynamics classes using Jupyter Notebooks. Jupyter Notebooks are a web-based programming environment widely used in software and other industries that allows students to combine code with equations and explanations of their work. By using this software to solve open-ended design problems, students move from the Remember, Comprehend, and Apply steps of Bloom's Taxonomy to the Analyze, Synthesize, and Evaluate stages. Successfully integrating Jupyter Notebooks with these classes has required a shift in the focus of contact hours, going from didactic presentation of material to active practice with problem-solving techniques; most class material has been moved online. This approach has been successfully implemented over several semesters, but there are nonetheless still improvements to be made, which are discussed at the end of the manuscript.

Introduction

Active learning is a practice where students engage with new course material, instead of passively receiving material presented by an expert [1]. A substantial amount of research shows that student outcomes are improved

by engaging in active learning [2]. This includes not only higher grades in courses, but also greater “mastery of higher- versus lower-level cognitive skills” [2].

Typically, levels of learning and cognitive skills are categorized by Bloom’s Taxonomy [3]. Bloom’s Taxonomy was established in 1956, when *Taxonomy of Educational Objectives: The Classification of Educational Goals* was published (Benjamin Bloom was one of the editors of this volume, whence *Bloom’s Taxonomy*) [4] and has undergone several updates since the original publication.

Bloom’s Taxonomy identifies six levels of learning; from lowest to highest these are:

1. Remember
2. Comprehend
3. Apply
4. Analyze
5. Synthesize
6. Evaluate

Most University-level courses achieve the first three levels of the Taxonomy, independent of the style of the course. However, as discussed by Freeman et al. [2], active learning promotes the higher three levels of learning: Analysis, Synthesis, and Evaluation.

Achieving these higher levels of learning is essential to train engineers who can approach the challenges facing 21st-century human endeavors. In addition to the levels of learning, modern engineers must be holistically trained to recognize appropriate solutions to these challenges. In this sense, holistic training encourages engineers to identify not only the technical aspects of a problem, but the ethical, social, economic, and environmental aspects of a problem as well.

University engineering programs in the United States are accredited by ABET, a “non-profit, ISO 9001 certified organization that accredits college and university programs in applied and natural science, computing, engineering and engineering technology” [5]. The ABET accreditation board has identified the need for holistic education in their recent redevelopment of the student outcomes criteria; item two in the list of seven outcomes states [6]:

an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors

and item four states [6]:

an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.

In light of these factors, the author identified an opportunity in the sophomore-level thermodynamics courses he teaches at the University of Connecticut (UConn). By leveraging modern open-source software, Web-based technologies, and widely-used classroom techniques, the author has implemented active learning to push students to higher levels of learning on Bloom’s Taxonomy and engage them in holistic learning. The remainder of this manuscript describes the author’s motivation to implement these changes in his classrooms, the technologies the author has integrated, and several lessons-learned from his experiences at UConn.

Motivation

Many traditional thermodynamics classes and textbooks rely on tables of properties for simple compressible systems that students use to solve problems. These tables usually require students to perform an inordinate number of simple arithmetic calculations. These calculations impede students’ understanding of the underlying principles of the system under study and increase the chances for a trivial error to creep into a problem solution.

Moreover, using tables limits the kinds of problems that students can study. Requiring students to interpolate in tables means they can realistically study the behavior of a given system under one set of conditions. Therefore, students cannot understand the behavior of a system under a range of states to identify optimal operating conditions, or how system performance changes as a function of inputs.

These factors combined limit students to solving problems with one, correct, answer at the end of the problem. However, no “real” problem has

one definitely-correct answer; due to the interaction of ethical, social, economic, and environmental aspects, the problems that engineers can expect to encounter after leaving the University generally have many solutions that require engineers to evaluate the outcomes and engage with stakeholders and communities to identify the appropriate solution.

In addition, it is well known that solution manuals for problems included with textbooks are readily available online. Although the use of such resources is explained to the students as a clear violation of the University Academic Integrity policy, students nonetheless utilize solution manuals and other similar resources to “assist” in solving homework problems. In addition to violating the Academic Integrity policy, using solution manuals inhibits student understanding of the material.

Therefore, from a purely pragmatic standpoint, it would be useful for instructors to have a way to redefine the given conditions in a problem. Of course, this can be done by hand, either by developing new problems or new solutions to existing problems. Both of these approaches involve a significant investment of time that could be better spent improving pedagogy in other areas. Thus, a method to replace the use of tables in thermodynamics problems would benefit both students and instructors.

Aside from the obstacles due to the use of tables, students often have difficulty communicating complex engineering evaluations to a broad audience. In previous surveys of our Capstone course in Mechanical Engineering at UConn, we have identified that students struggle to communicate, especially in writing, although they improve substantially over the year-long course [7]. Therefore, incorporating a communication element in the target course gives students the opportunity to practice prior to their Capstone project.

Finally, as discussed in the Introduction, lifting students to higher levels of learning 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 [2], especially since the courses enroll between 60–80 students per section.

Approach

The strategies discussed in this manuscript have been applied to two thermodynamics courses in the Department of Mechanical Engineering at UConn. The two courses, *Thermodynamic Principles* and *Applied Thermodynamics*

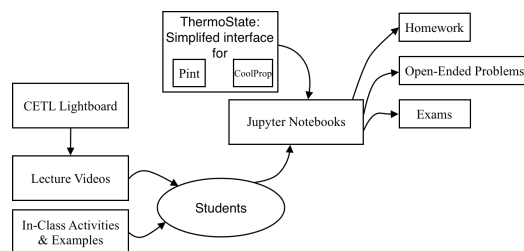


Figure 1: Overview of the interaction between elements of the approach used to engage active learning and move higher on Bloom’s taxonomy in the author’s thermodynamics courses.

are a sequence that covers the major topics in thermodynamics related to Mechanical Engineering:

- First law of thermodynamics
- Second law of thermodynamics
- Conservation of mass
- Identification of systems, states, properties, and processes
- Evaluating properties of simple compressible systems and ideal solutions
- Analysis of systems and cycles, including the Rankine, Brayton, Otto, Diesel, Stirling, Ericcson, and refrigeration cycles

Typical enrollment in these courses is approximately 150–180 students per semester, usually split into several lecture periods.

Figure 1 shows an overview of the elements the author has developed to engage students in active learning and higher on Bloom’s Taxonomy. Prior to class time, students watch lecture videos recorded using the Lightboard facility in the Center for Excellence in Teaching and Learning at UConn. These videos are embedded in an online quiz that reinforces the concepts from the videos.

During class time, students apply the knowledge from the lecture videos during guided in-class activities and examples. Outside of class, students utilize open-source web-based software to solve homework problems, take exams,

and conduct analysis for their open-ended problems and reports. These software projects include the Jupyter Notebook [8] and a custom Python library to evaluate thermodynamic properties called ThermoState [9].

Each aspect of this approach is discussed in more detail in the following sections.

Problem-Based Learning

The overall approach taken in this work is to incorporate problem-based (PBL) learning into the thermodynamics courses. According to Tatar and Oktay [10], who surveyed the literature on PBL, the most relevant aspects of PBL are [10]:

- More than one solution should be possible for the problem
- Authenticity of the problem, so that students can relate to and engage with the subject and are motivated to consider the problem thoroughly
- Students should not immediately be able to identify all of the relevant information and some research should be necessary
- Students should engage higher-level skills from Bloom's Taxonomy such as synthesis, analysis, and evaluation to make a recommendation, judgment, or decision
- The problem should connect students to new knowledge and concepts by extending their existing knowledge

These points satisfy many of the Motivations, the criteria identified for appropriate implementation of active learning, and the higher-level learning themes on Bloom's Taxonomy identified above. Thus, PBL seems to be an ideal approach to achieve the objectives of this work.

PBL problem statements are developed to incorporate student interests and tie into 21st-century engineering needs. These include environmental protection, health protection, economic considerations, and addressing inequities in access to, e.g., electricity among other resources. Several example problem statements are 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.

Design a solar collector plant using water/steam as the working fluid, operating on the superheated Rankine cycle. **Recommend** a location for your plant based on availability of solar energy and nearby communities that would use the power. **Estimate** the power required by the nearby communities and based on the local solar irradiance, **estimate** the area that needs to be covered by reflectors to produce that power output (this may require an **estimate** of the efficiency of the reflectors). Finally, **provide an estimate** of the annual power output and revenue from operating the power plant.

Not all of the projects are “serious:”

You are a moisture farmer on the planet Tatooine. Investigate the typical humidity of a summer day in the location where the Tatooine scenes were filmed in the Star Wars films. Design a collection system to collect enough water for 3 people to drink, cook with, and clean with for 1 day. Choose a refrigeration cycle to work with, and estimate the power input required and the annual cost to operate the system. Make recommendations for the feasibility of such a setup. Could a family make enough money to live on by farming moisture?

Each project should incorporate the aspects of PBL discussed earlier, particularly the aspects of engaging the interest of students and students employing higher-level learning skills. This latter point is accomplished on the sample assignments shown here by including a stage where students *recommend* a final decision, supported by their design and analysis.

In addition to the project assignments, a rubric is distributed so students are aware of the criteria they will be graded on. This rubric incorporates seven categories, with the points weighted towards a description of

the methods the students employed (i.e., the equations and thermodynamic states they used in their design) and the results, discussion, and recommendation from their analysis. The seven categories with their point values are:

1. Document Structure: 1 point
2. Methods: 4 points
3. Results and Discussion: 12 points
4. Organization: 3 points
5. Mechanics (spelling and grammar): 2 points
6. Formatting: 4 points
7. Completeness: 2 points

This totals 28 possible points for a report; an additional two points are awarded if students hand in a draft report prior to the submission of their final copy. Typically, graders will evaluate the draft and provide comments so students can improve their work before the final submission.

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.

The primary piece of software in use is the Jupyter Notebook [11, 8]. Jupyter Notebooks are a browser-based literate programming platform that allow users to combine prose, equations, multimedia content, and executable code *in the same document*. Jupyter Notebooks are free- and open-source software developed by an international team of software engineers, scientists, and educators.

Substantial documentation for the installation and use of Jupyter Notebooks are available online [12], so these topics will not be covered in this manuscript. In addition, Barba et al. [13] have developed a book discussing the use of Jupyter Notebooks in education. Interestingly, this book is itself written in Jupyter Notebooks, demonstrating the flexibility of the format.

In the author’s thermodynamic classes, Jupyter Notebooks serve three primary uses for students. First, students use the Jupyter Notebooks to conduct calculations for their open-ended PBL projects. This enables them to conduct multiple calculations and plot the results in an intuitive interface. Second, students complete their homework assignments in the Jupyter Notebook, so that they are familiar with the Notebook format before they conduct their projects. Third, students use the Notebooks on exams, in a manner similar to homework problems.

In addition to Jupyter Notebooks, the author has developed a Python library that simplifies calculations of thermodynamic properties for simple compressible systems by eliminating table lookups and interpolation. This library, called ThermoState [9], provides a simplified interface to the CoolProp [14] library. CoolProp provides accurate Helmholtz equations of states for 122 different pure fluids, including all of the fluids commonly used in problems in the thermodynamic courses (e.g., water, ammonia, R-134a, carbon dioxide, etc.).

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 commercially licensed, not open source, and cannot be integrated with Jupyter Notebooks. Other, more general, software such as Cantera [18] do not include the breadth of fluids necessary for most courses.

ThermoState also uses the Pint [19] library to handle automatic conversion of units. This helps eliminate one major class of errors students make—unit conversions and attempting conversions that are not dimensionally consistent. The author emphasizes the fundamental dimensions of quantities (i.e., length, time, temperature, amount, mass, electrical current, and luminous intensity) and the idea of dimensional homogeneity of equations as part of the course material. Since the automatic unit conversions conducted by Pint require dimensional consistency, students are equipped to understand the error messages when an inconsistent conversion is attempted and students are prompted to correct their work.

Despite the numerous advantages of using software for property evaluation, the author has found that entirely replacing table lookups and interpolation with software has changed students’ understanding of the physical nature of the vapor dome. In response to this observation, the author reintroduced “by-hand” problem solving using the tables for selected problems. In addition, the author typically requires students to sketch p - v , T - v , T - s , or

other similar representations of the phase space to emphasize the relationships between properties, especially pressure and temperature during phase changes. These sketches are required on both computer-based and table-based problems.

In addition to required table-based problem solving, the author emphasizes the physical nature of the phase change behavior by conducting a simple experiment during face-to-face class time. A beaker of water is set on a hot plate and brought to boiling. A thermocouple is placed in the water the temperature display is projected so the whole class can see. The water is left to boil for most of the lecture period so that students observe the temperature is constant at the saturation temperature during the phase change process. The author has also 3-D printed a representation of the p - v - T surface for water, including the solid, liquid, and vapor regions and the associated phase changes regions. These physical reminders of the nature of phase changes help reinforce that tables and software are only representations of physical reality.

Mixing table-based and software-based problems also affords the opportunity to reinforce the concept of reference states. The refrigerant fluids whose equations of state are implemented in CoolProp tend to use the IIR reference state ($h = 200 \text{ kJ kg}^{-1}$, $s = 1 \text{ kJ kg}^{-1} \text{ K}^{-1}$ at 0°C saturated liquid). However, the textbook that is used for our classes tends to use the ASHRAE reference state ($h = 0 \text{ kJ kg}^{-1}$, $s = 0 \text{ kJ kg}^{-1} \text{ K}^{-1}$ at -40°C saturated liquid). This prompts students to investigate why the absolute values of specific internal energy, specific enthalpy, and specific entropy differ between the software and the tables, and demonstrates that only differences in these properties should be compared.

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, typically by working on additional problems or examples. FTC has also been shown to be effective in increasing student engagement with the course material [20].

In practice for the author, this means recording lecture content in videos

to be posted on YouTube. Students watch these videos and complete a comprehension quiz early in every week of the semester. During face-to-face time, students work individually and in groups on examples and worksheets that support their problem solving capabilities.

Future Directions

After successfully 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 his thermodynamic classes. These include:

1. In-class activities have included group worksheets and discussions. However, other activities such as games, debates, and student presentations may also be effective uses of the face-to-face time.
2. Exams are an ongoing issue. Students need to use their computer to solve problems in the Notebook, but not all students have laptops they can bring into a classroom. In addition, violations of the Academic Integrity policy become much easier when students have access to search engines and chat features during exams; there may be methods to remove access to some of these, but they may not be easy to implement.
3. Distributing class materials to students is challenging. Depending on the learning management system at a University, posting links to homework assignments, lecture quizzes, and lecture videos may be a large administrative burden.
4. 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. This active learning practice has improved student engagement with with material and helped them climb Bloom’s Taxonomy to higher levels of learning.

Overall, the author implemented problem-based learning into the classroom. Problem-based learning encouraged students to examine material in open-ended problems, leading them to use analysis, synthesis, and evaluation that they would not use on traditional well-structured (i.e., “one correct approach”) problems.

To assist students with solving these kinds of problems, the author uses Jupyter Notebooks paired with the Python-based ThermoState library. Together, these give students the opportunity to avoid trivial arithmetic and examine systems at a range of conditions that would not be possible with traditional table-based methods. In addition, the author has flipped the classroom, moving most course content into video lectures and online quizzes that students view before coming to class. During class time, students work on group worksheets and other activities to reinforce problem solving techniques and leverage their comprehension of the material built outside of class.

This approach has been quite successful at UConn, with strong student approval (judged by responses on the end-of-semester student course evaluations) over several semesters of implementation by the author. Future steps involve continuing refinement of the in-class activities and procedures for handling assignments and administration of the course.

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